Characterization and machinability study of Rajasthan's marble stone for sustainable processing

Ph.D. Thesis

by

BHARGAV PRAJWAL PATHRI

(2013RME9044)

DEPARTMENT OF MECHANICAL ENGINEERING

MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY

JLN MARG, JAIPUR-302017, INDIA

August, 2018

Characterization and Machinability Study of Rajasthan’s Marble Stone for Sustainable Processing

Submitted in

fulfilment of the requirements for the degree of

Doctor of philosophy

by

BHARGAV PRAJWAL PATHRI

(2013RME9044)

Under the supervision of

Dr. Halal Singh Mali

&

Prof. Ravindra Nagar

DEPARTMENT OF MECHANICAL ENGINEERING

MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY JAIPUR

August 2018

DEDICATION

I dedicate this work to the most important people in my life:

My mom, dad, sister and my beloved wife

"Thank you for your help and support"

DECLARATION

I, **Bhargav Prajwal Pathri**, declare that this thesis titled, "**CHARACTERIZATION AND MACHINABILITY STUDY OF RAJASTHAN'S MARBLE STONE FOR SUSTAINABLE PROCESSING**" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis based on the work done by myself, jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Date:

Bhargav Prajwal Pathri
(2013RME9044)

CERTIFICATE

This is to certify that the thesis entitled "**CHARACTERIZATION AND MACHINABLITY STUDY OF RAJASTHAN'S MARBLE STONES FOR SUSTAINABLE PROCESSING"**, is a bonafied research work carried out under my supervision and guidance in fulfillment of the requirement for the award of the **Doctor of Philosophy** in the Department of Mechanical Engineering, Malaviya National Institute of Technology, Jaipur India. The matter embodied in this thesis is original and has not been submitted to any other University for the award of any other degree.

Signature of Supervisor

Dr. Harlal Singh Mali

Department of Mechanical Engg

MNIT, Jaipur

Signature of Supervisor

Prof. Ravindra Nagar

Department of Civil Engg

MNIT, Jaipur

Place: Jaipur

Date:

ACKNOWLEDGEMENT

I would like to gratefully and sincerely thank my supervisors Dr. Harlal Singh Mali and Prof. Ravindra Nagar for their discerning, uncompromising guidance, understanding, patience for helping me to complete my thesis. Their mentorship was paramount in providing a well-rounded experience consistent my long term career goals. They encouraged me to not only grow as researcher but also as an instructor and independent thinker. I am not sure many post graduate students are given the opportunity to develop their own individuality and self-sufficiency by being allowed to work with such impendence. I would like to thank all of the members of the research group, especially Jaikishan Sambharia and Deepak Rajendra Unune, for their constant support and encouragement given in hostel as well as in my research.

I am thankful to my parents Vishwendra Prasad and Latha for giving me freedom to choose my carrier path and allowing me to be as ambitious as I wanted. I am indebted to them for their constant encouragement to pursue my dreams. It was under their watchful eye that I gained so much drive and an ability to tackle challenges head on I would like to thank my beloved wife Prajwala. Her support, encouragement, quite patience and unwavering love were undeniably the bedrock upon which the past Nine years of my life have been built. Also, I would like to thank my sister sharanya and niece snithika make me forget all my stress by seeing her cute smile.

I acknowledge the partial financial aid provided by centre for development of stones (CDOS) research project No- 0290032, an autonomous institute supported by the Government of Rajasthan for funding the project.

I thank Malaviya National Institute of Technology (MNIT), Jaipur for supporting my research by providing the research scholarship and to the Advanced Manufacturing and Mechatronics Lab (AMMP), Materials Research Center (MRC) for providing the facilities and support, without which the present work would not be possible. I would like to thank Head of the Department, faculty, and staff members of Department of Mechanical Engineering, Materials Research Center, and various other departments in MNIT Jaipur for their help and support in direct or indirect way throughout my time in MNIT Jaipur. I like to thank all my lab mates Divyanshu Gupta, Nancy Chaudhary, Rupali Baghel, Umesh sahoo, Nitesh Kandodiya, Sandeep Tiwari and Arjun Yadav for their cooperation and support. I would also like to thank lab technicians Sandeep Thakur and Dipak Kumar for their assistance. I would like to thank Jacob from Ohio university and Kayle from Colorado state University for helping me correct my pre-synopsis report. Finally, I would like to thank my close friend Vartika Kulsherstha for her constant help and encouragement given for past many year’s.

Bhargav Prajwal

ABSTRACT

Rajasthan is known as majestic state as it produces more than 50 types of minerals and rocks. The state is endowed with vast deposits of natural rocks known as stones in local parlance and few amongst them are granite, marble, sandstone, limestone, slate and quartzite. Perhaps, nowhere in the world social, economic and cultural fabric of the society is found to be so intimately ingrained with stone and stone products as it is in Rajasthan state of India. The stone industries in India not only provided occupation to the people but also ignited the poetic expression in the people of this state so they vividly found expression in various colours and carvings in various marble build monuments of the state. Marble is a white based elegant looking stone, geologically a thermally metamorphosed rocks belonging mainly to Precambrian rock formations of Rajasthan, spread over in 16 belts in 15 districts of the State is much sought after stone. The world famous Taj Mahal and Victoria Memorial are built of Marble produced from the Mines of Makrana (Rajasthan). Ten types of marble on the basis of colour variation have been identified which are Plain white, Panther white, white veined Plain Black, Black Zebra, Brown, Green, Pink Adanga, Pink and Grey. The ever increasing popularity of the marbles of Rajasthan, growing demand for finished and unfinished products, discovery of new marble deposits and growing private and public supports have led to a significant growth in Marble Industry of this State. As a result, number of marble quarries as well as marble processing units have significantly gone up mainly during last one decade. However, whereas there is significant growth in production of finished and unfinished marble products, there is also simultaneous rise in waste generation as well; thereby causing concern towards the deteriorating environmental quality. A wide spread need is being felt to make this industry environmentally sustainable.

The aim of the project is to study the morphology of different marble stones present in and around of Rajasthan region such as (Makarana White, Bhainslana Black, Agaria White, Udaipur Green and Aandhi White) using petrographic analysis. Then, to characterize them physically, mechanically as well thermally in order to find out various properties which influence the wear of the tool. Finally, optimize the machining parameters such as feed, speed and depth of cut in order to find out the best possible combination to increase the efficiency of the machining as well as the tool life.

To find some possibilities and opportunities for development of the marble stone industry a complete Life Cycle Assessment (LCA) was developed scientifically using cradle to gate approach with neat venn diagrams and flow charts. The sustainable study was carried out using donut-modelling technique to represent the knowledge management strategies in safe and sustainable environment. By using, this donut-modelling technique an Index of sustainability or Environment Sustainability Index (ESI) has been proposed. Further, a case study was conducted in several industries to identify different cutters that are currently used in the Rajasthan region. Various facts and statistics like number of working hours and life of the tools were also estimated after the case study. The collected inserts of the tools from industries were characterized to find the composition. An energy audit was also, conducted in all these industries to find the energy consumption, and waste disposal methods that these industry currently carry out with a detail flow chart. The powder extracted from machining process is characterized rheologically with different coolants in order to find the behavior of viscosity with respect to temperature and time. A low cost 3-axis strain gauge milling tool dynamometer set up was designed and fabricated to record the forces generated while performing milling operations on marble samples, a multiphase digital energy meter is attached to Bridge port milling machine to find the energy consumption. The machining parameters like cutting force, speed, feed, amount of coolant supplied and depth of cut are optimized to increase the energy efficiency.

Diamond tool wear is effected by the mineral composition of the stones to be cut, different segment wear states that can be found, depending on the type of segments as well as the machining parameters. This wear was calculated radially by measuring the heights of all individual segments of the sawblade. A regression and correlation analysis was established between marble properties and specific wear rate. Significance of the relations were checked statistically and validity of the relations were also evaluated by using some statistic tests. The R-squared value which is also termed as the co-efficient of determination, it’s the segment of variance of dependent parameter which could be predicted by any independent parameter.

Rheological investigations of several mixtures were prepared using marble powder and different coolants with different ratios were mixed and tested using Bingham flow model to plot mean values of yield stresses on different samples plotted as a function of time showed highest value of yield stress for marble/water ratio of 0.5.

Specific energy consumption while performing milling operation on marble was calculated. It is a key parameter to be reviewed in natural stone industry which directly influence the scrutiny and fabrication scheduling. To know the effect of the parameters experiments were performed using Taguchi L16 orthogonal array to find the most significant parameters which help in minimizing the specific cutting energy Bridgeport Interact 1 MK-II 3-axis CNC milling machine having a maximum RPM of 4000. Diamond coated end mill cutters of Diameter 10 and 12 mm were used for the experimentation. A three phase digital energy meter is used to constantly record the power consumption. Artificial neural network is finally used to predict the specific energy (SE) and found that the results are in close agreement with the actual experiments.

Most of the marble processing activities are performed by small and medium scale industries (SME's) not only in India but worldwide. These industries have low efficiency and productivity due to the lack of new technologies, high productivity cost and coupled with lack of proper sustainable management system there by increasing the waste generated during the processing stage. There is a significant need within the sector for increasing the production efficiency, combined with substantial reduction in waste generated that can be achieved by endorsing technological innovations, following best available processing practices, incorporating energy saving technologies and modernizing the sectors management and organization structure will substantially increase the efficiency as well as production. A systematic approach for assessing the current energy and present environment status of a typical SME processing units of Rajasthan area, and proposes measures for meeting cleaner production principles. An evaluation methodology was developed considering the realistic plant operation scenarios. The total energy inputs for processing the products with their appropriate environmental indices like CO_2 emissions were calculated. Alternatively the CO2 emissions were also calculated by Gabi educational software for different industries and the best way of reducing the energy consumption is suggested by following alternate source of energy.

Table of Contents

List of Figures

List of Tables

NOMENCLATURE

GHG	Greenhouse gases
LOI	Loss of Ignition
SEM	Scanning electron microscopy
A	Weight of the dried sample
B	Weight of the specimen in air after immersion in water
R	Modulus of rupture
W	Breaking load
L	Length of span
Bi	Width of specimen
d	Thickness of the specimen
C	Compressive strength
F	Failure load of specimen in newton
Aa	Area of the breaking surface
n	order of reflection
λ	Wavelength of x-rays
d	Interplanar distance
θ	half angle between incident and reflected beam
AFM	Atomic force microscopy
DMA	Dynamic mechanical analyzer
TGA	Thermo-gravimetric analysis
h_{eq}	Equivalent thickness
d_p	Depth of cut
Va	Cutting feed
Vt	Cutting speed
ft	Radial force
fc	Tangential force
Kt and Kc	Cutting force co-efficients
Fc	Tangential cutting force

Ft	Radial force
$\tau 0$	Yeild stress
a	Viscosity term
b	Constant
M1	Makarana
M2	Bhainslana black
M3	Andhi
M4	Sea green
M5	Agaria
Q	Quartz
L	Lime
P	Priclase
H	Hematite
EDDG	Electro discharge diamond grinding
EDM	Electro discharge machining
SWR	Specific wear rate
V_Q	Quartz volume percentage
V_L	Lime volume percentage
V_P	Priclase volume percentage
V_H	Hematite volume percentage
Hg	Hematite max grain size
Qm	Quartz mean grain size
Lm	Lime mean grain size
Pm	Priclase mean grain size
Hm	Hematite mean grain size
SE_{cut}	Specific energy cut
DOC	Depth of cut
WOC	Width of cut
FW	Finishing waste
MW	Mining waste
PW	Processing waste
POLATW	polishing and transportation waste

LCA	Life cycle assessment
ESI	Environment sustainability index
LCEA	Life cycle energy assessment

Chapter 1: Introduction

"*The term marble is derived from the Latin word murmur which in turn is said to have coined from Greek word Marmorous meaning shining stone*". It is known for its pleasant colors, smooth and uniform textures and rigidity. In geological definition any calcareous rock capable of taking polish are classified as marbles. Furthermore the serpentine rocks, containing little calcium or magnesium carbonates, if looks aesthetic and capable of taking polish on them are also classified as marbles. Marble is defined commercially as any crystalline rock composed predominantly of calcite, dolomite, or serpentine that is capable of taking polish. Calcareous materials consists of approximately 57%, siliceous materials for around 38% and slate about 5% of total world production.

Each stone is formed under different chemical, physical and thermal conditions which results in formation of a wide variety of group of minerals and hence find different applications. These, rocks are hard, soft, permeable and impermeable. They are available in various size and shapes. Stones are used for various purposes starting from construction of roads, bridges, buildings, tables in kitchen, as gem stones or can be used as decorative items in your garden. Marble used in construction industry is termed as dimensional stone. Apart from marble uses in construction, medical and architectural industry, there are some general commercial uses of marble stone. Commercial uses of Marble include cemetery markers, commemorative tablets, creating artwork, curling, laboratory bench tops, paper industry, tomb-stones, whitening material in toothpaste, paint and paper. According to the marble features like texture, appearance, hardness, streak, toughness, resistance etc., it is used for various antiquity uses. Antiquity uses of marble include artifacts, monuments, and sculptures.

The defining feature of the marble stone is that unlike other minerals which have value mainly as a result of physical properties, the ultimate success of it in marketing the marble stone lies firstly in its appearance and secondly the possibility of producing rectangular blocks of suitable dimensions [1]. Hence, some authors term it as the '*ornamental stone*'. These, ornamental stones mainly emphasizes on the decorative aspect for its use to allow for successful production of the final product in the required dimensions. The major application of these dimension stones is in construction sector which accounts to almost 80%, with the funerary and monumental industry accounting to 15% and other special applications accounts to about 3% (shown in the Fig.1)

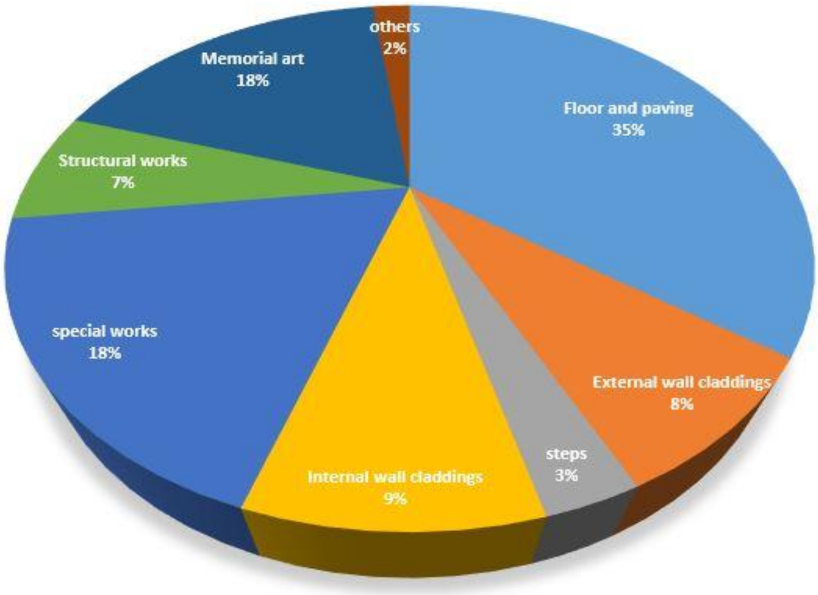


Fig.1 Use of marble stones

Marble extraction process begins from quarry, where big blocks are extracted from rocky mountains. This extracted blocks are supplied to the construction industries through three stages. At first stage extracted blocks are transported to cutting (factories and workshops) to be sliced and turned into required dimensions to suit construction and building applications. At Second stage, these blocks from cutting factories are sent to polishing processing units where required polishing is done. At final stage the remaining small pieces of stones which cannot be used for construction and building are transported to crushers where they are further crushed into aggregates of different sizes, to be directly used as raw material in concrete mixtures. Dried stone powder from polishing and processing’s units can be utilized at construction site. The remaining waste from buildings can be re-sized and returned back to quarries to fill the excavation site in order to reclaim the land and improve the landscape of the site. After demolishing the built houses for many reasons, stones from it can be re-used by returning back to the cutting and polishing process before being used as rebuild again.

1.1 Sustainability defined

Sustainability is defined by Brutland as " Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs", the process that helps to create a high quality life, while respecting the need to sustain natural resource and protect environment. In easy terms it can be explained as 'using, conserving and enhancing the societies resources so that ecological processes, on which life depends, are maintained, and the total life, now and in the future, can be increased. Sustainability can also be defined by (TBL) triple bottom line, it is an accounting framework that incorporates three dimensions of performance: social, environmental and financial. This differs from traditional reporting frameworks as it includes ecological and social measures that can be difficult to assign appropriate means of measurement. The TBL dimensions are also commonly called three Ps: people, planet and profits[2] [3].

As marble stone is a natural product, it is inherently environment friendly. Marble stone currently offers attractive, environmentally friendly attributes, including an enduring life-cycle, durability, ease of care and maintenance, recyclability, quarrying and manufacturing best practices. Construction of green building requires careful thought and planning. Conventional building practices consume large quantities of energy and water, while generating excessive ntional air emissions and waste streams. Implementing green building techniques reduces impacts on the environment and human health during both construction and operation of a structure as well as production of building materials. For this it is necessary to understand the marble stone processing and its sustainable production.

1.2 Marble stone processing

A block is a big rock which is extracted from the quarrying site or mainly open cast mines which has a dimension of about 2.2 m x 2.15 m x 3.2 m. Once these blocks are extracted, they are transported to the processing units, and the waste is sent to the disposal units using trucks and loaders. Once the blocks from the quarry reach the processing unit, they undergo a series of stages that transform them into final products. In today's market, high quality polishing and highly accurate dimensions are very important.

The processing phase is extremely vital for marble stone industry. The commercial value and the processing cost of all marble stones are not the same. Different stones have different processing cycles, require different machines and employ different technologies. Generally, the processing of marble stones is carried in the following stages viz. block squaring, sawing them into slabs, polishing of slabs, cutting slabs into strips, cutting strips into tiles and finishing.

1.3 Sustainability for marble stone processing

Over the past decades, there has been a huge rise of concern for environmental protection. Human activity has brought harmful effects on the environment in several ways, and it is a source of concern to deal with issues such as environmental sustainability, preservation of marble resources for the future generations, energy efficiency, change in the climate and many more. Some countries have already undertaken environmental safeguard policies, which are trying to reduce the pollution emissions by minimizing the usage of non-renewable resources. Building activities are the major cause of demand for construction materials. The need for raw materials for buildings makes quarrying activity strategically important for economy. Construction materials either aggregates, or marble stones are used in the development of all buildup environments, such as housing, building bridges, other civil engineering works like local hospitals, schools, roads, railways and other infrastructures.

Processing activity for the building and construction industry generates a huge amount of stone waste, since a significant percentage of total stone extracted usually left unused. Quarries of aggregates by their nature do not produce large amount of waste, while other processing's producing marble stones usually bring a huge amount of waste. The reason is that the marble stones are natural rock materials which are quarried and processed for commercial purposes. Extracted stones are formed into blocks, slabs, and tiles etc. which are required to be cut to specific dimensions according to the customer requirement like shape and size, to be economically attractive to be sold worldwide.

Processing waste require careful management to ensure the long term stability of storage and disposal facilities and to prevent and minimize air, water, soil contamination [4] . The inappropriate or unsafe management of waste at processing units continues to generate opposition from local communities, the general public, and non-government organizations and has contributed to the negative public perception on marble processing's. The technological advances and changes in the regulations have resulted in the significant changes in the waste management practices over the last 10 to 20 years, processing wastes at modern units are better managed than that were in the past [5]. Waste management plans are developed before a processing plant is constructed, and the reclamation of waste dumps and tailing ponds are incorporated into the design of the new processing plant.

1.4 International scenario of marble stone Industry

The important natural stones produced in the world in terms of market size are marble and granites respectively. Production of marble compared to granite is high so the waste generated is also high in terms of marble waste.

The major producer of the raw materials stone are China, India, Italy, Iran, Turkey, Brazil, Egypt, Portugal, USA, Greece, France and South Africa. While the major consumers of finished goods are China, USA, India, Italy, South Korea, Germany, France, Japan ,Taiwan Brazil and UK. Taking into consideration of the global natural stone sector, analysis was carried out to record the production at the international level. Data processing has been taken from different sources [6][7] and tabulated below in Fig.2 so as to include and compare data of production, exports and imports of the dimension stone sector.

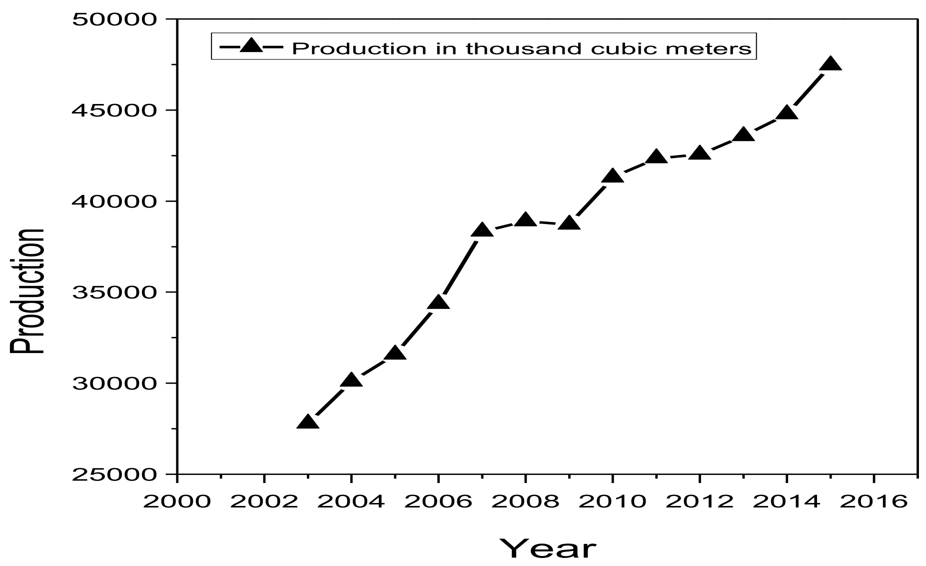


Fig.1.4.1 World production of marble stone in thousands cubic meters 2003-2015

Resources of marble stones are important in the world and almost every country produces dimension stones. Major exporting countries of marble in the world, are China, Italy, India, Spain, Turkey, Greece, Brazil and Portugal.

Table. 1.4.1 Exports of marble by different countries in cubic meters

	2011	2012	2013	2014	2015
India	8147	7572	8719	9511	11634
China	34381	36794	42941	38570	36450
Egypt	17425	21346	20740	16878	15987
USA	3406	4415	2263	6816	7354
Italy	14551	5363	5570	6948	7746
Germany	841	995	1655	1434	1543
UAE	8526	4273	1635	3686	4356
Other Countries	26007	29010	34649	32613	35654

Table. 1.4.2 Imports of marble by different Countries in cubic meters

	2011	**2012**	**2013**	**2014**	**2015**
India	1766	1668	1784	2914	2078
China	16892	21427	25067	21745	24567
Egypt	9123	10164	14135	14611	15435
USA	286	2327	1246	1343	1434
Italy	83686	122605	143384	147388	153455
Germany	131	427	356	367	423
UAE	11072	12680	2067	3815	3987
Other Countries	11054	16445	16390	7960	15456

Observing the trends, over the period (2011-2015) there is a positive slope of increased extraction of marble stones, and the effort to reuse the produced waste is also in rise due to the environmental concerns by many industries and also their efforts put in increasing the quarrying efficiency, and gradual improvement in the quarrying techniques. As regards to the western countries has predominantly leading centuries in the marble stone industry. However, as a result of entry of new countries like (China, India, Iran and other countries) entering the world market of stone sector, Italy has gradually lost its place in the market in terms of marble stone production. Over all, China has grown into top ten countries in the production of dimension stones, reaching the top position now.

Table. 1.4.3 Dimensional stone producers worldwide, thousand cubic meters, in 2003, 2010 and 2016 [6], [8]

	2003		2010		2016	
S.No	Country	Production	Country	Production	Country	Production
1	China	6481	China	12222	China	24345
2	India	3148	India	4907	India	12233
3	Italy	2907	Italy	3704	Italy	4507
4	Spain	2130	Spain	3148	Spain	4508
5	Iran	1796	Iran	2889	Iran	3122
6	Brazil	1185	Brazil	2500	Brazil	3123
7	Portugal	833	Portugal	2130	Portugal	3233
8	USA	833	USA	1019	USA	4123
9	Greece	537	Greece	685	Greece	1245
10	France	463	France	611	France	1287
	Others	7463	Others	7481	Others	10656
	Worldwide	27778	Worldwide	41296	Worldwide	72384

In conclusion we can say that the performance of world leaders in the production of the marble stone like Italy, Spain, Greece and Portugal, has dropped, and the emerging economics such as China, India, Italy and Spain has been exploding with the production.

1.5 Indian Scenario of marble stone industry

Marble industry of India is one of the historic ornamental and construction material that has history dating back from 3200 BC. These dimensional stones have left deep imprints in the architectural heritage of country. A number of temples, forts, and places of ancient Indian civilization have been carved out locally. These stone architecture has even contributed to the present era with modern buildings like the Presidential house, Parliamentary house and Supreme Court made from a high quality sandstone from Rajasthan. The increasing fame of Indian stone has forced the demand for its extraction, these stones are also been exported to many countries like USA, Germany, France, etc.

Due to its high demand and extraction at the same time has led to tons of waste deposits. The marble resources have been reported to be present in many states of India like Rajasthan, Gujarat, Haryana, Andhra Pradesh, Madhya Pradesh, Jammu & Kashmir, Maharashtra, Sikkim, Uttar Pradesh, and West Bengal. Among above mentioned states, marble deposits of economic importance are present in states of Rajasthan, Gujarat, Haryana, and Andhra Pradesh and also in Madhya Pradesh as per the reports of Indian bureau of mines.

Gujarat has large resources of marble in Banaskantha, Bharuch, Vadodara, Kachchh, and panchmahal districts. The Ambaji area in Banaskantha district and chinchpura area in Vadodara district are the main producing centers [8], Marble of Vadodara occur in different shades like green, cream, pink and white.

In Haryana, marble deposits are located in the district of Mahendragarh. Most important localities are Antri-Beharipur, Zainpur, Chappra-Bibipur, Nangaldurgu, Islampur and Dhanota-Dhancholi. Marble of this area occurs in variegated colours and banded forms. It enjoys the reputation as 'Patiala Marble' with black and white bands.

Marble deposits of Maharashtra are of calcitic and dolomitic type which are located in the areas of Katta-Hiwara, Kadbikhera, Sakaritola, Pauni,Chorbaoli, Deolapar, Mansar, Kandri, Chargaon, Junewani villages in Nagpur district. In Katta-Hiwara, the marble is light-pink to grey in colour. The marble of Kadbikhera-Sakaritola is pink calcitic marble while the marble deposits of Mansar and Kandri areas are dolomitic type.

In Uttarakhand, white marble of limestone occurs in Pithoragarh district. In Jharkhand, huge deposits of marble are available in Semra-Salatua and adjoining areas of Palamu. Pink marble occurrences are reported from Hesadih area, Singhbhum district.

The marbles of Khammam of Telangana district is of white and green, Occurrences of pink, purple, yellow and variegated marbles are reported in Cuddapah, Kurnool and Anantapur districts. The dolomitic marble of Cuddapah, Kurnool and Anantapur districts is other upcoming resource centre for off-white, coloured, greyish-black marbles which take good polish and are being exploited by private entrepreneurs.

Table. 1.5.1 Stones available in different districts of states

States	Districts of state where marble resources available
Gujarat	Banaskantha, Bharuch, Vadodara, Kachchh and panchmahal
Haryana	Mahendragarh, Antri-beharipur, Zainpur, chappra,-bibipur, Nagaldurgu, Islampur, Dhanota-dhancholi
Madhya-Pradesh	Jabalpur, Katni
Maharashtra	Katta-Hiwara, Kadbikhera, Sakaritola, Pauni, Chorbaoli, Deolapur, Mansar, Kandri, Chargaon, Junewali
Uttarakhand	Pithorgargh
Uttar Pradesh	In Mirzapur at Hingha and geria
Jharkhand	Semra-salatua
Andhra-Pradesh	Khammam, Cuddapah, Kurnool and Anantapur

1.6 Rajasthan marble stone industry with respect to sustainable processing

Marble stone of Rajasthan is the most preferred stone in India. The marble stone industry of Rajasthan has extremely high percentage of waste generation like solid marble waste, powder and slurry which are the major sources for environmental degradation where marble quarries and processing's are located. The marble waste generation varies widely from 30 % by weight (in mechanized mines using wire saw cutting methods for extraction of marble blocks) and 60% to 70% by weight through un-mechanized mining. Over the years, processing and exploration companies have been greatly criticized for their destruction of the environment. Hence, there is a great deal and necessity to study the sustainable processing of marble stone industry in order to protect the environment.

Due to the lack of proper waste management has led to the waste being dumped on open lands is causing severe threat to the environment in Rajasthan and in nearby areas of the state. Taking note of the situation, and being promoted by a local NGO (Non-government Organization) and other environmental organizations, the Supreme Court ordered a complete ban on marble mining in 2002, over the whole state of Rajasthan. But this ban did not last long, due to various reasons; some of them being: concerns of the state government for development activity, fear of un-employment, changes in the policy and permission regimes. Marble industry of Rajasthan is currently employing over 1 million people [9] Out of all the states Rajasthan has the distinction of having the best among Indian resources of good quality marble. Out of 33 districts in Rajasthan 20 districts have marble in one or other forms. The important regions where marble deposits are present are given below [10]

a) Udaipur-Rajsamand-Chittorgarh region
b) Makarana-kishangarh region
c) Banswara-Dungarpur region
d) Andhi(Jaipur)- Jhiri(Alwar) region and Jaisalmer region

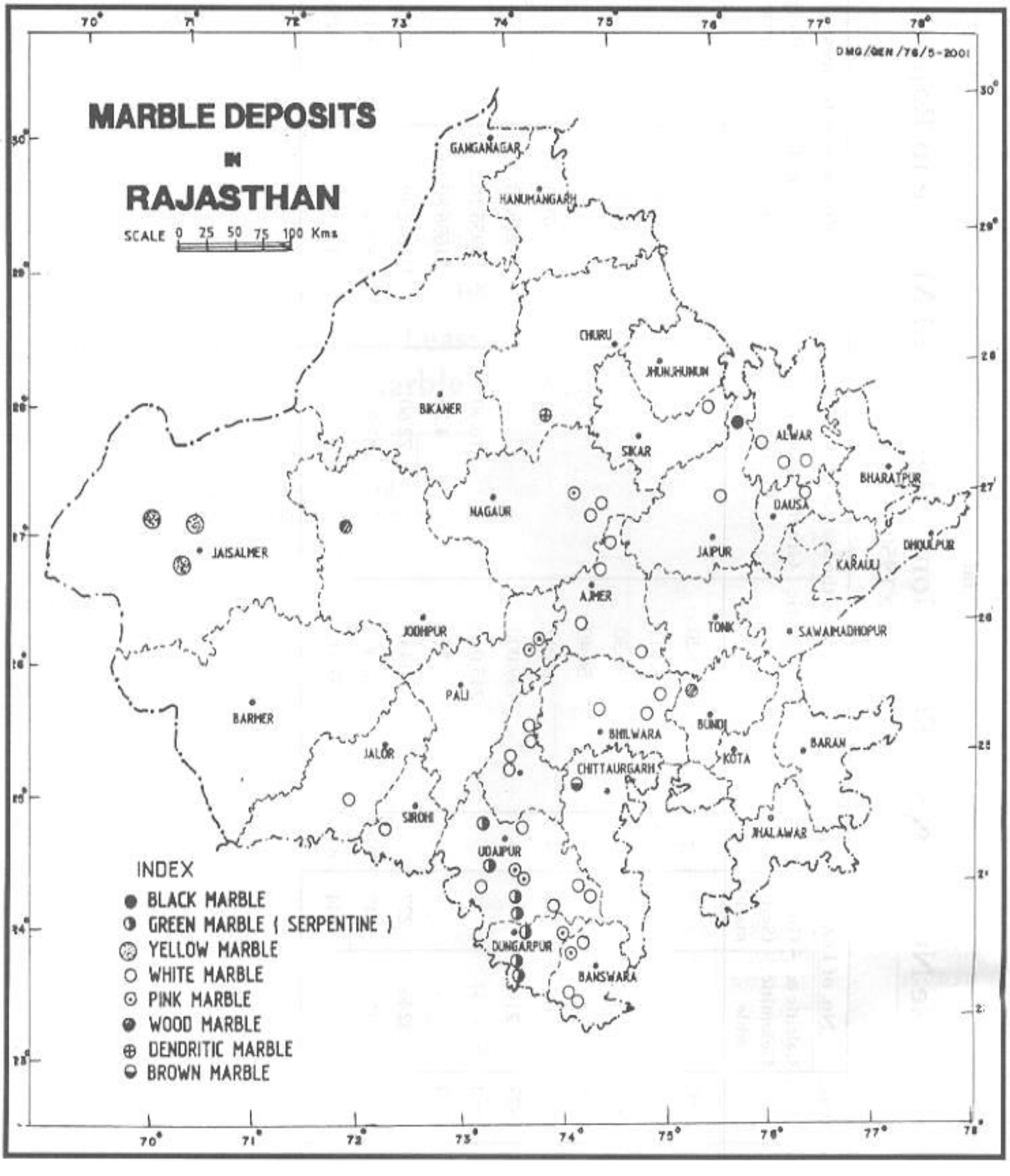


Fig. 1.6.1 Marble deposits in Rajasthan [3]

1.7 Significance of research

The primary goal of this project is to classify the marble stones present in and around the area of Rajasthan, characterize them and do the machinability study in order to optimize their cutting parameters. A detail life cycle assessment of the marble industry from cradle to grave has been done to identify different wastes generated in each stage of the process. Energy audit as well as life cycle energy assessment is done for the processing unit to analyze the carbon emissions being emitted while processing. The powder obtained while processing is collected and characterized rheologically with different coolants to identify which coolant is best suited while machining the marble. Finally, the Specific energy consumption as well as the forces generated while performing milling operations were calculated, and a method to predict them using Artificial Neural Network (ANN) was proposed.

Concerning stone waste re-use, there are a number of studies which focused on finer portions, at the microscale level [11]. In addition this research took in consideration of physico-mechanical characterization of marble samples and their powder from the processing plants. Furthermore, the tool bits that are currently used for cutting the marbles were collected from different processing units and where characterized to know the chemical composition of them. It was noticed that the waste generated at the processing site was re-used at different enterprises (such as agriculture, paper industry, cement industries etc.) They were also encouraged to sell the waste at lower prices in order to get rid of it, with the only advantage of reducing the landfill costs. The re-use of stone waste in the construction industry is identified as the most profitable, since the quarrying and processing activity is strictly related to the building industry. Hence, processing companies have necessary skills and expertise to evaluate the economic risks, thus they are more eager to undertake the production of new products.

Besides, another important goal of the project is to find out the carbon emissions from a processing unit is considered to improve upon the emission released to the atmosphere by moving from the conventional energy to the solar energy. Since, the percentage of carbon emissions from the processing units is very high that causing lot of damage to the environment.

Carbon dioxide emissions

Carbon dioxide is the major GHG which absorbs part of the suns radiation that continuously strike the earth's atmosphere and warming up. The presence of the greenhouse gases (methane (CH_4), Nitrous oxide (N_2O), Fluorinated gases) in the atmosphere is the natural phenomenon, vegetation, volcanism, and natural rock weathering, and also anthropogenic activities can generate it by burning fossil fuels and biomass, and they come from all sorts of everyday activities like using electricity, heating homes in winter, driving around town, burning coal/wood.

Water can take the form of an invisible gas called water vapor. Water vapor is naturally present in the nature, and has a strong effect on the weather and climate. As the planet gets warmer, more water evaporates from the earth's surface and becomes vapor in the atmosphere. Water vapor is a greenhouse gas so more water vapor in atmosphere leads to even more warming. This is a classic example of a positive feedback loop, which happens when warming causes changes and leads to even more warming. As a result, atmospheric carbon concentration has multiplied amounting to 391 ppm exceeding the industrial levels by 40%. As expected, CO_2 dominates the total forcing with methane and the CFCs becoming relatively smaller contributors to the total forcing over time.

Marble industry is the major contributors for carbon dioxide

Marble industry in Rajasthan produce more than 3500 metric tons of marble powder slurry per day[12][13]. It generates both stone waste and stone slurry. Solid waste results from the rejects of quarrying site, liquid substance consisting of particles originated from the sawing and polishing process and water used to cool and lubricate the sawing and polishing machines. Marble stone slurry generated accounts to 40% of the final product from stone industry. This is obvious because the stone industry presents an annual output of 68 million tons of processed products. Hence, the industry should commit towards the sustainable patterns. In Rajasthan the settled marble dust is disposed and dumped in and around the quarrying site results in environment pollution, threatening both agriculture and public health. Therefore, utilization of this waste marble dust in construction, agriculture, glass manufacture and paper industry would help in usage of this waste and protecting the environment. This waste can be used to produce new products, in road way constructions, in making pavements and as admixtures so that the waste is utilized more effectively and reducing the environment pollution. It is estimated that the Rajasthan marble processing enterprise produces around $1800m^3$ (4500 tons) of marble waste annually, by using this waste as replacement of cement can indirectly reduce CO_2 emissions into atmosphere by 4500 tons annually. The reasons stated above is the key basis for initiating the project. Main idea behind the project is to develop some customized tools which help in cutting marbles to a more thinner dimensions which reduces the waste generated. Another, idea of this research is to look into some management strategies to collect the waste generated while cutting and utilize it in other applications, so that waste would no longer be dumped. To have more comprehensive idea of utilizing the waste it is essential to look into the sustainability and Life cycle analysis aspects of the industry.

1.8 Organization of thesis

The aim of the project is to study the morphology of different marble stones present in and around of Rajasthan region such as (Makarana White, Bhainslana Black, Agaria White, Udaipur Green and Aandhi White) using petrographic analysis. Then, to characterize them physically, mechanically as well thermally in order to find out various properties which influence the wear of the tool. Finally, optimize the machining parameters such as feed, speed and depth of cut in order to find out the best possible combination to increase the efficiency of the machining as well as the tool life.

Firstly a broad analysis of the international scenario of stone sector was performed, to quantify the quarrying production trends and to evaluate various wastes generated while marble quarrying. Aim of this analysis is to find some opportunities to implement some management strategies to reduce the waste. The analysis in chapter one evaluated that waste accounts for a minor part of total stone extracted. But quarrying waste and processing waste combine amounts to majority of the total stone extracted.

A typical lifecycle assessment of the Rajasthan marble stone was investigated in the same objective to find some scope to utilize them as byproducts for some other purpose without being dumped to the environment. Energy audit of several processing plants were done, as other objective was to minimize the energy consumption in any industry. The audits different parameters were annual consumption of electricity, machines used to process marble stones, and their capacity to process per day. With the help of the data obtained from the audit various factors were evaluated which are discussed in chapter

3. Later, a complete life cycle energy assessment is done to find out the carbon emissions into the atmosphere is explained in chapter 4.

Most of the processing plants that are existing around Rajasthan are small scale industries, they typically use different machines to cut marble blocks, and fabricate their own tools to cut into blocks of different shapes and sizes according to market requirement. One of the objective was to collect these tools and analyze for their chemical composition to check the probability of manufacture customize tools which reduces the cost of the tool. The tools characterized found that they mostly use iron powder in the metal matrix as well as silicon powder as abrasives since the cost of availability of these materials are less (when compared to the circular and wire saw) for the metal matrix with diamond particles suspended in it. If the hardness of the marble increases then the iron particles are replaced by cobalt or nickel according to the required composition. The slurry which is a semi solid waste generated during the cutting process is usually disposed either to the sedimentation pits or to the sedimentation and filtration towers.

After some preliminary studies on processing industries five different marble samples were selected and are physico-mechanically characterized. Petrography analysis of these samples revealed the mineral properties, grain size, distribution of grains, etc. which are explained in the chapter 5.1.1, simultaneously they are also graded according to the hardness number. Marble powder obtained while cutting these five samples were rheologically characterized using different coolants in 5.3. Coolants used while machining carry away most of the heat generated while machining. The rheological characterization helped to analyze how these coolants behave while machining, whether their rheology remains same or change with the temperature etc. are described in chapter 5.3

Machinability parameters effect the cutting performances of the circular diamond sawblades, the interaction of many effective parameters like mechanical properties (Uniaxial compressive strength, tensile strength, young’s modulus, hardness, abrasiveness, water content), sawing characteristics (force, traverse speed, specific removal rate, peripheral speed, depth of cut, specific energy, cutting mode), textural properties (grain size, grain shape, mineral type and content) saw design (diamond properties, matrix properties, machine vibrations, operator skill), working conditions (machine power, amount of water used, environment/climate change) were studied in the chapter 6.1. The specific energy consumption and the forces generated while performing milling operations were analyzed in chapter 6.3. Some innovative cutting technologies were studied in the chapter 6.4 and a patent applied and their details can be found in Annexure- II. The forces generated were calculated using two types of dynamometers 1. Strain gauge type dynamometer which was fabricated in the lab whose construction details can be found in Annexure I, and the second type of dynamometer was a piezo electric based Kistler ® dynamometer and the results were compared for the possible errors.

Chapter 2: Literature review

2.1 Processing of marble stones

Marble processing is gaining popularity due to increase in its usage in construction industry. Today almost all modern architectural design of houses and malls include the final touch of beautiful shades of marble in exterior as well as interior portions. Rajasthan has large deposits of superior quality of marble stone in different regions. The possibility of getting the marble stone in block forms will reduce the waste and improve the profitability. Once, the extraction of the blocks from the quarry are done they are sent to the processing units to further process into tiles, slabs etc. There are various machines present to carry out different operations on the extracted marble blocks. According, to the final product requirement the machines may also vary. The following are some of the machines exclusively used for the processing of the marble stones.

2.1.1 Cutting machines

Cutting of large blocks in the processing industries are carried out by using gang saws, wire saws and circular saws.

2.1.1.1 Gang saw

Gang saw is designed and constructed ideally to cut marble stone blocks in slabs with high efficiency. A gang saw has a number of adjustable blades that allow for the thickness of the slabs to be adjusted. The gang saw can cut the entire block of stone into slabs at one time. The blades of the gang saw are made of alloy steel with the diamond segments welded at the periphery. Depending on the thickness of the block to be cut the size of the disc varies. Large disc machines are fitted with discs of larger diameter, which can cut the blocks measuring up to 1.7 meters.

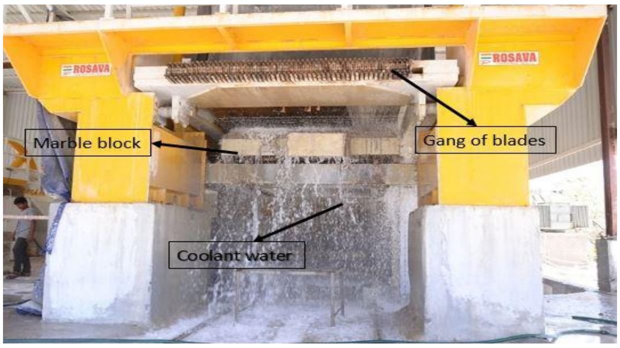


Fig. 2.1.1.1 Gang saw machine

Miguel et.al. [14] studied the sawability by multiblade gangsaw, correlating the interaction between diamond tools, machine characteristics and stone parameters. The correlation between indentation depth and stone parameters, showed good results, for uniaxial compression strength. In order to predict the production of slabs per hour, a multiple linear regression model showed a correlation approximately to 100% between variables and passed several significance tests. As final result, the model indicated an explanatory equation with the most important parameters of the cutting process: block length, block width, vertical sawing speed and uniaxial compressive strength.

E Rodrigus et.al. [15] studied the surface finish of the marble and granite stones using a multiblade gangsaw. The marble samples showed mineralogical similarities, but great difference in cutting speed and cost of the industrial process. It discusses results in relation to knoop hardness, amsler wear, deep abrasion and petrography. They concluded from the experimentation that the texture of the stone has the most important influence on the cost of production of polished slabs.

Abraham et.al. [16] presented state of arts in cutting procedures used for stone processing. In this study they found that the reduction in the thickness of blade has a direct repercussion on profitability. A new tool is presented with cutting thickness half of that of the best achieved in conventional tool, band saw with welded diamond segments. The first prototypes are built, cutting tests are carried out and the features of the cut are studied. In the second part, existing studies on measurement of cutting force in conventional tools are reviewed and the prototype band saw machine is monitored. Cutting forces in this new process are studied, with measurement of tangential force and feed force under various working conditions.

N careddu et.al. [17] studied marble processing of three different factories for future use of $CaCO_3$ – microfine dust. the sludge deriving from processing is mainly composed of Calcium carbonate and it has a great potential as secondary raw material or by-product as long as the chemical properties of the sludge meet the parameters required by current environmental laws. They explained how tool wears out while processing and how consumables end up as sludge.

Mendoza et.al. [18] studied the environmental performance of multi-blade gangsaw and diamond multiwire saw technologies and compared them to the life cycle assessment. Results demonstrated that diamond multiwire saw technology contribute 30% of water savings, 40% of energy savings and 80% of material savings per square meter of polished granite tiles (60 x 40 x 2 cm) production. These resource savings contribute together to reduce the products environmental footprint by 35% to 80%.

Hieres et.al. [19] studied the dimensional stone production process, block splitting into slabs which are considered important in terms of time, costs and quality of final products. They found that parameters of the cutting process have a great variability while cutting. Depending on those parameters, the steel blades settled in an oscillation frame and an abrasive slurry characteristics also depend on the marble stone. Their study showed a relation between the characteristics of selected stones and steel blades and shot consumption within the sawing process. The higher the quartz contents of the marble the higher its abrasion resistance, which results in higher consumption of steel shot during sawing.

2.1.1.2 Wire saw

To minimize the risk of cracks, fissures, and other aesthetical damage to the marble stone, fabricators use a machine called the wire saw which helps in gently separating the marble. Two 3 inch wide holes are drilled perpendicularly to each other. Once the holes connect, a heavy-duty wire embedded with artificial diamonds is fed through and secured to a flywheel, forming a loop. A powerful engine applies massive torque to the flywheels, which circulates the diamond embedded wire at a very fast rate. Since, diamond is much harder than the marble, the friction is quickly wears it away, leaving a smooth cut plane. A conventional stationary wire cutting machine for the processing industry weights around six tons and has a cutting motor frequently fitted of between 10 – 20 kW. The cutting tool is a steel wire, usually from four to five millimeters thick, on to which diamond beads are attached. These beads have the same structure as the diamond segments sintered polycrystalline diamonds in a metal matrix. There must be separation between the diamond beads to allow for the removal of cut away material, and 30 – 40 beads are usually fitted per meter. The element separating the beads may differ depending on the type of wire, which may be springs or injected polymer, but normally vulcanized rubber or plastic.

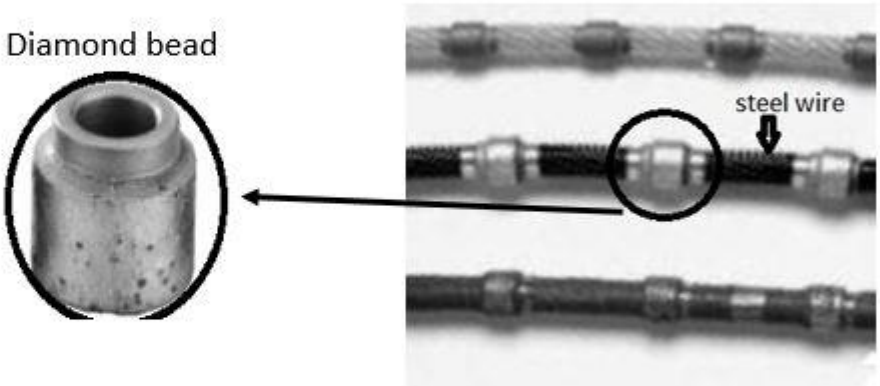


Fig. 2.1.1.2 wire saw machine with diamond beads

C.Sung et.al. [20] Studied the brazed diamond grid design for diamond saws, they described the fabrication process and said that the diamond grits in conventional tools are held in matrix either by electroplated nickel or sintered metal. As a result, these grits are distributed randomly and they are buried mechanically. The segregation of diamond grits often results in densely and sparsely spaced regions. Thus, some grits are wasted due to redundancy; and others, shattered because of overload. Moreover, as the mechanical retention force is weak, all grits are easily knocked off by the strong impact force generated during cutting. The controlled spacing of diamond allows optimal performance of each grit with minimal waste. The chemical bonding further prevents premature loss of the grit. Moreover, brazed diamond can protrude higher for aggressive cutting. The new technology has been applied to make diamond wire saws with half the amount of diamond used as compared with conventional diamond wires. The brazed diamond grid allows a two-fold increase of cutting speed over conventional diamond saws without compromising the life. If this technology is applied to other types of diamond saws, the result would be a dramatically improvement of productivity accompanied by a sizable reduction of cost.

C Y Hsu et.al. [21] investigated the wire saw machining of ceramics by ultrasonic vibration in this study. Material removal rate, wafer surface roughness, steel wire wear, kerf width, and flatness during machining ceramic were selected as quality character factors to optimize the machining parameters (swinging angle, concentration, mixed grain and direction of ultrasonic vibration) to get the larger-the-better (material removal rate) and the smaller-the-better (wafer surface roughness, steel wire wear, kerf width and flatness) machining characteristics by Taguchi method. The results indicated that wire swinging produces a higher material removal rate and good wafer surface roughness. Ultrasonic vibration improved material removal rate, without affecting the flatness under different machining conditions. Experimental results show that the optimal wire saw machining parameters based on grey relational analysis can be determined effectively and material removal rate increases from 2.972 to 3.324 mm2/min, wafer surface roughness decreases from 0.37 to 0.34 μm, steel wire wear decreases from 0.78 to 0.77 μm, kerf width decreases from 0.352 to 0.350 mm, and flatness decreases from 7.51 to 7.22 μm are observed.

H K tonshoff et.al. [22] developed a wire sawing process for many applications in the field of natural stone and construction materials, especially for very thick materials or components that are difficult to access. Diamond wire cutting was limited to small carbon-steel shapes, such as pipelines for transporting gas or oil under the sea. In particular, the task of cutting pure steel components offers new fields of applications, e.g. treatment of nuclear power or off-shore-components. The application of the wire sawing process for these specific cutting operations requires the development of diamond tools adapted to the cutting process. In this paper, the basic principles of wire sawing are explained and the background of diamond wire cutting of steel components is discussed. The interaction between tool and the workpiece is described in detail.

Mohammad et.al. [23] predicted the performance of the diamond wire saws as an important in the cost estimation and the planning of the stone quarries. An accurate estimation of sawability helps to make the planning of the rock cutting projects more efficient. In this paper, the performance prediction of diamond wire saws in cutting carbonate rocks were studied on 14 different carbonate rocks in stone quarries located in Iran. Rock samples were collected from the quarries for laboratory tests. Uniaxial compressive strength, Brazilian tensile strength, Schmidt hammer value, and Los Angeles abrasion were determined in the laboratory. Performance prediction was evaluated using simple and multiple regression analyses. Finally, a new model was proposed for predicting the production rate of diamond wire saw. It was concluded that the production rate of carbonate rock using diamond wire saw can reliably be estimated using the developed model.

G.Q. Huang et.al. [24] investigated on the breakage of the diamond wire saw during stone processing. A lot of broken wire samples were collected from factories and observed macroscopically and microscopically. The results indicate that the breakages were mainly fatigue failure. And statistic of results show that all the breakage sites centralize on two sections. Reasons for the two break sections are also discussed in detail. Furthermore, sawing experiment was conducted to study the effect of the process parameters and the results reveal that the breakage of the wire saw is sensitive to the processing parameters. Finally, some proposals for manufacture and application were presented.

Y. Ozcelik et.al. [25] investigated the the effect of rock anisotropy, associated with the bedding planes of the rock in strength of the rock, on the efficiency of diamond wire cutting machines, and also on the vibration of the cutting machine. While investigating the cutting efficiency, the unit wear on the diamond bead, cutting rate and specific energy have been taken into consideration. Hoop rotation (1100 rpm) and tensioning amperage (29A) were used as constant cutting parameters for different cutting angles (from 0^0 to 90^0) depending on the bedding planes for two different rock types. During the cutting operations, the unit wear on beads were measured and the average cutting rate and vibration values that occurred with the diamond wire cutting machine were recorded. In addition the strengths of the rocks were determined for the core samples prepared from the anisotropic two rock samples considering different angle values from parallel to and perpendicular to the bedding plane of the rock. Then, there relationships between the angles of the bedding planes (ABP) and various variables such as the strength of the rock, unit wear, cutting rate, specific energy and vibration were investigated. Finally, the cutting efficiency of diamond wire cutting was found to be sensitive to the rock anisotropy and it was revealed that the cutting operations should be performed parallel to the bedding planes as much as possible in terms of economy.

Hanifi Copur et.al. [26] tested different marble samples with a linear cutting test rig using chisel-type cutting tools with 0^0, 15^0, 30^0 and 45^0 sideways angles at different depths of cut and tool spacing's, to determine stone cuttability, cutting characteristics of chain saw machines and effect of Unsymmetrical and symmetric sideways angles and different cutting patterns on cutting performance (tool forces, specific energy, optimum cutting geometry). A deterministic model was suggested for predicting performance of chain saw machines using the results of linear stone cutting experiments, and the laws of kinematics. The results of experimental studies and in-situ investigations indicated that the cutting action of chain saw machines can be successfully simulated by linear cutting experiments and the suggested model is proven.

S C jain et.al. [27] used a neural network models to predict the cutting performance of the diamond wire saw machine from shear strength parameter cohesion and machine parameters peripheral speed and thrust, and the results were compared with multiple regression models. It was concluded that applicability of ANN for cutting performance prediction of diamond wire saw machine in dolomitic marble is more reliable than the regression models. The determination coefficients for the predicted and observed values for ANN and regression models were for cutting rate 0.998 and 0.896 and for wear rate 0.999 and 0.967, respectively. Also standard errors of estimates for ANN and regression models were for cutting rate 0.00133 and 0.339 and for wear rate 1.08 e-006 and 0.02, respectively. The peripheral speed and thrust parameters have positive impact on both cutting rate and beads wear rate. Cohesion has positive impact on beads wear rate and negative impact on cutting rate.

B.C. Liu et.al. [28] experimented with trajectory and mechanism of diamond wire saw and were theoretically analyzed. Sawing experiments of marble and granite are carried out to verify the results of the theoretical analyses. Both the analyses and experiments indicate that sawing trajectory of diamond wire saw is approximately an involute of circle. The wire tension and the unit linear pressure determine the shape of the involute. Furthermore, the main rock-fracturing mechanism of diamond wire sawing is Hertzian Fracture because linear wire speed is so high and the unit linear pressure is so low that the stone cannot be voluminously fractured. The materials removal is achieved by high speed grinding so that the sawing debris is very fine.

A ersoy et.al. [29] investigated the wear characteristics of circular diamond saws for cutting of different hard abrasive rocks. The principle factors requires for considering in predicting the wear rates are type of diamond saw, the saw operating parameters and the characteristics of the cut rock. A single rock property index is not a sufficient basis for predicting wear performance. A variety of ten types of rocks were cut in the laboratory with two types of circular diamond saw using a fully instrumented cutting rig at different feed rates, depths of cut and at constant peripheral speed. Quantitative determinations of a wide range of textural, mechanical and intact properties of the rocks were also made.

Y Ozcelik et.al. [30] developed a regression models related with the wear of beads are developed for horizontal and vertical cutting separately. The vertical and horizontal wear rate models yields similar results. Therefore, it is appropriate to use only one of these models.

2.1.1.3 Abrasive water jet cutting

Water jet cutting is used to cut pieces, make holes for appliances and create beveled edges. In water jet cutting water is pressurized to 60,000 psi and allowed to shoot out in a concentrated stream. Travelling at 2.5 times speed of sound the stream mixes mid-air with a powdered abrasive (e.g. aluminum oxide and garnet) before striking the marble. The result is a precise hyper erosion that can be used for three dimensional and two-dimensional applications. Due to the degree of precision a computer is used to control the entire cutting process.

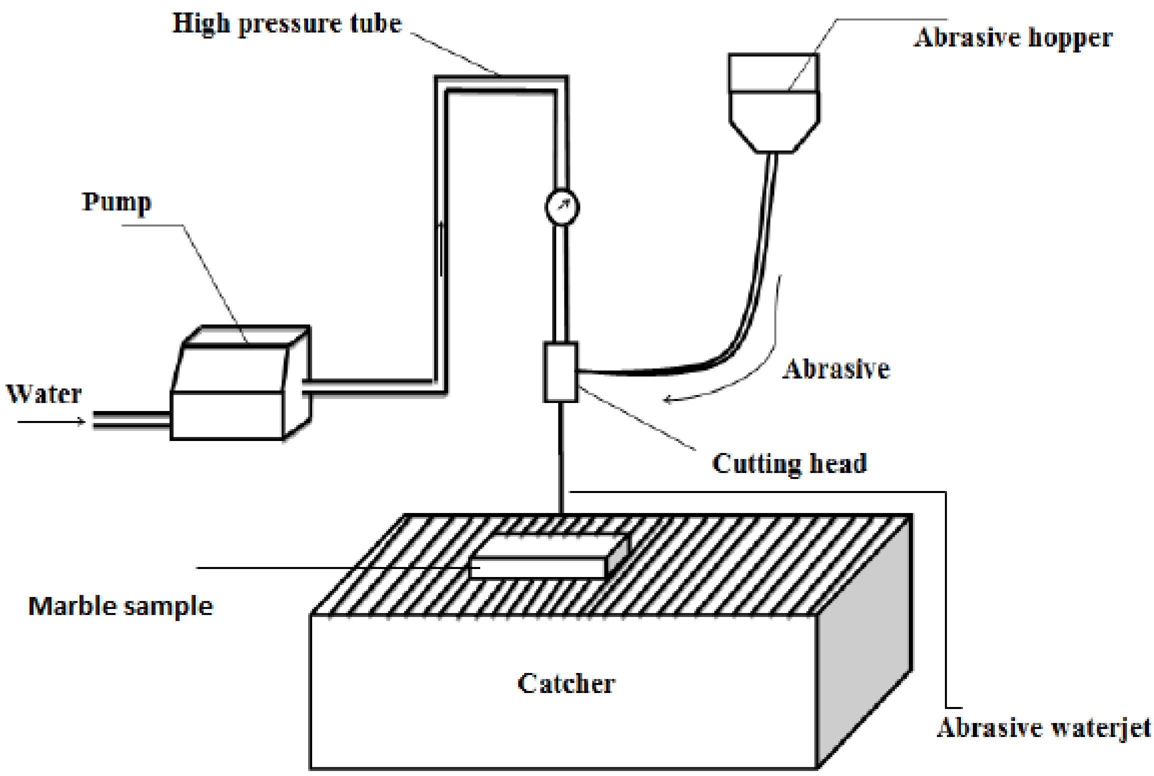


Fig.2.1.1.3.1 Abrasive waterjet cutting

M A Azmir et.al. [31] conducted some experiments to assess the influence of water jet machining (AWJM) process parameters such as surface roughness, of glass fibre reinforced epoxy composites. Taguchi method and analysis of variance was used to optimize the AWJM process parameters. After experimentation type of abrasive materials hydraulic pressure, standoff distance and traverse speed were found to be significant factors in controlling the surface roughness.

M. Ramulu et.al. [32] investigated graphite/epoxy composite material which machined by water jet machining process. Topography and morphology of machined surfaces were evaluated with surface profilometer and scanning electron microscope. The surface characteristics and the micro mechanisms of material removal for both the processes were analyzed and compared.

Several studies concentrated calculating the machinability study of granites using water jet cutting [33][34] and to find a correlation between abrasion wear and different Physico-mechanical properties of the samples to identify the property that is effecting the wear most. In the current study different marble samples were considered and tested for their rock properties as well as machine operating parameters to find a correlation between mineral as well as physico-mechanical properties which is effecting the wear. Specific energy consumption and forces were calculated while performing milling operations on the samples.

M Junkar et.al. [35] presents an explicit finite element analysis (FEA) of a single abrasive particle impact on stainless steel in abrasive water jet machining (AWJM). In experimental verifications of different shapes of craters on workpiece were observed and compared with FEA simulation resulted by the crater sphericity. The influences of the impact angle and particle velocity were observed. Results of the FEA simulation are in good agreement with those obtained from the experimental verification. The presented work gives the basis for further FEA investigation of AWJ machining, where influences such as particles rotation and other process parameters will be observed.

F.L. Chen et.al. [36] investigated emerging technology which can shape almost all engineering materials, but it also produces a characteristic striated surface finish which limits its potential applications. In this study, the characterization of different materials' cut surfaces is investigated using a scanning electron microscope. The effect of abrasive particle distribution in the jet on striation formation is detailed. A non-invasive technique, Laser Doppler Anemometry, is used to analyse the abrasive particle distribution in the jet. Furthermore, the mechanisms of striation formation are discussed in detail and an effective striation minimization technique applied to the cutting process is outlined.

A. M. Hoogstrate et.al. [37] has discussed the developments in equipment process as abrasive water jet milling, and turning, to exploit the advantages of abrasive waterjet technology completely, thereby eliminating or minimizing the disadvantages. It is mainly based on several discussions held at STC-"E" meetings in recent years and on input provided by many CIRP-members. Abrasive waterjet machining.

L.M. Hlaváč et.al. [38] they studied the relation between the declination angle and cutting wall quality The values of the limit traverse speeds predicted from the theoretical equations were compared with values experimentally determined on selected samples.

C.Ma et.al [39] studied the taper edges produced by the abrasive waterjet cutting on the kerf of workpiece being cut. The kerf geometry has been measured using an optical microscope. Using these measurements, a simple empirical correlation for the kerf profile shape under different traverse speed has been developed that fits the kerf shape well. The mechanisms underlying the formation the kerf profile are discussed and the optimum speed for achieving the straightest cutting edge is presented.

Gökhan AYDIN et.al [41] worked on assessment of the surface quality of the granite but by abrasive water jet. Abrasive water jet (AWJ) cutting has been increasingly used in various industries due to its considerable advantages over the conventional cutting technologies. Although many studies have been carried out to fully understand the cutting performances of the AWJ for a variety of materials, the studies focused on the rock machinability by abrasive water jet in terms of cut surface quality are required. In this study, cut surface quality of a granite cut by an abrasive water jet is experimentally analyzed. The cutting performances are assessed in terms of the cutting wear zone and surface roughness. The experimental studies are conducted on the basis of Taguchi's orthogonal array. Effect of the process parameters is presented as mean responses in detail. Additionally, analysis of variance (ANOVA) is used to evaluate data obtained statistically. Major significant process factors affecting the cutting wear zone and surface roughness are determined. As a result of the study, it is determined that the highly effective parameters on the cutting wear zone are the traverse speed and the abrasive size respectively. Similarly, the water pressure, the traverse speed and the standoff distance are found as highly effective process parameters on the surface roughness of the marble.

2.1.1.4 Circular diamond saws

Circular sawing with diamond-impregnated segments attached to a circular steel core is extensively used for cutting marble and other structural stones. With the growing use of natural marble as a construction material, there is increasing demand on reducing the sawing costs and increasing production efficiency. Diamond impregnated segments on the saw periphery consist of randomly dispersed diamond abrasive grains embedded in a metal matrix. As sawing proceeds, the segments wear down and new diamonds emerge from the matrix. In general, the metal matrix and the diamond wear rates should be appropriately matched in order to facilitate efficient cutting and high wear resistance of the segments. The productivity achieved in sawing of marble is related to the mechanics of the process, as well as the wear resistance of the diamond segments. Forces, power, and energy have been extensively investigated for virtually all types of machining processes, including sawing and grinding.

Fig. 2.1.1.4.1 Circular diamond saw

Processing of marble to various dimensions stones also on the rise especially [40], using circular diamond blades/saws. Wearing of diamond blades/beads are not only affecting the productivity [40] and the cost of this process, but also the waste generated during processing. Circular blade wear is one of the important aspect to be considered in stone processing due to the two tribological contacts of both surfaces, mainly one being the contact of abrasive-marble, causing primarily the erosion of saw blade and second the chips formed during machining will cause the wear due to the bonding of the chip to the metal [41]. So, while stone sawing, the identification of wear mechanism is a very complex task due to various contacts that are possible while sawing the stone. When considering the use of diamond tools for sawing, both abrasive wear and erosive wear play a vital role. In fact, the complex nature of wear makes these investigations more time-consuming, and mostly it addresses only isolated aspects like specific wear mechanisms or processes.

I. G. Gyurika et.al.[42] worked on finding optimal opportunities at stone machining processes done by diamond tool, for this they used different type of stones used in wider and wider range to produce covers, pavements, tiles, statues, souvenirs. They found one of the possible solutions to increase productivity is to optimize the stone machining processes. Their aim of the first phase is to create an overall knowledge of stone machining, highlighting the stone cutting process with disc. After acquiring the knowledge the next step is to execute the researches optimizing the stone machining processes.

Boyog et.al.[40] presents the wear characteristics of circular diamond saws in the cutting of different hard abrasive rocks Circular diamond saw of wear is affected by a range of factors. However, the principal factors that require consideration in predicting wear rates are the type of diamond saw, the saw operating parameters and the characteristics of the cut rock. A single rock property index is not a sufficient basis for predicting wear performance. A variety of ten types of rocks were cut in the laboratory with two types of circular diamond saw using a fully instrumented cutting rig at different feed rates, depths of cut and at constant peripheral speed. Quantitative determinations of a wide range of textural, mechanical and intact properties of the rocks were also made. Wear (weight loss and height loss) of saw were measured after a series of test in each rock type. The wear of saws can take many forms, however, the most common wear mechanism operating on saws during the rock cutting is abrasion. Impact loading and impact fatigue also accelerates the wear of saws. The analysis indicated that the statistical model for the rock saws have potential for practical application. The application of multiple regression analysis to diamond saw performance is novel and the technique shows promise for the prediction of saw wear in specific rock types. The ability of the technique to provide a mathematical characterization of the performance of new cutting saws in the specific rocks may prove to value to saw manufacturers and users.

The correlation and regression models try to attempt and provide a closer approximation to the saw blade wear with respect to mechanical and mineral properties. Previous researchers have developed some predictive models to address a range of varieties in igneous granites (Aydin et al., 2013) but not marble. From the literature review it can be seen that a lot of study was carried out for calculating SWR of diamond tools for granites, but only few papers were found on marble stones may be the wear of diamond tools were of less interested from a research point of view and another reason being marble are less hard compare to granite. Even in that granites, they worked without knowing entirely their genesis, crystal size distribution and mineral percentage (Tönshoff et al., 2002).

Toshoff has significantly contributed to research for calculating forces occurring during marble and granite processing [45]. The relation between brittleness, destruction specific energy (sdcs) using tungsten carbide (WC), polycrystalline diamond compact (PDC) and impregnated diamond bits on circular diamond blades were obtained for each series of drilling and cutting operations (Aslantas et al., 2009). An experimental study for the investigation of sawing performances of different marbles was carried out by [47] considering specific energy as a criterion for sawing efficiency to determine the optimum sawing conditions. They found that shallow cutting depths and low traverse speeds are inefficient, it is also possible to predict specific energy of sawing by combining the dominant work piece properties. An investigation of frame sawing with diamond blades was taken up [48] under different cutting conditions with single point cutting tool on marbles. They found that the cutting mechanism of the marbles was due to plastic deformation and brittle fracture of the stones, these are further influenced by cutting conditions like depth of cut, cutting coolant, tip shape of the tool and the properties of the stone. A study considering specific energy and specific wear rate were used as the sawability criteria to investigate the influence of cutting mode on sawing performance [48] and found that down-cutting process results in high impact loads leading to wear more quickly, while up-cutting process found to be more efficient process in terms of specific cutting energy.

2.1.2 Drill cutters

Diamond drill bits are used for marble stone they come in different sizes and shapes primarily of two basic tip styles, solid tip bits and hallow core drill bits. There are also two basic types of diamond drill bits relating to the application of diamond they are sintered and bonded.

Solid drill bits have diamond on the tip and the sides of tip. These type of bit drills a complete hole by grinding a full hole as the size of the tip. Core drill bits are hallow at the tip are often called hole saws, since they grind or saw a circle to create the hole. Since solid tip bits will drill out the complete hole, they are only effective for smaller holes in hard materials. Solid tip bits are not designed for extremely hard materials such as very hard stone or porcelain tile or for drilling large holes. Core drills only drill out a portion of the resulting hole, so they will drill much faster than solid tip drill bits. Core drills can also be used to drill large holes and can be used on most non-ferrous hard materials such as glass, stained glass, ceramic, porcelain and fiberglass, porcelain tile, limestone, slate, marble, granite and other stone materials. Bonded diamond drill bits have the diamonds bonded to the edges of the drill bit tip. These diamond drill bits are generally slow-speed bits and are fairly inexpensive. During use, the diamonds eventually wear off of the bit due to the hardness and abrasiveness of the material being drilled. Sintered diamond bits have the diamonds embedded directly into the metal tip of the bit. As the tip wears down, new diamonds come to the surface. Sintered diamond drill bits are often designed for deep drilling in stone, concrete or masonry. Sintered diamond drills are more expensive and because they are heavy duty, they drill more slowly, but they last longer. Depending upon the material being drilled and the drilling techniques used, Sintered diamond bits can last 30 to 50 times longer than a bonded diamond bit, sometimes even longer. The life of any type of diamond drill depends upon the hardness, abrasiveness and thickness of the material being drilled and the specific drilling techniques used (drill speed, pressure and lubrication). The diamonds of a drill bit don't actually wear out as much as they wear off due to heat and friction caused by the extreme hardness and abrasiveness of the material drilled.

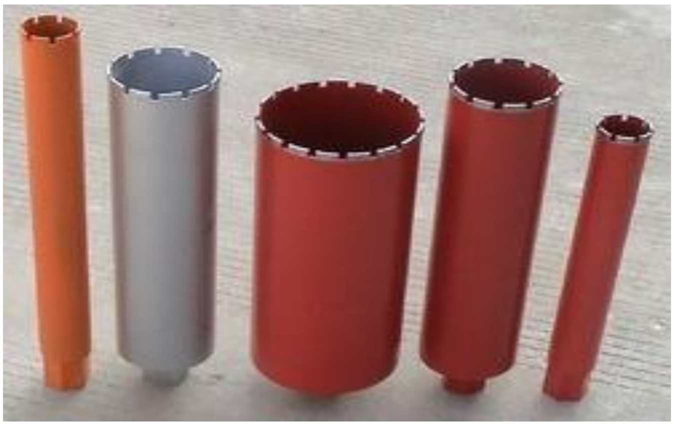


Fig.2.1.2.1 Different dimension core drill bits

M. Stavropoulou et.al. [49] discussed about the continuum mechanics and discrete modeling were applied to investigate numerically rotary drill cutting experimental results on four marbles. Rock-cutting tests were performed by a new portable rotary micro drilling tool currently employed in practice for the quasi-non-destructive characterization of strength properties of rocks. It is found that the predictions of the continuum model are in full accordance with measured forces during drilling. It is also shown that the cohesion and internal friction angle are the most important parameters affecting the rock drilling resistance, as is depicted by the limit analysis theory of plasticity. Moreover, the calibration of the discrete element model on the experimental data permits the approximate estimation of the mode-I fracture toughness for each type of marble.

E. Detournay et.al. [50] postulated that the cutting component of T and W is proportional to the depth of cut per revolution, $\delta = 2\pi v/\omega$, and that a linear constraint exists between the frictional component of T and W, a linear relation is derived between the specific energy E and the drilling strength L two quantities with dimensions of stress, that are respectively proportional to T and W, and inversely proportional to δ. The original assumptions appear to be justified when the model is tested against published experimental results, as the data point cluster along a line in the E-L diagram. Interpretation of experimental data suggests that the contact friction coefficient actually reflects the internal frictional property of the rock. It is also proposed that the influence of the bit design on the drilling response is embodied in a single number γ, which depends on the shape of the cutting edge and on the distribution of cutters on the bit body.

G Exadaktylos et.al. [51] studied the degradation of the monumental stones due to the interaction between the material and environmental factors At present there is no method which can measure with sensitivity, reliability and quasi-non-destructively the cohesive properties of stones both at the exposed surface and at larger depths (few centimeters), which can be used both in laboratory and in situ. They verified the capability of a phenomenological model to characterize the cohesional properties of stones and the influence of wear on drill-bit performance based on appropriate microdrilling measurements performed by using a new portable Drilling Force Measurement System (DFMS).

Vijayender Singh et al.[21] worked on development of specific grinding energy model, specific grinding energy is one of the most important performance parameter of the grinding process. Primary energy components of specific grinding energy are the major contributors to the total specific energy consumption in grinding. For high strength and hardness materials such as advanced ceramics, specific grinding energy requirement is extremely high which will eventually cause higher material removal cost of such materials. Detailed study of various components of specific grinding energy may help to reduce this energy consumption by appropriate choice of the grinding process parameters. This work studied in detail the four primary components of specific grinding energy namely chip formation energy, primary and second rubbing energy and the specific ploughing energy for two different engineering materials a ductile mild steel and a hard conductive ceramic. Single grit experiments have been conducted in new and more realistic manner to replicate the actual grinding process and to develop the theoretical models of the specific energy components. Study of specific ploughing energy also helped to explain thoroughly the concept of size effect in grinding.

Sanjay Agarwal et al.[22] worked on experimental investigation of surface/subsurface damage formation and material removal mechanisms in SiC grinding. The difficulty and cost involved in the abrasive machining of hard and brittle ceramics are among the major impediments to the wide spread use of advanced ceramics in industries these days. It is often desired to increase the machining rate while maintaining the desired surface integrity. The success of this approach, however, relies in the understanding of mechanism of material removal on the microstructural scale and the relationship between the grinding characteristics and formation of surface/subsurface machining-induced damage. In this paper, grinding characteristics, surface integrity and material removal mechanisms of SiC ground with diamond wheel on surface grinding machine have been investigated. The surface and subsurface damages have been studied with scanning electron microscope (SEM). The effects of grinding conditions on surface/subsurface damage have been discussed. This research links the surface roughness, surface and subsurface damages to grinding parameters and provides valuable insights into the material removal mechanism and the dependence of grinding-induced damage on grinding conditions.

2.1.3 Mill cutters

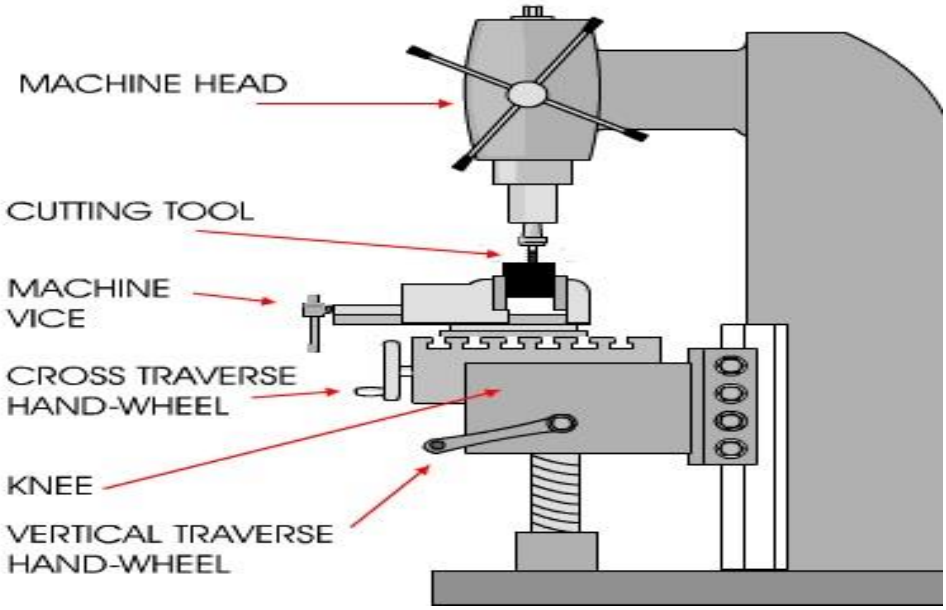


Fig. 2.3.1.1 Milling machine with milling cutter

Diamond coated end mill cutters are used to perform various operations on the marble stone, for performing various profiling or edge profiling various profile routers are used according to the specific requirement.

S. Malkin et.al.[52] worked on advanced ceramics evaluation and mechanism of stock removal and ground surface quality. The aim of this work is to evaluate the mechanism of stock removal and the ground surface quality of advanced ceramics machined by a surface grinding process using diamond grinding wheels. The analysis of the grinding performance was done regarding the cutting surface wear behavior of the grinding wheel for ceramic work piece. The ground surface was evaluated using Scanning Electron Microscopy (SEM). As a result it can be said that the mechanism of material removal in the grinding of ceramic is largely one of brittle fracture. The increase of the $\mathbf{h_{max}}$ can reduce the tangential force required by the process. Although, it results in an increase in the surface damage, reducing the mechanical properties of the ground component.

B.Brook et.al.[53] done experimentation on rock sawing operation, a single diamond particle acting as a sliding indenter expends energy by generating compression in the rock in the form of a 'stress epicenter' through the action of confined crushing: this compression causes the rock fracture mechanism. It is not a cutting operation per second indeed sharp diamond particles can be a liability. The sawing requirement is for a high strength, high heat resistance indenter, with a potential for displacement that is compatible with that of the rock. Currently used tests for rock strength do not indicate energy consumption, but the Shore and Brinell hardness tests are relevant. However, the consumed energy is predictable from a new index of rock strength, called Brook hardness, which has been specifically developed for sliding diamond indenters. The 'stress epicenter' is located with reference to the diamond indenter through a force vector which is stable for all circular sawing velocities, but it changes with frame sawing and drilling because they operate at about a tenth of the sawing velocity. The 'stress epicenter' is at the location of the crushed, compacted material under the indenter. Changes in the position of the stress epicenter can increase energy efficiency by as much as 100% and reduce the generation of vertical force by as much as 70%. Drilling tests using feed/revolution as the measure of penetration are used to simulate the variable velocity of frame saws by reducing the revolutions/minute. These tests reveal a previously unrecorded sawing mechanism that can improve the use of frame saws because strong granite can now be frame sawn with diamond. This improved potential should also apply to drill bits if they use feed per revolution as the means of penetration, instead of a static bit load. By measuring diamond by volume rather than by weight, and considering alternative options, accurate tool control can now be achieved, with every aspect being predictable. Optimization of rock sawing operations has shown that performance can be increased by 100–200% with tools removing as much as 30 tons in saw cuts per carat of diamond consumed. Because some rock mechanics terms used in the paper may have different meanings in the rock sawing context, a glossary of terms with further explanations is included at the end of the paper.

S.Liu et.al.[54] studied dynamic characteristics of marble under impact loading and high temperature. Dynamic mechanical experiments were carried out on marble under different temperatures and different impact loadings by using the high temperature split Hopkinson pressure bar (SHPB) experimental system which is set up by integrating the 100 mm diameter SHPB with high temperature device. Combining the transformation of mineral components with the change of mineral particles under high temperatures, the dynamic mechanical characteristics are analyzed and the essence of rock fracture is explored. The experimental results show that the stress–strain curves under impact loadings and different temperatures have the same change law below 800^0 C. When temperature exceeds 800^0 C , the densification stage prolongs, the curve moves towards right quickly, the slope decreases and the yielding stage extends evidently. The dynamic mechanical characteristics of marble take on obvious temperature effects. The peak stress, peak strain and elastic modulus with the same impact velocity fluctuate in different extents with the increase of temperature before 400^0 C. When temperature is above 400^0 C, the peak stress, peak strain and elastic modulus increase order line nearly linearly with the increase of temperature. There is remarkable difference among dynamic failure modes of marble under different temperatures. Especially, when temperature reaches1000^0 C, the fragments are powder and uniform particles.

An experimental study was carried out on some marble stones in which specific energy of the sawing was presented and found that the specific energy, decreased with increasing traverse speed, cutting depth and flow rate of cooling fluid. The results also indicate that the mineralogical properties could primarily responsible for the specific energy rather than physico-mechanical properties [55]. The experimental study to determine most significant rock properties influencing saw blade wear performance were calculated. The results revealed that the maximum grain size of quartz and alkali feldspar minerals were the most dominating factors influencing the specific wear rate. In order to be more pragmatic, we may adopt the mechanism of material removal by lateral fracture, which was proposed by [56] for ceramics. The number of parameters involved to assess the tool wear makes the problem highly complex. The derived analytical approaches are not fully able to solve such complex phenomenon. So, mostly to address this issue, the researchers makes use of some empirical relationships. By literature review it can be seen that most of the rock wear mechanism models are qualitative, involving description and interpretation.

2.2 Sustainability of marble stone processing

Marble stone industry is considered one of the main economic resource in most of the countries especially in Rajasthan state of India. This sector contributes widely to local production, exports and employment. Moreover it is considered one of the primary resource in building and construction. Environment protection, economic prosperity and respect for the need to promote social equity, constitute a prerequisite for any modern industry aiming to operate in a sustainable manner [57]. The natural stone industry in Rajasthan is a sector comprising large small and medium scale industries (SMEs), despite the fact that they consists dynamic extraction often lacks the resources to apply novel technologies and management schemes to achieve sustainable performance. Despite of financial growth of the Rajasthan stone industry, there is a recognizable difficulty to keep up pace with the technological innovations, and breakthrough in terms of equipment, production chain or adoption of holistic environmental and management strategies. The stone extraction industry constitutes a sector significantly affected by the principle of sustainable development, focusing on need to develop the mineral wealth, to provide economic prosperity, environment protection and social equity. Further, development of this sector will create opportunities, including employment, transfer of skills and technology, development of local infrastructure and services and development of national trade. However, parameters like non-renewable nature of natural resources, increased energy consumption land take, potential impacts on soil and water, constitute main challenges faced by this marble stone industry, indicating the requirement of holistic approach and effective sustainable planning and operation. The term sustainable development began in use in the early 1970's and over the year has become a common word for envirnmental and social scientists. The most popular definition came from the report of the world commission on environment and development in 1987 (also termed as Brundtland report), which means the development that meets the needs of the present without comprimising the ability of future generations to meet their general needs. The reuse of the traditional construction materials attests to their high value over the long term. In fact the practice has always demonstrated the inherent value of traditional raw materials and their products in confronting the issue of sustainability, in broder sence of preserving resources- material for future generations [58]. Environmental concerns are very important for sustainability because of the natural environment is where we live and sustainability requires that we recognize our limits of the environment. The key environment issue is to minimise our impact on global eco system and maintain the erath in a healthy state. The economic dimension is a important issue to be addressed the depletion of non-renewable resources, global constraints on economic growth, and correct procedures for assigning costs on economic growth, and correct procedures to assign costs to environmental pollution and other negative impacts currently borne by society as a whole. While recognizing the importance of maintaining a balance between all three elements of sustainable development. Throughout the history of buildings the symbolic value of architectural marble and stone materials in the new construction has gone hand in hand with the practice of recycling,demonstrating, at various levels, an intrensic awareness of reuse as a tool for minimizing waste of material and energy. Now-a-days sustainability is rarely considered from a long term perspective, and when it is, and the approach tends to be from a broad theoretical standpoint. In the past, however it was a common and necessary aspect of construction management, when the waste of materials was a forbidden luxury.

Being a third producer of the marble in the world approximately 85% of India’s production is received from Rajasthan and almost all mining processing activities are concentrated around Udaipur. Rajasthan has around 4000 marble mines and about 1100 marble gang saws (processing plants) [10] . The industry involves Mines, Processing plants, Cutters for the production of tiles for walls and floors, articles, waste reproduction and other ancillary works. Due to these processes stone slurry generated corresponds to about 40% as final product. In recent times agreeing to the article of times of India, it has alleged that “There are 250 marble processing units in the industrial field and they are dumping about 70 tons of slurry daily as a result of which about 700x500 meters of the valley has been ruined” this dumped slurry is posing a menace to life, flora and fauna of the vale [59] The following some of the hazards listed

1. When hazardous waste is dumped on the land, it reduces the prosperity, water absorption and water percolation leading to poor land quality.
2. In monsoons the stone slurry is carried out to the rivers, road drains, wells, bore wells and other water bodies which affect the quality of the water. So, ultimately it is damaging the aquatic life.
3. When the stone slurry becomes dry, the fine particles are quickly dispersed and it leads to air pollution.
4. Most of the Indian people depend on agriculture and botany, the dried slurry from the rain water as well as the air deposits on the land and may affect the growth of the vegetation and plants.
5. Already grown trees and bushes have died out and new ones do not grow (Rajasthan). Animals have also been deprived of their food and shelter.
6. There are a number of accidents due to improper dumping of the mine waste on roads and quarry sites.

I. S. Buyuksagi et.al. [40] focused on the environmental economic, and social impact of marble stone industry in the Middle East and North Africa region taking Palestine as a case study. It presents the lifecycle of marble stone, with adequate indicators, and proposes strategy for proper and efficient use of resources including natural stone, water and energy during production processes. 3Rs (Reclaim, Reuse and Recycle) principles are used to minimize the waste at each stage of marble stone lifecycle and hence improve its material efficiency. Marble stone sector is modelled using doughnut-modelling technique taking into account most of the factors influencing this sector. The value contribution of this sector is discussed showing the rational relation between consumption and production.

A.gazi et.al.[60] worked on energy efficiency and environmental assessment of a typical marble quarry and processing plant Marble is one of the most aesthetically pleasing, durable and long lasting decorative and building materials and plays an important role in the economy of several European countries. The majority of quarrying and marble processing activities worldwide are performed by Small-to-Medium Enterprises (SMEs), whose operations are characterized by low productivity coupled with low penetration of new technologies, high production costs and an overall lack of sustainable resource management coupled with significant amounts of waste material produced mainly during the quarrying stage. There is a marked need within the sector for increases in production efficiency coupled with substantial reductions in material waste that can be achieved by adopting best available production and processing practices, promoting technological innovation, incorporating energy saving technologies and modernizing the sector's organizational structure and management practices. The present work provides a systematic approach for assessing the current energy and environmental status of a typical European marble quarrying and processing SME and proposes measures for meeting cleaner production objectives. An evaluation methodology was developed, through consideration of several realistic plant operating scenarios. The total energy inputs for specific products and processes together with appropriate environmental indices (equivalent CO2 yield) were calculated and compared to corresponding data from similar companies across the European Union. Possible measures that may improve overall plant energy efficiency and environmental impact are also proposed.

Pappu et.al. [45] worked on solid wastes generation in India and their recycling potential in building materials they say presently in India, about 960 million tonnes of solid waste is being generated annually as by-products during industrial, mining, municipal, agricultural and other processes. Of this 350 million tonnes are organic wastes from agricultural sources; 290 million tonnes are inorganic waste of industrial and mining sectors and 4.5 million tonnes are hazardous in nature. Advances in solid waste management resulted in alternative construction materials as a substitute to traditional materials like bricks, blocks, tiles, aggregates, ceramics, cement, lime, soil, timber and paint. To safeguard the environment, efforts are being made for recycling different wastes and utilize them in value added applications. In this paper, present status on generation and utilization of both non-hazardous and hazardous solid wastes in India, their recycling potentials and environmental implication are reported and discussed in details.

Surender et.al, reported on quarrying, development and environment: A case study of Bijolia mining area in Rajasthan, Indian mining is essentially a destructive development activity where ecology suffers at the altar of economy. Unfortunately, in most regions of earth, the underground geological resources (minerals) are superimposed by above ground biological resources (forests). This is particularly more prominent in India. Hence mining operations necessarily involves deforestation, habitat destruction and biodiversity erosion. The extraction and processing of ores and minerals also lead to widespread environmental pollution. However, mankind also cannot afford to give up the underground geological resources which are basic raw materials for development. An unspoiled nature can provide ecological security to people but cannot bring economic prosperity. Scientific mining operations accompanied by ecological restoration and regeneration of mined wastelands and judicious use of geological resources, with search for eco-friendly substitutes and alternatives must provide the answer. A case study of Bijolia mining area in Rajasthan, India, gave some sensational revelation of the impact of mining on human ecosystem.

Use of marble waste and marble slurry needs to be explored as a replacement for conventional raw materials [61]. Some of its utilities can be "As filler material for road embankments, for manufacture of bricks, manufacture of Portland cement, manufacture of ceramic tiles, manufacture of thermoset resin composites, manufacture of lime, manufacture of activated calcium carbonate, hollow blocks and wall tiles, manufacture of ground calcium carbonate, as a neutralizing agent and filler for paints and rubber, as a concrete aggregates, as an asphalt filler, in waste water treatment, in the treatment of sewage sludge to quell obnoxious fumes, in the filter beds as screened aggregate".

Marble waste produced from the extraction, renovation and demolition of buildings and other constructions structure is considered priority waste and is generated several million tonnes globally. Recycling and utilization of this waste would be a significant contribution to the environment lead to sustainable development towards adoption of zero waste principle. One of the promising technology to convert this waste into value added products is geopolymerization and it involves a chemical reaction between solid alumina-silicate oxides and alkaline activator solution at ambient temperature or slightly elevated temperatures [62]

Marble waste can be used to produce innovative nano-composite acrylic sheets incorporated with marble waste granules (MWG) were produced by free radical polymerization of methyl methacrylate (MMA). The study of physico-mechanical properties showed an improvement of adhesion between PMMA/SiO2 nano-composites and (MWG) [63]. The introduction of SiO2 induced an extraordinary improvement of the abrasion resistance of PMMA matrix. The moduli of elasticities, maximum strain, impact absorbed energy and scratch resistance are explained on the basis of (MWG) porosity and adhesion. The manufactured nano-composites sheets are cost effective in comparison with natural marble and possess the ability to have wide range of wonderful colours due to the inclusion of marble stones in a polymer matrix. In addition the sheets display other specific properties such as light weight, colour stability, electric insulation, low flammability, low water absorption and excellent mechanical properties [64].

Removal of copper (II) from some environmental samples by sorptive flotation using powdered marble wastes (PMW), which are widespread and inexpensive and may represent an environmental problem, as the effective inorganic sorbent and oleic (HOL) as the surfactant. The main parameter's (i.e initial pH, sorbent, surfactant and copper concentration's, stir times, ionic strength, temperature and the presence of foreign ions) influencing the floatation of PMW and or Cu (II) were examined. Nearly 100% of PMW and Cu (II) were removed from aqueous solutions of pH7 after stirring for 10 min at room temperature (~25^0 C). The procedure was successfully applied to recover Cu (II) spiked to some natural water samples [65].

An experimental study which investigates the effect of the use of marble powder (MP), as partial cement substitution, on the fresh and hardened properties of fibre-reinforced self-compacting concrete (FRSCC) of non-uniform size (length) and aspect ratio of fibre used for each length of steel fibre (25, 30 and 50 mm), three percentages (0.5, 0.8 and 1%) were used to improve the performances of FRSCC. All mixtures of concrete specimens prepared with 30% of MP were evaluated [66]. The use of steel fibre and MP has a significant effect on the mechanical performances. The increase in ultrasonic pulse velocity, compressive strength, splitting tensile strength and flexural strength reaches 2, 8, 16 and 29% respectively. The addition of fibre enhanced the ductility significantly. The results indicates that high volume of MP can be used to produce FRSCC [66].

Alzboon et.al. [67] have studied the possibility of recycling stone cutting slurry in concrete production as a replacement of portable mixing water. The results showed an improvement of all concrete and motor characteristics: concrete compressive strength had increased by 21 %, flexural strength by 18 %, mortar compressive strength by 11 %, and flexural strength by 11.7%. Slump values of concrete were reduced by 58 % such results emphasized the feasibility of reusing slurry sludge in concrete and mortar production.

Hameed et.al. [68] made use of Crushed Rock Dust (CRD) in concrete mix will reduce not only the demand for natural sand but also the environmental problem. In brief the successful utilization of CRD will turn this waste material into a valuable resource.

Unfortunately limited research has been done to explore effective utilization of CRD in concrete mix. Zain et al. (1999) recommended that the CRD in the aggregate.

Todays world is facing a major environment problem like global warming, ozone depletion, waste accumalation, air and water pollution etc. Over the last few decades many researches on environment protection referes that the concerns on global climate change is growing rapidly. So, there is an urgent need to take steps to mitigate these undesirable problems arising from our modern lifestyle to save our world and environment. Buildings play an improtant role in consumption of energy all over the world. This sector has an high influence over the total natural resource consumption and also on the emmissions released. A building uses a lot of energy from the construction phase, to reuse as well as for the final demolition stage. This energy can be direct or indirect. Direct energy used in construction, operation, renuation and demolition in a building. While indirect energy is consumed by production of material used in its construction as well as in technical installations. The social economic and environmental indicators of sustainable developmet of construction and building is drawing attention which is a globally emerging sector and a highly active industry in all developed and developing countries[69][70].

Asif et.al. [71] did a life cycle assessment (LCA) study on the household products used in construction house in scotland and analyzed five main materials of construction (wood, aluminium, glass, concrete, and ceramic tiles) and their assosiated environmental impacts. In the study it was found that concrete used an energy equal to 65% of the total embodied energy of the home, then followed by timber 13% and ceramic tiles 14% of embodied energy respectively.

Marble stone waste produced from the extraction, renovation and demolition of buildings and other constructions structure is considered priority waste and is generated several million tons globally. Recycling and utilization of this waste would be a significant contribution to the environment lead to sustainable development towards adoption of zero waste principle. One of the promising technology to convert this waste into value added products is geo-polymerization and it involves a chemical reaction between solid alumina-silicate oxides and alkaline activator solution at ambient temperature or slightly elevated temperatures [62]. Marble waste can be used to produce innovative nano-composite acrylic sheets incorporated with marble waste granules (MWG) were produced by free radical polymerization of methyl methacrylate (MMA).

The study of physico-mechanical properties showed an improvement of adhesion between PMMA/SiO2 nano-composites and (MWG) [64] The introduction of SiO2 induced an extraordinary improvement of the abrasion resistance of PMMA matrix. The moduli of elasticities, maximum strain, impact absorbed energy and scratch resistance are explained on the basis of (MWG) porosity and adhesion. The manufactured nano-composites sheets are cost effective in comparison with natural marble and possess the ability to have wide range of wonderful colors due to the inclusion of marble stones in a polymer matrix. In addition the sheets display other specific properties such as light weight, color stability, electric insulation, low flammability, low water absorption and excellent mechanical properties.

Arola et.al.[32] have studied the possibility of recycling stone cutting slurry in concrete production as a replacement of portable mixing water. The results show an improvement of all concrete and motor characteristics: concrete compressive strength had increased by 21 %, flexural strength by 18 %, mortar compressive strength by 11 %, and flexural strength by 11.7%. Slump values of concrete were reduced by 58 % such results emphasized the feasibility of reusing slurry sludge in concrete and mortar production.

2.2.1 Life cycle assessment

Life cycle assessment is a set of procedures for compiling and examining the inputs and outputs of materials and energy and its associated environmental impacts directly attributed to the functioning of a product or a system throughout its life cycle.

Life cycle assessment (LCA) methods have been used for environmental evaluation of product development of many industries for a long time, although the application of it in building and construction sector is stared from the past 10 years [94]. Life cycle assessment is a tool for systematically analyzing the environmental performance of product or process over its entire life cycle, including raw material extraction, manufacturing, use, reuse, and end of life, disposal and recycling. Hence, considered as cradle to gate approach. The international organization for standardization (ISO) have formulated and adopted an environmental management standard in 1900 as part of its 1400 series, in which 14040 series was focusing on establishing methodologies for LCA similar approaches have been adopted by many international organizations.

The environmental impact of three flooring materials [72] linoleum, vinyl flooring and solid wood flooring during their life cycle were assessed and compared through life cycle assessment (LCA). The purpose of this study is to assess and compare the environment impact from cradle to grave for floor coverings. From the study they found solid-wood floorings were more environmently friendly to use compare to the other two materials.The authors finally stressed that there is a need to assess maintainence and landfill (end-of-life) impacts to build more comprehensive understanding of the study.

2.2.1 Energy audit

Energy audits are very crucial and exploded as there is an increasing demand to lower expensive energy costs, pollution and move towards sustainable future. Their importance have magnified since energy spending is a major expense in any industry it almost contributes to 20-40 % of total manufacturing cost [73] Some benefits of energy audits are given below:-

1. The audit will not only inform you of opportunities but provide you with financial analysis. This will enable prioritization based on financial benefit and return on investment.
2. Provide you with solid, easy to understand technical information regarding the proposed energy conservation measures.
3. Provide you with emissions analysis to help you understand the benefits of your decisions from an environmental standpoint.
4. Understand where energy is used and which areas are worth focusing on the most

Some brief audits of different industries are discussed below to identify the parameters and remidies.

Fabiano et al.[74] studied the potential for increased green house gas (GHG) mitigation benefits through an increased use of wood products in building. His study determined the GHG outcomes of the extraction, manufacture, transport, use in construction, maintainence and disposal of wood products and other building materials for two popular house designs in Sydney, Australia. The study showed the significant GHG emission savings were achieved by optimizing the use of wood products for the house designs.

Christopher et al.[75] did analysis of different stages of brick production process and the materials used in each stage. They did analysis including raw material acquisition, industrial production, packaging and transportation. Energy use and emissions are quantified and the potential environmental effects are assessed. The study indicated that the emissions to the environment are attributed to the energy use, directly at the site with the combustion of pet-coke and diesel and indirectly with the use of large amounts of electricity. The emissions of CO_2 make up the biggest percentage of all releases to the atmoshpere.

Wu et al.[76] developed a method to assess the environmental impacts of building materials based on their environmantal profiles. The evaluation of the seriousness across environmental impact catagories is a key step has been discussed in detail. Production of some building materials was analysed by Tulay [77] with regard to their environmantal impact through a specifically developed method. As a result all examined building materials were found successful with 51% in resource efficiency, 52% in energy efficiency, 68% in water efficiency, 62% in waste production, 72% in effects on human health. The examination also showed that more energy is consumed in the production of raw materials such as glass, aluminium, fibre wood, plywood, and PVC, where as much less energy is consumed for materials such as marble gas concrete and water proofing materials. Finally the environmental impact of including phase change materials (PCM) in a typical mediterranean building was studied by Alvaro et al.[78] the study was developed for the real monitered cubicles, and second for additional hypothetical scenarios, when PU is added to the reference cubicle. The addition of PCM does not produce a significant variation of global impact results because the impact savings achieved during the operational phase are balanced out with the manufacturing impact of PCM. From this study they recommended that It is better to use salt hydrates than paraffins in order to reduce the manufacturing/disposal impact. The use of PCM throughout the year has to be maximized. The benefits of the PCM will increase in locations where the weather conditions are similar all the year long, since the PCM will perform more cycles.

V. Liguori et.al. [79] studied the energy and environmental audits of marble slabs and tiles produced in the Custonaci basin, along with a simple comparison with that produced in Carrara. The results indicate that the use of explosives is not so meaningful for air emissions but it causes a large amount of solid waste. A comparison with the Carrara marble production suggests a solution, by substituting the explosive with straddle bearing in order to achieve more control in the moving operations of marble blocks.

2.3 Characterization of marble stones

The property of a stone to withstand chemical, physical and environmental degradation is also governed by intrinsic properties such as mineralogical and microstructural parameters[80]. The method of investigating mineralogical properties is by petrography analysis. These methods give important information like (mineral, shape, size, texture and phase). One such method is to reduce the waste is identify the process parameters at each stage that may be quarrying, processing or polishing and optimize these process parameters in order to increase the efficiency of the cutting, processing and polishing process. The following paragraphs discusses the influences of morphology, mineral grain size and microstructure on stone machinability.

2.3.1 Effect of morphology of marble stones

Marble stone is usually made of minerals which combine together to make up its individual properties. Hardness, is defined as the resistance offered to the indentation which directly depends on the average hardness of minerals that make the surface of the stone. It is evident that it is the strength, fracture toughness, modulus of elasticity of stone limits resistance to mechanical wear and fragmentation. We know that most of the stones present in the area of Rajasthan is made of the following composition.

Table. 2.3.1.1 Composition of Rajasthan stones [42]

S.No	Type of stone		**Chemical composition**					
		Calcium oxide(CaO)	Silica (SiO_2)	Aluminum Trioxide(Al203) + Ferrous Oxide (Fe2O3)	Potassium Oxide + Sodium	Sodium	Magnesium Oxide (MgO)	Loss of Ignition (LOI)
1	**Marble**	**35-40**	**3-25**	**10-12**	**0.06-1.0**	**0.05-1.12**	**2-3**	**38-43**
2	Granite	1-3	73-76	19-22	5-7	4-7	004-0.09	0.01-0.05
3	Sandstone	38-42	15-18	1-2	0.35-0.5	0.40-0.62	14-16	32-34

If a stone is resistant to withering and aggressive to chemical environments, it is due to the presence of carbonate and silicate in it. The resistance of silicate minerals follow the principle of Goldsmith, which shows that quartz and feldspar are very resistant to weathering, while more presence of mafic minerals such as amphiboles and olivine are less resistant. These minerals may change to whitish gel when they come in contact with acids. Suphide minerals present in the stone are more reactive and can be easily transformed to suphates and hydroxides. If iron suphide pyrrhotite is present in the stone it is likely to cause damage. The minerals produced by the chemical reaction of suphide pyrrhotite cause the volume increase and may damage the surface when it is used as an aggregate in concrete. Resistance to fire strongly depends on the minerals present in the stone. The minerals which has anisotropic thermal expansion example being the calcium, as well as different minerals with large variations in thermal expansions are less resistant to thermal wear. Stones used as aggregates in other materials should have the thermal expansion equal to that of the matrix thermal properties. The combination of minerals may also have an influence. This can be exemplified by sandstone, in which the sand grains can be referred to as component grains and the minerals in between as the cementitious material. In the withering of sandstones, the cementing minerals represent a greater limitation on the durability of the stone. It is well known that calcite cemented sandstone is less durable than a comparable quartz-cemented sandstone. Sandstone cemented with cryptocrystalline silica in the form of opal is also less durable.

P.N. Manoudis et.al. [81] demonstrated that the modification of a commercial siloxane protective composition by the addition of silica nanoparticles substantially enhances its protective efficiency and renders the treated stone surface super-hydrophobic and self-cleaning. The extent of surface hydrophobization depends on nanoparticle concentration and reaches a maximum value of ~ 160° at 1% w/v of nanoparticles for the case of white Greek marbles (Naxos, Pentelic and Thassos) treated with the modified composition. The investigation of the surface morphology by scanning electron microscopy (SEM) reveals the presence of micron-sized protrusions (10–100 μm in diameter) formed by nanoparticle aggregates consolidated by the siloxane polymer. The diameter and surface density of the protrusions depend on nanoparticle concentration. The Nano-dimensions of the silica particles are essential for the superhydrophobization of the treated marble surfaces. In the case of micron-sized silica particles that were mixed with siloxane and were applied accordingly on similar white Greek marbles, the superhydrophobic effect was not achieved and the observed water contact angles were substantially lower.

P. Maravelaki et.al. [82] evaluated the environment on weathering of monuments of Istria stone in Venice, systematic mineralogical, petrographical and elemental analyses of depth profiles were performed on samples of surficial crusts (dendritic black, compact black, grey and white). Decay products of deposition and interactions between gases and stone, including wind-blown dust, marine salts, anthropic aerosol, gypsum and nitrates, are incorporated into the mineral matrix down to a depth of 10 mm.

Asmus et.al. [83] studied heat conduction analysis is prescribed to characterize the removal of encrustations from stone by means of pulsed laser radiation. Ruby laser experiments were performed on marble and limestone samples, and the results are compared with the analysis as well as with air abrasive and flash lamp cleaning, optical microscopy, and scanning electron microscopy. Electron microprobe x-ray fluorescence analyses were used to evaluate the results. For the most friable stones, the laser flux could be increased 42% above the incrustation removal threshold before stone damage was detectable.

Vasco Fassina et.al. [84] studied traditional mechanisms of the causes of marble and stole decay. This is a very important research task because it can help to clarify the influence of past treatments on the velocity of stone decay. To assess the morphology of deterioration, samples of marble included in resin were analyzed in cross-section by means of optical microscopy and scanning electron microscopy interfaced with an energy dispersive X-ray system. Focused attention on: the identification of old treatments carried out on the surface as a maintenance operation; weathering of old treatments carried out in restoration works at the beginning of this century and most recently in the 1960's carried out to stop the decay; thin yellow patina extensively present on different lithotypes, Istrian marble stone; and an extensive grey appearance of the surface of the marble.

2.3.2 Effect of grain size of marble stones

Texture and characteristics of a marble stone are corollaries of the properties of the grains that compose the marble, and of the interactions of grains. Marble is a metamorphic rock, metamorphic conditions mineralogical composition and grain characteristics are the substantial features for the development of the mass of marbles.

Grain size is the classifying and defining parameter for marble. In general particles are of non-spherical shape thus the grain diameter depends on the technique of its determination.

It has been said that finer grain sized stones have a greater strength [85], demonstrated that the compressive strength of granites increased with increasing specific surface. A coarse-grained stone has both low strength and low fracture toughness. Not only the grain size but also the grain distribution also effect, the large size range gives higher strength to the stone and wear resistant to the fragmentation and better strength when compared to equi-granular stone. Marble and other limestones which are subjected to cyclic thermal loading may start the crack initiation at the grain boundary and extends through out leading to failure. If the grains are wide spread this phenomenon of crack formation and propagation can be reduced. A mineral that is present in small amounts and has different deformation properties, such as Young's modulus, from the surrounding mineral matrix, may cause stress concentrations along its boundaries. This effect is valid both if the mineral is softer, such as lime, or stronger, such as quartz. There is a difference between grain contact and a phase contact the former being the mineral contact between the same phases or different such as quartz-quartz and quartz-feldspar. These two phases have different strengths, young’s moduli and other properties. A phase contact will therefore have a greater influence on mechanical properties of stone than a grain contact.

Y. Ozcelik et.al. [86] experimented on diamond wire cutting of different marbles to evaluate the wear on diamond beads and average cutting rate were determined in cutting operations. They prepared thin section marble samples for determination of textural characteristics and texture coefficients. The relationships between textural characteristics and wear rate were considered and are found that by decreasing grain size increases the wear rate. Furthermore, relationships among the texture coefficients and, wear on diamond beads and cutting rate were also investigated and significant relationships between these values were found. This study implies that textural characteristics have to be considered in selection and design of diamond beads in marble industry.

Osman Gencel et.al. [86] performed physical and mechanical tests on cement blocks they produced. The cement type turns out to be an important factor. Mechanical strength decreases with increasing marble content while freeze-thaw durability and abrasive wear resistance increase. Waste marble is well usable instead of the usual aggregate in the concrete paving block production.

Yimin Lin et.al. [88-89] studied surface Nano crystallization, by surface mechanical attrition treatment, and deformation surface layer with Nano-crystalline grains was produced on AISI 321 austenitic stainless steel by means of surface mechanical attrition treatment (SMAT). Low-temperature nitriding of SMAT and un-SMAT AISI 321 stainless steel was carried out in pulsed-DC glow discharge. The effect of SMAT pretreatment on the microstructure and properties of the stainless steel were investigated using X-ray diffraction, scanning electron microscopy, transmission electron microscopy, Vickers hardness tester and UMT-2MT tribometer. The results showed that the plasma nitriding of AISI 321 steel can be enhanced considerably by means of SMAT process before nitriding, and a much thicker nitrogen diffusion layer with higher hardness was obtained for the SMAT samples when compared with un-SMAT samples. In addition, the wear resistance and load capacity of the nitrided layers on the SMAT samples was much higher than that of the un-SMAT samples due to the thicker S phase case and the gradient nitrogen diffusion layer.

J.E. Lindqvist et.al. [89] studied the properties of stone materials and they divided them into intrinsic properties such as chemical and mineralogical composition, grain size and porosity, and into functional properties related to a technical application. The latter described how the stones respond to conditions in the environment such as mechanical load, freeze–thaw cycles and exposure to moisture, and are controlled by the intrinsic properties. This implies that intrinsic properties can be used in order to assess the functional properties of the stone if it is possible to identify and quantify the related critical parameters.

A. Tosun et.al. [90] studied the liquid marbles are hydrophilic liquid drops encapsulated with a hydrophobic powder. They behave as micro-reservoirs of liquids able to move rapidly without any leakage and are promising candidates to be applied in genetic analysis where 2D microfluidics and lab-on-a-chip methods are used. The manipulation of liquid marbles using gravitational, electrostatic and magnetic fields were recently investigated. In this work, they determined the evaporation rates of PTFE marbles formed by encapsulating PTFE micro powder on a water droplet in a closed chamber where relative humidity and temperature was kept constant. Evaporation rates of PTFE marbles were compared with the rates of pure water droplets in terms of evaporation resistance, ϕ parameter and it was found that PTFE marbles have longer life-time than water droplets so that ϕ values were found to increase regularly from 0.365 to 0.627 with the increase of RH of the evaporating medium. The barrier effect of PTFE micro particles at the water–air interface was more effective when water was evaporating slowly. PTFE water marbles have life-time of 26–60 min to retain their spherical shape under normal atmospheric conditions which is suitable for many promising applications in microfluidics, genetic analysis, electromagnetic actuators and valves.

2.3.3 Effect of microstructure of marble stones

Porosity is an important characteristic of stones microstructure, the size, shape and distribution of the individual pores over the grain can have a conclusive effect on the behavior of stone mechanical stability, and durability when used as building material. So, the moisture properties of the stone is directly related to the porosity. Moisture exchange may also occur between different porous materials. In the case of capillary water suction, due to the higher suction force in finer pores, transport is much easier from coarse porous material to fine porous material than the other way around. For a damaged stone surface with a coarsened pore structure, capillary transport will be efficient as far as the damaged area, and water transport to the surface will mainly occur through vapour transport. This may cause efflorescence and frost damage as discussed below. This effect may be enhanced by the increased rate of water ingress through the coarsened surface.

Non-destructive tests (porosity and ultrasonic wave propagation) and destructive tests (uniaxial compressive strength and slake durability test) were performed over available samples. Furthermore, the tests were carried out under different conditions (i.e. air cooled and water-cooled) in order to study the effect of the fire off method. The results show that uniaxial compressive strength and elastic parameters (i.e. elastic modulus and Poisson's ratio), decrease as the temperature increases for the tested range of temperatures. A reduction of the uniaxial compressive strength up to 35% and 50% is observed in air-cooled and water-cooled samples respectively when the samples are heated to 600 °C. Regarding the Young's modulus, a fall over 75% and 78% in air-cooled and water-cooled samples respectively is observed. Poisson's ratio also declines up to 44% and 68% with the temperature in air-cooled and water-cooled samples respectively. Slake durability index also exhibits a reduction with temperature. Other physical properties, closely related with the mechanical properties of the stone, are porosity, attenuation and propagation velocity of ultrasonic waves in the material [91].

Erhan Güneyisi et.al. [92] studied the binary and ternary use of marble powder (MP) and ground granulated blast furnace slag (GGBFS) have been investigated in the production of self-compacting mortars (SCMs). The marble powder was obtained as an industrial by-product during sawing, shaping, and polishing of marble. A total of 19 SCM mixtures were proportioned having a constant water-binder ratio of 0.40 and the total binder content of 550 kg/m3. The control mixture contained only portland cement (PC) as the binder while the remaining mixtures incorporated binary and ternary blends of PC, MP, and GGBFS. After mixing, the fresh properties of the SCM were tested for mini-slump flow diameter, mini-V funnel flow time, initial and final setting times, and viscosity. Test results indicated that the inclusion of MP increased the V-funnel flow time, setting times, and viscosity of SCMs whereas decreased the hardened properties. Using GGBFS, on the other hand, decreased the V-funnel flow time and viscosity while increased the setting times of SCMs.

A Ersoy et.al. [93] studied the performance of the saw A wide range of textural, mechanical, physical and intact properties of the rocks were quantitatively determined. Operating parameters of the diamond saws were continuously monitored during the cutting trials. Generally, down cutting method was applied in the experiments. The effects of the operating and rock parameters on the performance of the diamond saws were examined and relations between the cutting variables are described. Correlations between textural, physical and mechanical properties of the rocks with specific cutting energy of the saw are also highlighted.

D. F. Howarth et.al. [94] studied the dimensionless quantitative measure of rock texture, describing grain : shape, orientation, degree of grain interlocking and relative proportions of grains and matrix (packing density) has been developed. Data required for the model are obtained by image analysis of thin sections and concerns percentage areas of grains and matrix, length, breadth, perimeter, orientation and area of each grain in the viewing window. The results of rock strength, diamond and percussion drillability tests in eleven sandstones, marbles and igneous rocks are reported, and correlated with the developed texture coefficient. The texture coefficient returns highly statistically significant correlations with rock strength and drillability data. Sandstones have low texture coefficients and high drillability whereas igneous rocks have high texture coefficients and low drillability. With particular reference to percussive drillability it is suggested that extensional crack propagation in the sandstones in an energy efficient process since fracture paths propagate through the weak phyllosilicate matrix. Extensional crack propagation in the igneous rocks is an energy intensive process since a significant proportion of the available drilling energy is consumed in the formation of intra-granular fracture paths.

2.2 Grading of marble stones

A variety of marbles are produced and marketed under various trade names on the basis of colour, shade and pattern. These are i) Plain White Marble, ii) Panther Marble, iii) White- Veined Marble, iv) Plain Black Marble, v) Black Zebra Marble, vi) Green Marble, vii) Pink Adanga Marble, viii) Pink Marble, ix) Grey Marble and x) Brown Marble.

The marbles have also been classified by their genesis and chemical composition as under:

a) Calcite Marble: It is a crystalline variety of limestone containing not more than 5% magnesium carbonate. Colour and design wise, it may vary from grey to white to any colour, and even figurative light- brown to pink.
b) Dolomitic Marble: It is a crystalline variety of limestone containing not less than 5% or more than 20% magnesium carbonate as dolomite molecules.
c) Dolomite Marble: It is a crystalline variety of dolomite containing in excess of 20% magnesium carbonate as dolomite molecules. It has variegated colours and textures. As the whiteness increases, the luster and translucency increases to an extent that it starts resembling with onyx. The main advantage of this marble is availability of exotic colours and patterns and its low maintenance cost. Marbles of Banswara in Rajasthan and Chhota Udepur in Gujarat belong to this category.
d) Siliceous Limestone: It is a limestone containing high silica with smooth appearance due to fine-grained texture. It is difficult to cut and polish this type of marble but once polished, it gives a pleasant look. It is available in several colours and designs. The pink marble of Babarmal and Indo-Italian variety from Alwar belongs to this category.
e) Limestone: Several varieties of limestone are being exploited and used as marble. The Oolitic limestone of UK, Black Marble of Bhainslana, Katra &

Sirohi and Golden-yellow Marble of Jaisalmer belong to this category. This type requires frequent maintenance in the form of polishing as they are non-metamorphosed and hence are softer in nature.

f) Serpentine or Green Marble: This marble is characterised mainly by the presence of a large amount of serpentine mineral. It has various shades of green varying from parrot-green to dark-green and is known for having varying degrees of veinlet intensities of other minerals, chiefly carbonate of calcium and magnesium. Most of the green marbles from Gogunda, Rikhabdeo, Kesariyaji and Dungarpur belong to this category. This marble is mostly used for panelling. The darker variety of this marble, which is so dark-green that it looks like black, has been termed as Verde Antique.

g) Onyx: It is a dense crystalline form of lime carbonate deposited usually from cold water solutions. It is transparent to translucent and shows a characteristic variegated colour layering due to mode of deposition. Such type of marble is found in Kupwara district in Jammu and Kashmir. It is used for making decorative articles.

h) Travertine Marbles: It is a variety of limestone regarded as a product of chemical precipitation from hot springs. The depositional history has left exotic patterns, when this is cut into thin slabs and polished, it become translucent.

Splendid varieties of marble are spread all over Rajasthan mainly in the districts of Nagaur, Udaipur, Rajasmand, Banswara, Dungarpur, Jaipur, Sirohi, Bhilwara, Ajmer, Bundi, Alwar, Chittorgarh, Churu and Pali Prominent clusters for processing and quarrying of marble in Rajasthan are

Marble has classified into 10 groups by Bureau of Indian Standards (Indian standard Institute i.e ISI). Rajasthan is most fortune state where all 10 groups specified below are occurring[10].

1. Plain white marble
2. Panther marble
3. White Veined marble
4. Plain black marble
5. Black zebra marble
6. Green marble
7. Pink Adanga marble

Makarana	1. Makarana white was used in Tajmahal. 2. Makarana is now a developed marble centre with hundreds of marble quarries, modern slab & tile processing and stone crafts units. 3. Important varieties are super white, Albeta, Adanga, Kumari, Dongri, Pink etc. 4. Major centre for marble handicrafts.
Kishangarh	1. Situated 100 km from Jaipur. It is the major market outlet for stones quarried in Makarana and Rajsamand. 2. About 300 modern gangsaws. 3. About 2000 traders. 4. Edge cutting Machines apprx. 500 5. Spread over area of 15 sq.kms
Rajsamand	1. Deposits of a variety of white & greyish white marble like Morwar, Agaria, Dholikhan, Arna, Jhanjhar, Dharmeta etc. 2. Quarries using diamond wiresaws, chainsaws and handling equipment 3. About 250 modern gangsaws & 20 tiling plants. 4. Cluster spread over a stretch of 40 sq.kms from Nathdwara to kelwa and amet.
Udaipur	1. Deposits over 100 million tons. 2. Rajasthan green- export bonanza quarried from Rikhabdeo-Kesariaji, 660 Kms from Udaipur city, and 650-700 mines in operation around Udaipur. 3. Green marble, Pink Marble, Onyx Marble, Black marble, White marble 4. Indian pink comes from Babarmal- 26 Kms from Udaipur City Babarmal Pink – a fine grain hard marble with black and white bands. 5. Fast developing modern quarries using diamond wiresaws 6. About 150 modern quarries using diamond wiresaws. 7. 150 modern gangsaws & 20 marble tiling plants
Banswara	1. A variety of white to offwhite soft dolomitic marble (fine to medium grained).
Jaipur	1. With deposits over 50 million tons, Jaipur has variety of white & greyish white marble with important varieties being Pista, Oynx, Indo Italian, Black, The quarries are currently non-operational due to environmental restrictions. 2. Several modern gangsaw & tiling plants is a throbbing trade outlet for exports and marble handicrafts.
Abu Road	1. Abu Road in the sirohi District is a major cluster for processing of marble and is surrounded by extensive marble quarries around selwara. It is also a processing centre for marble from Gujurat.
Churu	1. Bidasar in churu district is famous for its forest brown and forest green marble varieties.

8. Pink marble
9. Grey marble
10. Brown marble

Natural stones can be classified according to their mineral content and the process of formation. Most of these minerals can be identified by their color, hardness, and crystal structure. However a wide range of crystals are difficult to identify. Good stones are characterized by durability, hardness, strength, amenability to dressing, appearance, weight, grain size, compactness, porosity and absorption.

In order to be suitable as building stones, a rock should have specific qualities such as capacity to stand the ravages of time and weather, requisite strength to bear strain and super-incumbent weight, attractive color and general appearance. Its structure must also be such as to allow quarrying into good sized blocks or planes. India possesses extensive deposits of different kinds of building and monumental stones. It is one of the few major countries known for the production and export of natural building stones of various colors. The most important building stones in India are the granites/and allied rocks, sandstone, limestone, slate and marble.

In earth science, rocks are classified according to their origin, irrespective of the micro and macroscopic appearance, physical properties, chemical and mineralogical classification of rocks. A mineral is considered structurally homogeneous with a fixed composition made by inorganic process.

Rocks are mainly divided into three categories they are:-

a) Igneous Rocks

These rocks are formed from by the cooling and crystallization of the silicate of magma on the earth surface or inside the earth surface. Igneous rocks have crystalline in appearance, although non-crystalline igneous rocks do occur. Some examples of igneous rocks are: basalt, granite, syenite, diorite etc.

b) Sedimentary Rocks

These are the rocks which are formed from the pre-existing rocks by the process of denudation along with the organic origin. The term includes both solidified and unsolidified material, the process of conversion of unsolidified to coherent sedimentary rocks is called diagenesis. Sedimentary rocks are categorized as calcitic (sandstone, conglomerates, etc.,), organic (limestone, chert, coal etc.,), chemical (travertine, evaporates etc.).

c) Metamorphic Rocks

The rocks from the transformation of pre-existing rocks by heat, pressure, and some fluids within the earth crust. Metamorphic processes is carried out in the solid state and include recrystallization, changes in the chemical composition as well as mineral of the parent rock. Some examples of the metamorphic rocks are amphibolite, magmatite, phillite etc.

2.5 Machinability study of marble stones

During stone machining numerous parameters needed to be taken into consideration to achieve appropriate efficiency, tool life and productivity. Diamond is almost the single tool material to machine harder stones. Diamond disks implement the cutting of stone blocks into cubes, rectangular. The statue shaped surfaces are also produced by disks and milling tools. Erosy [40] are introducing the system of the parameters affecting stone machining that is more detailed, than one in this research. During the machining of the stones as a result of the work piece-tool interaction the following phases periodically implement:

- ✓ Penetration of diamond increases the pressure influencing the stone
- ✓ Diamond increases the pressure until the initiation of fracture
- ✓ Diamond grain removes the chip because of the fracture

The affecting parameters of stone cutting can be divided into different groups and with the knowledge of these parameters productivity and tool life can be increased.

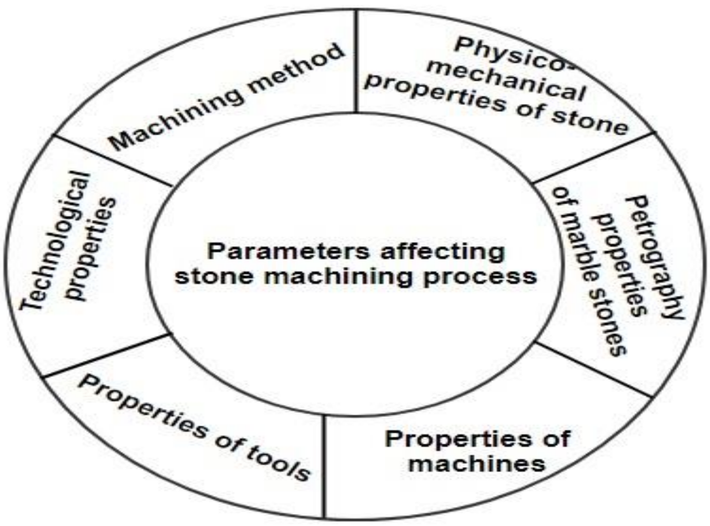


Fig. 2.5.1 Parameters effecting machinability

Mechanical and physical features of the stone pieces greatly influence the machining process. Minerals in the stone affect the machining and also the diamond stone in different ways. Other parameters affect forces between the diamond and the work piece, stress distribution in the stone and temperature between the tool and the work piece. One of the most important properties of stones is strength. Strength is a resistance against an external mechanical effect. Strength can be defined with the highest stress or energy that the stone material can bear without damage. Strength of stones is defined by compressive strength most of the times. In case of cutting processes the impact strength is also really important because during the machining process the stone material is influenced by cycle impact stress because of the continuous contact with the tool. Hardness is also a really important physical stone property. In a case of stone cutting processes Mohs hardness sequence is generally used to determine the degree of hardness of minerals The essence of this system is that minerals with greater number can scratch the minerals with smaller number in all cases. Shore Scleroscope hardness test is also a common solution of hardness testing. The essence of this solution is that a diamond inserted hammer is being dropped on the test stone in a curved path and the hardness is calculated from the rate of recoil. Another essential parameter is abrasivity that decisively affects the machining process. Appropriate tool material and technological parameters must be chosen according to the wear properties of stones. A relatively abrasive material needs to be cut with a completely different technology than a less abrasive material, like marble.

2.5.1 Effect of petrographic properties on machinability

One of the biggest problems at the machining of stone with diamond tool is that the stones generally have not got homogeneous contexture. It is true for almost every type of stones in building industry that they consist of several mineral types and their distribution and density in given areas of these minerals is not permanent. According to the previous sentences, in a case of stone machining the properties of minerals that build up the stone materials and the average weight percent of minerals of stones need to be taken into consideration. The inhomogeneous contexture also means that the researchers cannot create so detailed algorithm that is able to completely model the stone machining process. Reason of this statement is that the minerals of stones take place randomly inside the stone. Maximal and average size range of grains of minerals that build up the stone is a common measure at machining tests. There is a close connection between this property and the relative frequency of the given mineral type in the stone. Quantity number of the minerals is defined by Streckeisen diagram. Measurement solution for classifying igneous rocks is a diagram based on the relative quantity of mineral phases in stones. Measure of binding force between each mineral is another important petrography property that influences stone machining. It is easy to accept that in a case of materials with harder binding it is harder to detach each grain from the surface and because of this we need to use stronger technological parameters and harder tools.

J. Xie t.al. [95] investigated parameterization of micro-hardness distribution in granite related to abrasive machining performance. bulk value and deviation value of granite micro-hardness were proposed as micro-hardness parameters in order to parameterize micro-hardness distribution in granite and evaluate abrasive machining performance. First, drilling, grinding and sawing experiments were conducted for 10 kinds of granite in laboratory to investigate effect of micro-hardness parameters on abrasive machining efficiency. Then, the regression formula of micro-hardness parameters and abrasive machining efficiency was considered as an evaluation mode to predict abrasive machinability of granite. Finally, sawing and polishing experiment were carried out in manufactory to validate the evaluation mode. Experimental results show that abrasive machining efficiency increases with decreasing bulk value and deviation of granite micro-hardness. In addition, there exists good correlation between granite micro-hardness parameters and abrasive machining efficiency and their regression formula may be used to evaluate the abrasive machining performance in industrial production including sawing efficiency and tool life, but actual polishing quality only relies on mineral optical property.

Mohammad Ataei et.al. [23] did a performance prediction of diamond wire saws is important in the cost estimation and the planning of the stone quarries. An accurate estimation of sawability helps to make the planning of the rock cutting projects more efficient. In this paper, the performance prediction of diamond wire saws in cutting carbonate rocks was studied on 14 different carbonate rocks in stone quarries located in Iran. Rock samples were collected from the quarries for laboratory tests. Uniaxial compressive strength, Brazilian tensile strength, Schmidt hammer value, and Los Angeles abrasion were determined in the laboratory. Performance prediction was evaluated using simple and multiple regression analyses. Finally, a new model was proposed for predicting the production rate of diamond wire saw. It was concluded that the production rate of carbonate rock using diamond wire saw can reliably be estimated using the developed model.

N. Gunes Yılmaz et.al. [85] made experimental studies with an intent in establishing the most significant rock properties influencing sawblade wear performance in the processing of ‘true’ granites. To achieve this goal, microstructural characterization of nine different rock samples was made on thin sections using polarized petrographic microscope for the determination of mineral modal composition, grain size distribution and other textural features. The samples were also tested for their physico-mechanical properties. Sawing experiments of the studied rocks were performed on a full-scale side-cutting machine, and specific wear rate SWR was adopted as the criteria for sawblade wear performance. The results showed that maximum grain size of quartz and alkali feldspars were found to be the dominant factors influencing SWR. Physico-mechanical rock properties did not correlate with SWR. A new prediction model of specific sawblade wear rate is proposed.

2.5.2 Effect of technological properties on machinability

Technological parameters used in cutting process greatly influence the efficiency of stone machining and the wear process of the tool. During milling and cutting the same three technological parameters determine the efficiency of machining. Feed (F) defines the orbital velocity of the tool. Dimension of feed is mm/min. On the same rotational speed when feed rate is higher the edges of diamond tool (single diamond grains or covered inserts) detach more material in a given time range. Rotational speed is also an important parameter. Rotational speed defines how many revolutions are needed to be made by the tool. In case of higher rotational speed the quantity of chip detached by the cutting edge decreases and as a result of this a more advantageous wear rate can be reached. Third general affecting parameter is the depth of cut. The life time of the tool can be greatly increased with choosing the appropriate depth of cut. During stone machining when the depth of cut is higher the impact forces are higher during the machining and because of it the opportunity of breaking of the diamond grains increases. Naturally other parameters also influence the efficiency of stone machining but the literature that studies the cutting and machining of stones highlight these three parameters.

2.5.3 Effect of tool properties on machinability

In case of all materials the appropriate tool choice is really important from the point of view of efficiency of the cutting process. This fact is also true by stone cutting and milling. Diamond tools are used on a large scale to machine hard stones. During milling processes it is very important to choose the appropriate size (for example diameter) tool but also important the appropriate choice of insert cover. It is also essential to apply appropriate insert angles from the point of view of the forces. In case of stone table cutting typical properties of the disk is diameter, material and type of segments, and concentration and size of diamond grains in the segments.

I.S. Buyuksagis et.al. [96] experimented using circular sawing with diamond segmented sawblades is a machining process that represents a major cost item in the processing of marbles and other natural stones. Therefore, determining the optimum sawing conditions for a particular stone is of major importance in stone processing industry. In this work, utilizing a fully instrumented block-cutter, an experimental study was carried out to investigate the sawing performances of seven different types of marbles during circular sawing with a diamond segmented sawblade. Considering specific energy as a criterion of sawing efficiency, optimum sawing conditions valid for the tested marbles have been determined. Finally, statistically reliable equations were established to predict specific energy of sawing from simple laboratory rock property test procedures.

H.K. Tönshoff et.al. [22] used wire saw for cutting pure steel components offers new fields of applications, e.g. treatment of nuclear power or off-shore-components. The application of the wire sawing process for these specific cutting operations requires the development of diamond tools adapted to the cutting process. In this paper, the basic principles of wire sawing are explained and the background of diamond wire cutting of steel components is discussed. The interaction between the tool and the workpiece is described in detail. Results are presented of a project on further developments of the diamond wire sawing technique, emphasizing the applications for metal components.

C.Y Wang et.al. [97] made investigations on frame sawing with diamond blades. The kinematic behavior of the frame sawing process is discussed. Under different cutting conditions, cutting and indenting-cutting tests are carried out by single point cutting tools and single diamond segments. The results indicate that the depth of cut per diamond grit increases as the blades move forward. Only a few grits per segment can remove the material in the cutting process. When the direction of the stroke changes, the cutting forces do not decrease to zero because of the residual plastic deformation beneath the diamond grits. The plastic deformation and fracture chipping of material are the dominant removal processes, which can be explained by the fracture theory of brittle material indentation.

J. Xie et.al. [98] made studies on bulk value and deviation value of granite micro-hardness were proposed as micro-hardness parameters in order to parameterize micro-hardness distribution in granite and evaluate abrasive machining performance. First, drilling, grinding and sawing experiments were conducted for 10 kinds of granite in laboratory to investigate effect of micro-hardness parameters on abrasive machining efficiency. Then, the regression formula of micro-hardness parameters and abrasive machining efficiency was considered as an evaluation mode to predict abrasive machinability of granite. Finally, sawing and polishing experiment were carried out in manufactory to validate the evaluation mode. Experimental results show that abrasive machining efficiency increases with decreasing bulk value and deviation of granite micro-hardness. In addition, there exists good correlation between granite micro-hardness parameters and abrasive machining efficiency and their regression formula may be used to evaluate the abrasive machining performance in industrial production including sawing efficiency and tool life, but actual polishing quality only relies on mineral optical property.

2.5.4 Effect of machining method on machinability

During cutting and milling process equally two machining methods is distinguished. There are significant differences between the two strategies in the area of nascent forces. The two machining methods are compared by the cutting process of the stones. Diamond grain fully penetrates to the material at the moment of the collision during the down-cutting process. This machining method results maximum thickness at the beginning of cutting process and because of it the forces that affecting the grains are high. According to the previous sentence, during the machining of hard stone types, like granite, as a result of the impact loads the grains fracture and/or drop out from the matrix. This effect ruins the diamond tool in a short time. In case of up-milling the diamond grain in the moment of the collision with the work piece starts detaching minimal chip thickness. This chip thickness grows during the material cutting while the diamond grain is crumbling and wearing. Advantage of up-milling strategy is the more favorable wear process and the drawback of up-milling is that a particularly high stiffness machine is needed for the appropriate application.

R.M. Miranda et.al. [99] made experimental studies to determine the influence of material properties on the cutting mechanisms involved in abrasive waterjet (AWJ) of calcareous stones. SEM analysis was performed to investigate the material removal mechanisms. Two Portuguese calcareous stones were tested with different genesis and thus structural and mechanical characteristics. It was found that rock hardness and porosity have a significant effect on the cutting mechanisms investigated. In harder homogeneous rocks, like marbles, cutting occurs due to intergranular cracking and cleavage of calcitic grains. In limestones, the material removal process mostly involves intergranular cracking and material sliding along the argilous matrix and between this and calcitic grains. Plastic deformation of the matrix can also be observed.

An experiment performed by I. S. Buyuksagiset.al. [96] shows that cutting depths and workpiece travel speeds are highly inefficient. Although efficiency (specific energy) improves with cutting depth and workpiece travel speed, the improvement does not continue indefinitely and levels of certain values. Statistically reliable correlations found suggest that it is possible to predict specific energy of sawing by combining the effects of dominant workpiece properties. Therefore, if supported by further test data, it is likely that sawability evaluation of large number of samples can be realized rapidly without conducting direct sawing tests which involve lengthy and complicated testing procedure.

2.5.5 Effect of machining parameters on tool wear

The material removal rate is mainly influenced by the mechanical as well as the thermal loads acting on the diamond grains to withstand. The load on the diamond grains will mostly effected by the machining parameters. They depend on the following machining conditions.

1. The greater depth of cut, the smaller is the active grain face in contact area. Because of the greater contact length, the temperature at the tip is elevated.
2. The higher the feed velocity, the larger is the active grain face in contact area, and hence smaller is the temperature generation on the diamond grain

3. The higher is the grinding velocity, the higher is the thermal loading on the grain tip. Hence, the active grain size area reduces, the mechanical shock impulse at the beginning of the machining process decreases.

Besides the process parameters, a major influence can be found by the mode of machining process. If the machining is carried out in down cutting mode, a single grain reaches maximum chip thickeness at the beginning of the process. While in the up-cutting mode the chip thickness is maximum at the the beginning of the contact. In this case elastic deformation occurs at the beginning of the process and when the critical chip thickness is reached, chips are formed. This leads to different wear characteristics in up and down cut modes [44].

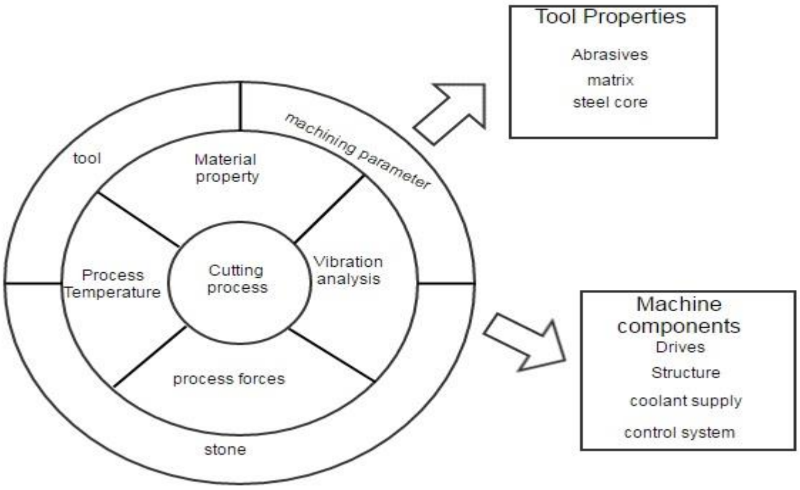


Fig. 2.5.5.1 Cutting and machine parameters

Based on the vast literature review done on sustainability study, characterization and machinability study on marble stones the following research gaps were identified and are listed below.

2.6 Research gaps

1. Grading of marble stones present in the regions of Kishangargh, Makarana, Udaipur and Rajasmand has not been carried out.
2. Sustainable study on extraction of marble from cradle to gate approach for this region has not been reported it helps in finding the parameters which are effecting the efficiency of cutting/quarrying resulting in waste generation.
3. Mechanical and Thermal characterization of the stones specific to these regions has not been reported.

4. Detailed morphological studies of these stones specific to these areas have not been reported in literature.
5. Machinability parameters optimization specific to the cutting machine were carried out by few.
6. Energy audit of the marble stone industry can be taken as a challenge in order to increase the efficiency of the machines and reduce the waste generated.

The overall aim of the project is to formulate a broad planning and framework for stone and marble industry of Rajasthan. Based on the literature review and research gaps identified the following objectives were identified which fills the gap in the knowledge management.

2.7 Objectives

1. To study the lifecycle Assessment and Life cycle Energy Assessment of the processing industries
2. To grade the marble stones present in different regions (Makarana, Agaria, Bhainslana, Udaipur green and Aandhi) of Rajasthan based on their properties.
3. To study the Thermal / Mechanical Properties (Strength, Hardness, Modulus etc.) of the marble stones.
4. To study the morphology (microstructure, its atomic alignments, grain boundaries etc.) of the stones.
5. To design and fabricate the strain gauge 3-axis milling dynamometer
6. To study the Machinability Parameters (MRR, surface roughness etc.) for the stones of Rajasthan and relate them to their overall characteristics.

Chapter 3: Materials and methodology

3.1 Sustainability study

Sustainability is defined as achieving the three pillars of sustainability must be sustainable. These pillars are social, economic and environmental. To achieve sustainability in the marble and stone industry there is a need to acertain the industry in terms of these three pillars.

Residual sludge from dimensional stone plants, which originated both from the gangsaws with the abrasive circular and frame saws, is classified as waste and causes many problems for the marble stone industry. The problems include fine size powder distribution, heavy metals and some petroleum hydrocarbon content, all of which is in recovery and reuse. The waste is often disposed on landfill sites and open areas which cause a severe air pollution as well as water pollution. The current cost assosiated with the sludge landfilling can exceed 3-5 % of operating costs for dimensional stone working industries, and its management is subject to periodic legislative regulation reform. The main problem is related to the sludge management which can be explained as follows.

If careful attention is paid to the sludge management treatment and its characterization, economic and environmental benefits are possible. To, achieve these benefits, it is necessary to consider systematic treatment of sludge to obtain secondary raw materials or new products which need to be certified not only on the basis of physical characteristics but also by means of appropriate chemical analysis to guarantee that products are not contaminated. To boost their reusability they must be sent to a local treatment plant, which is often cheaper than disposing them as waste. There are a number of factors that contribute to the viability of sludge treatment and reuse, the quantity of produced waste, which must be sufficiently large to justify the construction of treatment plant, the quality of waste, the reliability of the waste source in terms of both consistent quality and quantity, transportation cost and the market demand for products obtained from sludge treatment all these solutions are derived from the literature review done in the chapter 2.2 (sustainability of marble stone processing).

3.1.1 Life cycle assessment

As dicussed in the chapter 2.2.1 life cycle assessment of marble stone and its assosiated literature, four steps of LCA standard includes: goal and scope definition; inventory analysis, lifecycle impact analysis as shown in Fig. 3.1.1.1

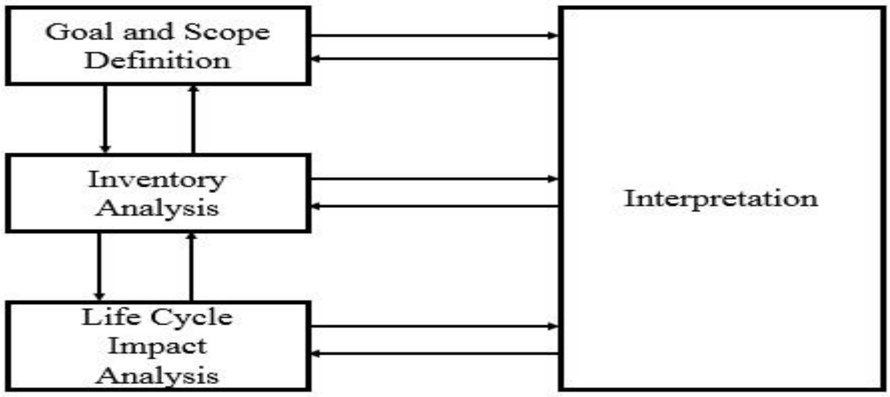


Fig.3.1.1.1 LCA frame work based on ISO14040

In order to find out some chances and possibilities for development of this industry, it is important to look in detail the life cycle analysis of marble extraction starting from rock to construction as shown in Fig. 4.1.1 in chapter 4.1. This flowchart of lifecycle of marble stone starting from quarrying stage where big blocks of rocks are sliced using (mechanized or non-mechanized) techniques. These sliced stones are then shaped to suit various applications in building and construction industries like claddings, flooring, tiles etc. The scientific flow chart is designed for an easy way of understanding the whole extraction process.

Marble extraction process begins from quarry, where rocks are extracted from rocky mountains. This extracted rocks are supplied to the construction industries through three stages. At first stage extracted rocks are transported to cutting (factories and workshops) to be sliced and turned into required dimensions to suit construction and building applications. At Second stage, these rocks from cutting factories are sent to polishing processing units where required polishing is done. At final stage the remaining small pieces of stones which cannot be used for construction and building are transported to crushers where they are further crushed into aggregates of different sizes, to be directly used as raw material in concrete mixtures. Dried stone powder from polishing and processing units can be utilized at construction site. The remaining waste from buildings can re-sized and returned back to quarries to fill the excavation site in order to reclaim the land and improve the landscape of the site.

After demolishing the built houses for many reasons, stones from it can be re-used by returning back to the cutting and polishing process before being used as re-build again. The lifecycle of marble extraction has been completely designed in the form in order to facilitate a better understanding of the whole process. The stone can be considered as a sustainable material throughout the processes, since it goes through the cycle back and forth.

3.1.2 Energy audit

After the marble is quarried it is sent to the local industries for further processing to be done on the natural stone. To do the energy audit it's important to look in detail what are the different processes that the natural stone undergo before it emerges as the final product ready for the construction. So, by focusing on different steps a natural stone encounters we can easily able to calculate the energy consumption at each stage of the process. The following flow chart in Fig. 3.1.2.1 are the different activities of the processing that a marble block undergoes before finally emerges as slab/tile which is used in construction.

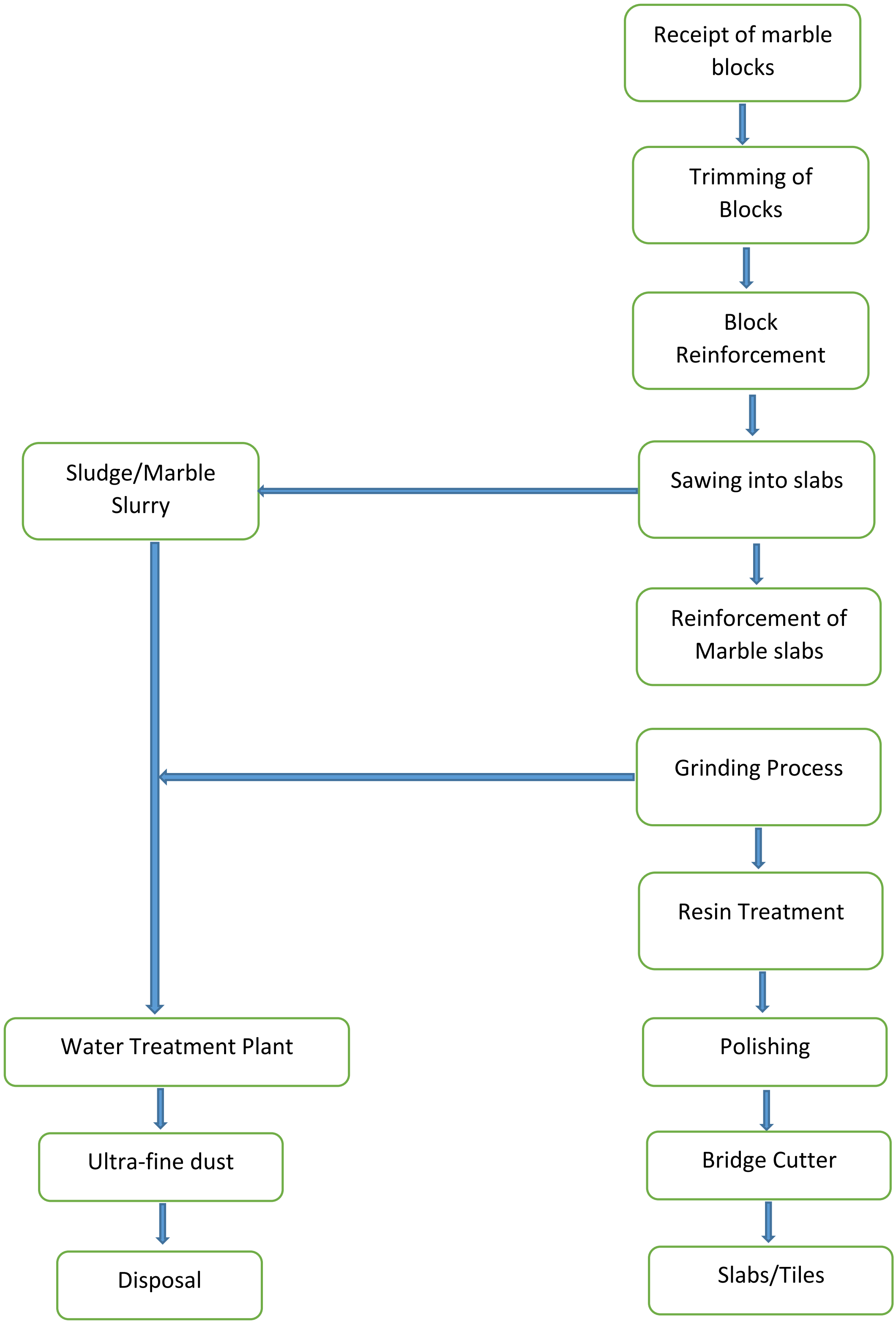


Fig. 3.1.2.1 Marble processing layout

Most of the energy consumed in a typical production process flows through the large horsepower engines. The energy audit data helps to identify the machines that are overloaded or idle and also helps in maintenance. The utility bills can be reduced as well as the Industries building durability can be increased with the energy audit study. Energy consumption of each machine is calculated using the following equations. Electric power supply to a 3 phase AC motor:

$$\mathbf{PkW = \eta m\ 1.73\ U\ I\ PF / 1000}$$

Where,

PkW = power (kW)

ηm = motor efficiency

U = voltage (V)

I = current (A, amps)

PF = powerfactor

$$\text{Energy consumed} = \eta m\ 1.73\ U\ I\ PF\ T / 1000$$

T= runtime

3.1.3 Life cycle energy assesment using Gabi

Life cycle energy assesment (LCEA) methods have been used for environmental evaluation of product development of many industries for a long time, although the application of it in bulding and costruction sector is stared from the past 10 years. Life cycle assesment is a tool for systamatically analyzing the environmental performance of product or process over its entire life cycle, including raw material extraction, manufacturing, use, reuse, and end of life, disposal and recycling. Hence, considered as gate to gate approach. The internatioal organization for standardization (ISO) have formulated and adopted an environmental management standard in 1900 as part of its 1400 series, in which 14040 series was focusing on establishing methodologies for LCEA similar approches have been adopted by many international organizations. The four steps of this standard includes: goal and scope definition; inventory analysis, lifecycle impact analysis.

Following the standards a gate to gate approach for a marble processing plant is designed, the goal of the process is to identify the energy consumed to produce a unit slab and tile from intial quarrying process. For this a systamatic inventory plan is designed as shown in Fig. 3.1.3.1. For each process the energy requirements are calculated and tabulated in various tables, further the life cycle impact analysis was done using an educational package GaBi.

The entire data base for evaluaion of lifecycle energy assessment of a processing plant using GaBi software package is given step wise below.

Step:1 Enter new project and activate the project.

Step:2 Go to the plans and create a new plan with the same name as that of the project name.

Step:3 Create a lime stone floor of 5 mm (since the grain size of the lime varies from 2 – 5 mm) taken maximum grain size as reference

Step:4 Creating a multi wire cutter

Select new process – construction materials – stones and elements

Multi wire cutter – input flows – give

1. Electricity (A.C power) – 716 kWh
2. Lime stone minerals – density (2.69 g/mm^3) – 15.14 m^3 is the volume of the block

   (2.69 x 10^6 x 15.14) = 40.73 x 10^6 kg
3. Water (feed water) – 1200 kg

Now define Out-flows of the process

1. Create new object – stone slab – valuable substance

   Minerals – lime stone – Number of pieces = 4.3 x 10^6 kg
2. Create new object – cutting waste (rock woll) – (waste for recovery)

Step: 5 Create a new process for Block cutter

Construction material – stones and elements

Step:6 Create a new process for Lime polishing machine – construction industry – coatings – reactive resins.

Input flows – electricity – 2.2 Mj – Tiles – 8.61E003

Step:7 Create – truck – Diesel mix at refinery, 3-electric grid mix

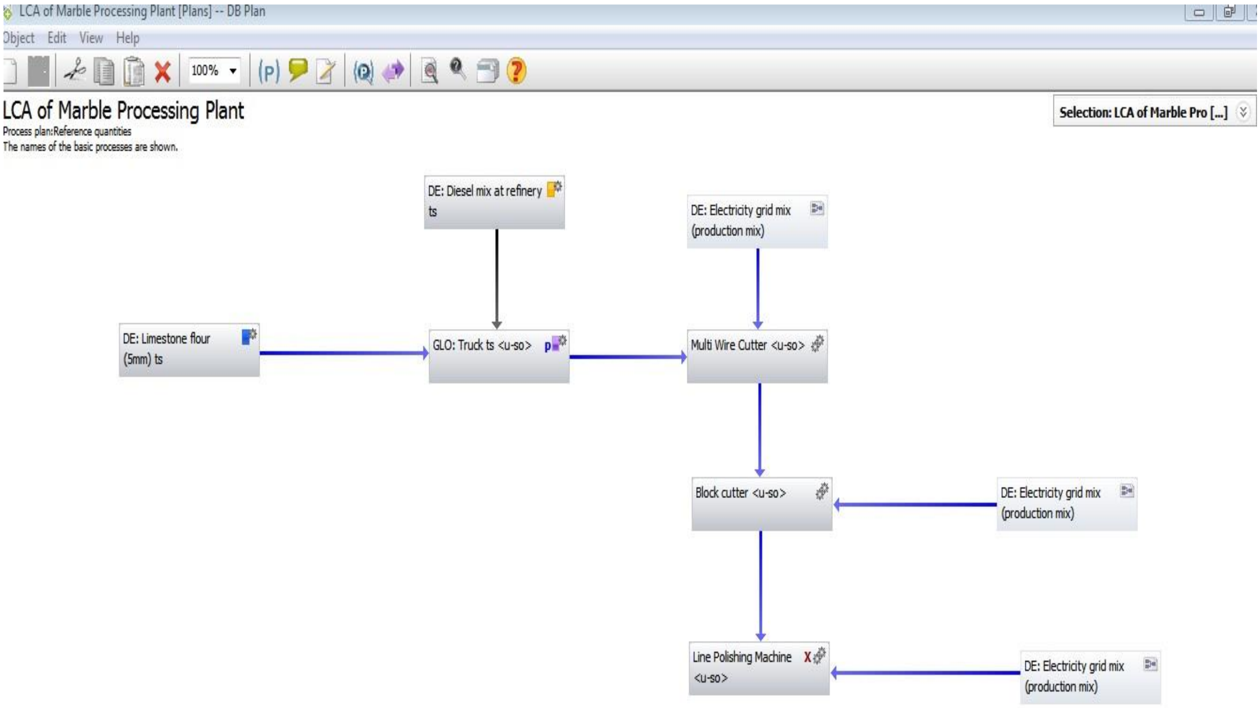


Fig. 3.1.3.1 Plan for the process

3.2 Characterization and grading of marble stones

Today there is a vast array of scientific techniques available to the material scientist that enables the characterization. Characterization enables quantification of physical properties important for success of a part used in a given environment. So, far the research focused on the relationship between the structure of material and its properties/applications. When a material is fabricated in the lab, how it is possible to assess whether the model is correct. Depending on the nature of the material being investigated, a suit of techniques may be utilized to assess its structure and properties. Whereas some techniques are qualitative such as providing an image of a surface, others yield quantitative information such as the relative concentration of atoms that comprise the material. Recent technological advances have allowed material scientists to accomplish something that was once thought to be impossible to obtain actual two/three dimensional images of atomic positions in a solid, in real time. It should be noted that the sensitivity of quantitative techniques also continues to be improved, with techniques now being able to easy measure parts per trillion (ppt) concentrations of impurities in the bulk sample.

3.2.1 Characterization of marble stones

Natural stone has been an important building material in construction for thousands of years. A significant part of world's heritage are built of marble stones. Throughout cultural history marble has had great significance as a decorative material and in particular as a material for statues. Marble production and its use have been reported since the Neolithic age. Industrial quarrying of marble began in the Mediterranean countries during the Bronze Age. In previous years efforts were made to develop a method for identifying the provenance of the marble. While the provenance of marble used in modern buildings is mostly well documented, this is rarely the case for the historical objects. This, is particularly true for white marbles that often look similar, especially from a macroscopic point. Since, mainly pure marbles were extracted from the quarries, characteristic colored zones, or impurities within single blocks led to a negative selection of these blocks. This is why marble provenance can only rarely be designated by macroscopic criteria alone. On the other hand, knowing the provenance of the material is utmost important. Results from provenance studies prove the extraction of material from specific quarry. The synthesis and characterization of material is the first and foremost important step during the experimental research in condensed matter physics and material science. The quality of samples greatly depend on the synthesis method used. In addition, the proper selection of synthesis parameters helps to carry out desired properties in the sample.to be characterized along with the desired potentials. Structure, surface, morphology, grain growth, transport of electrons within material and magnetic properties depend on material synthesis.

3.2.1.1 Thin section analysis of marble stones

In marble provenance analysis, petrography is an important method to be evaluated in which the proportions of major minerals (calcite, dolomite) and different accessory minerals (mostly mica, quartz based ore minerals), and its associated grain size and grain shapes as well as fabric characteristics like abundance of preferred grain elongation or schistosity can identify a specific quarry or quarry subarea. Marble petrography i.e. the mineral composition and texture properties can be conveniently derived from standard (30μm) petrographic thin sections using an optical microscope.

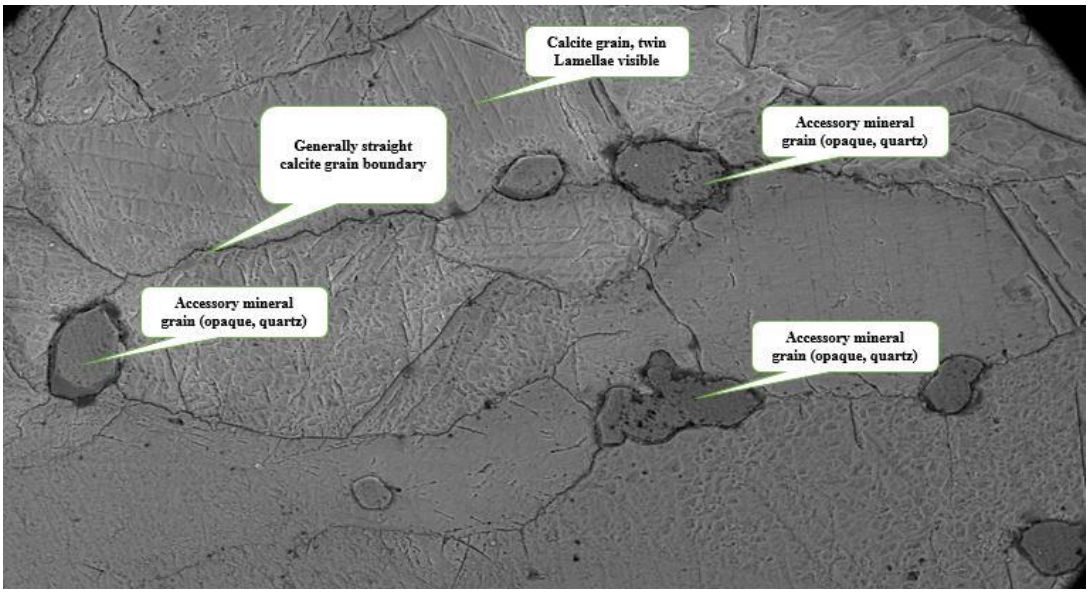


Fig.3.2.1.1.1 SEM picture of the marble sample highlighting some fabric features that are important in provenancing (Taken 500x).

Fig 3.2.1.1.1 shows a typical micrograph of marble thin section which is relatively isotropic sample. Since, thin section analysis infers to the shape parameters of inherently three dimensional mineral grains from two-dimensional sections, the measures derived are an approximations. In consequence, only a large number of measurements yields representative results. In thin sections usually 100 µm diameter of carbonate grains can be measured with the microscope. This approach leads to qualitative results, there is no clear standard on gauging the grain size. Going into more detail, also the geometric characteristics of carbonate grains are of major interest. Besides grain size and shape, twinning type and the nature of grain boundaries have been successfully used as provenance factors.

For petrographic study different marble blocks were collected from the quarrying site and were cut to required dimensions (50mm x 50mm x 50mm) at the processing unit (M1-M5 as shown in Fig. 3.2.1.1.1). Petrographic analysis mainly comprises of establishing a relation between mineral compositions with the grain size distribution. For the study thin sections/slides were developed via each sample of marble and inspected under polarised microscope the equipment used has an arrangement of 5MP camera (Carl zeiss) to take the pictures. Petrographic interpretations, compositions of mineral and their grain size variations of the marble samples are specified in chapter 5 of Tables 5.1.2.1, 5.1.2.2 and photomicrographs of the samples are shown in Fig. 5.1.2.3.

Fig.3.2.1.1.2 Marble samples tested for micrographs

3.2.1.2 Physico-mechanical characterization

The physico-mechanical properties that were tested are presented in the chapter 4 for the selected marbles. The process of laboratory tests performed on the samples are summarized below.

3.2.1.3 Water absorption

To determine the water absorption the list of the apparatus that are necessary to carry out the experimentations are: vessel, oven, weighing balance, and desiccator. The size of the sample is 50x50x50 mm. primarily the samples to be tested are dried in oven at 60^0 C for 48 hours till constant mass is reached. To achieve this, difference between the two successive weights at an interval of 24 hours shall not be greater than 0.1% of the mass of the specimen. Then, cool the specimen at room temperature for 30 minutes and weigh the sample. Let the weight be ‘A’. Immerse the specimen completely in distilled water in a water vessel at 24^0 C for 48 hours. Remove specimen from water vessel after 48 hours, then wipe it with a damp cloth and weigh the sample. Let the weight of it be ‘B’.

Calculation:

$$\text{Water absorption } \% = (B-A)/\ (A \times 100)$$

Where:

A = Weight of the dried sample

B = Weight of the specimen in air after immersion in water

3.2.1.4 Modulus of rupture

To determine the rupture energy of the sample the apparatus that are required to perform the experimentation are: weighing instrument, oven, linear measuring device and universal testing machine (UTM). The size of the specimen required for testing is 200 x 100 x 60 mm it should be smooth, rectangle, honed or polished.

Dry conditioning: Dry the specimen in oven for minimum 48 hours at $(60\pm2)^0$ C till constant mass is reached. To obtain this condition weight the specimen at 46, 47 & 48 hours. Weight should be constant.

Calculations:

$$\text{Modulus of Rupture } R = (3WL)/\ (2B_i d^2),$$

Where,

R = Modulus of rupture (Mpa)

W = Breaking Load (N)

L = length of span (mm)

B_i = Width of specimen (mm)

d = Thickness of specimen (mm)

3.2.1.5 Compressive strength

To determine the compressive strength of the specimen the apparatus required for conducting the experimentation are: compressive testing machine, oven, weighing instrument, and Vernier caliper. The size of the specimen required is 50 x 50 x 50 mm (cube). Specimen is kept in oven for 48 hours at (60 ± 2) o C till constant mass is reached. To obtain this condition the specimens are weighed after 46, 47& 48 hours. Weights were kept constant during the experimentation then the specimens were removed from oven and allowed to cool to room temperature before testing.

Test Procedure

After cleaning and removing any dirt present in the sample, specimen is loaded by applying force perpendicular to rift. Specimen is kept at the centre of the lower platen with the help of circle and line marked on the lower platen. Switch on power supply, then stabilizer switch and the peace rate controller switch. Close pressure release valve. Leave the equipment to get warm up, till 1000 counts. After warming up press pace controller switch to make it zero. Lower the platen until the specimen will start touching the upper platen. At certain value the specimen will breaks and machine stops automatically. Note down the reading, this reading gives the failure load, let it be denoted by 'F'. Calculation the surface area of the specimen in mm^2 let it be 'Aa'

Calculation:

Compressive strength C = F/A,

Where,

C = compressive strength in MPa

F = failure load of specimen in Newton

Aa = area of the breaking surface in mm^2

3.2.1.6 Flexural strength

Flexural strength of the marble samples can be determined according to ASTM C880 test standard. In this testing method marble samples are first cut in large panels or slabs. The load is applied at the quarter point of these specimens. This load is increased continuously until these samples get fractured. The maximum load at which the fracture occurred is recorded and also the flexural stress that occurred at this load is also recorded. Five samples are to be tested both in dry and wet conditions as well as both parallel and perpendicular to the rift plane. During the testing note that the length of the samples must be 10 times the thickness. The samples should also have fine abrasive finish in the tension face. The samples can have different thickness and surface finish levels as required. To completely understand the microstructure of marble samples testing in three orientation is necessary.

No of samples = 20 Nos (10 each in wet and dry conditions as well as 10 each in parallel and perpendicular to the rift plane) a total of 40 samples

Size of the sample = 350 x 100 x 30 mm

3.2.1.7 X-ray diffraction

For the structural characterization of 3D- polycrystalline bulk, 2-D thin films, usually XRD technique is used to identify the phase purity, types of phases and crystallographic structureof the sample. Panalytical X pert pro is the XRD used for testing of samples, it is a versatile equipment designed for various applications like powders, thin films, epitaxial layers, machined materials and ceramics etc. The use of the fix optical modules, sample platform and rotating tube feature enable the user to change the system from a high resolution or stress texture point focus application to normal Bragg-Brentano line focus configuration or a reflectrometry system.

Fig. 3.2.1.7.1 XRD machine

X-ray diffraction is a powerful non-distructive testing method for determining a range of physical and chemical characteristics of materials. It is widely used in all fields of science and technology. The applications include phase analysis, i.e the type and quantities of phases present in the sample, the crystallographic unit cell and crystal structure, crystallographic texture, crystalline size. X-ray diffraction results form the interaction between x-rays and electrons of atoms. Depending on the atomic arrangement, interferences between the scattered rays are constructive when the path difference between the scattered rays are constructive when the path difference between the two diffracted rays differs by an integral number of wavelengths. This selective condition is described by braggs equation, also called as “Bragg’s law”

$$n\lambda = 2d\ sin\theta$$

Where d is the interplanar distance (d-spacing), θ= half angle between incident and reflected beam n = order of reflection, λ= wavelength of x-rays.

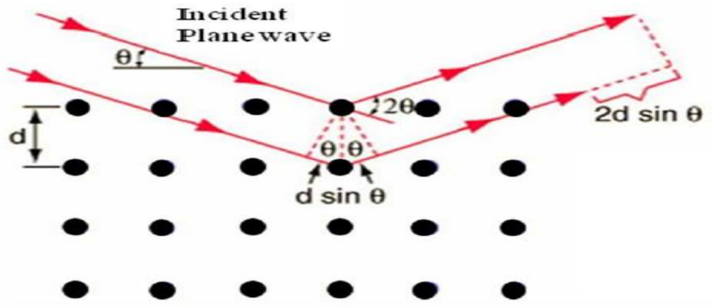


Fig. 3.2.1.7.2 Schematic representation of x-rays by crystallographic plane

3.2.1.8 Scanning electron microscope

Microscopes use electrons rather than visible light to produce the magnified images, especially objects having dimension smaller than the wavelength of the visible light, with linear magnification exceeding a million (10^6). An electron microscope forms a three dimensional image on a cathod ray tube by moving a beam of foussed electron across an object. High powered indirect microscope produces an image by bombarding the sample with a beam of high energy electrons. The electrons emitted from the sample are then scanned to form a magnified image which allows the examination of the structure and morphology of materials. In addition to its great magnification, the SEM also have a great depth of field. SEM is used for studying the surface topography, micro structure, and the chemistry of metallic and non metallic specimens at magnifications from 50 upto 1,00,000X. Due to its high depth of focus SEM is frequently used for studying fracture surfaces. High resolving power makes SEM quite useful in metallographic examinations. Nova nano FE-SEM 450 (SEI) provides ultra high resolution characterization and analysis giving precise nanometer scale information. It gives a resolution of 1.4 nm at 1KV & 1 nm at 15 KV. The SEM is coupled to EDAX detector for measuring the element chemical composition.

3.2.1.9 Thermo-gravimetric analysis(TGA)

TGA measures the amount and rate of change in the weight of a material as a function of temperature or time in a controlled atmosphere. Measurements are used prilimnary to determine the composition of materials and predict the thermal stability at temperatures 1000^0C. The technique can characterize materials that exhibit weight loss or gain due to decomposition, oxidation, or dehydration. In thermal gravimetric analysis a continous graph of mass change against temperature is obtained when a substance is heated at a uniform rate or kept at constant temperature. STA 6000 (perkin elmeris) is used. A sensor has the capability to measure both TG and DTA measuements. This advanced sensor is optimized to achieve flat DTA baselines and high sensitivity. The corrosion resistant pure platinum pan holder and reference ring make the instrument suitable for a wide variety of samples and applications. While measuring the sample are heated from room temperature to 1000^0 C at a rate of 5 degrees per minute untill 1000^0 C, and the graph is plotted.

Fig. 3.2.1.8.1 TGA machine

3.2.2 Grading of marble stones

Table 3.2.2.1 Mohs Hardness number of various minerals

Mohs Hardness Scale	
Mineral	**Hardness**
Talc	1
Gypsum	2
Calcite	3
Fluorite	4
Apatite	5
Orthoclase	6
Quartz	7

Topaz	8
Corundum	9
Diamond	10

One of the important tests for identifying specimens is the Mohs Hardness Test. This test compares the resistance of a mineral to being scratched by ten different reference minerals known as the Mohs Hardness Scale (Shown in chapter 5 Table 5.2.1). The test is useful because most specimens of a given mineral are very close to the same hardness value. This makes hardness a reliable diagnostic property for most minerals.

Marble is a metamorphic rock resulting from the re-crystallization of limestone softened from heat and pressure. Main constituents are calcium and dolomite. Hardness ranges from 6.5 to 9 on the MOH scale for marble and granite. Marble is usually heavily veined and shows lots of grains. Dimensional marble specifications include smooth textures, ease in crafting sculptures, hence highly manageable. It is a reasonably strong and durable stone. It takes good polish, popularly used as wall claddings, floors, skirting's, table tops, treads and risers, sculptures, artifacts, etc. Marble is classified into three categories:

Dolomite: If it has more than 40% magnesium carbonate.

Magnesium: If it has between 5% and 40% magnesium.

Calcite: If it has less than 5% magnesium carbonate.

Slate

Slate is a very fine grained metamorphic rock derived from the sedimentary rock 'shale'. Slate is composed mostly of mica, chlorite and quartz. Characteristically, the rock may slit into relatively thinner slabs and can break easily. Some slates take very good polish, are extremely beautiful and more cost effective than most other wall and floor coverings. Slate has a fine to medium grained surface texture. It renders a very graceful, natural finish to any building or home.

Serpentine

It is identified by its marks, which look like the skin of a serpent. Hardness rates from 2.5 to 4 on the MOH scale and most popular colors are green and brown. Contains lots of magnesium, and has an igneous origin. It does not always react well to recrystallization or diamond polishing.

3.3 Machinability study

Machinability parameters while processing stones

The cutting performances of circular diamond sawblades are effected by the interaction of many effective parameters listed below in the Table 3.5.1 below the parameters can be categorized as sawing characteristics, saw design, relation between textural and mechanical properties.

Table 3.3.1 Effective parameters in sawing process

Non- controlled parameters related to the stone properties		Parameters that can be partially controlled	
Mechanical Properties	Uniaxial compressive strength Tensile strength Youngs modulus Hardness Abrasiveness Water content	Sawing characteristics	Force Traverse speed Specific removal rate Peripheral speed Depth of cut Specific energy Cutting mode
Textural properties	Grain size Grain shape Mineral type and content Degree of type of cementation Bonding Matrix type and content	Saw design	Diamond properties Matrix properties Machine vibration Operator skill
-	-	Working conditions	Machine power Amount of water used Environment/Climate

3.3.1 Force and Energy consumption

Energy consumption is the main cost effective item in the marble machining process by using segmental circular sawblade, milling operation or any other type of process. Therefore, there are many profits to take measures to reduce the energy consumption. There exist many parameters to be focused on in order to reduce the energy consumption. The primary parameters effecting are speed, feed, depth of cut, flowing speed of coolant and diameter of the tool. Secondary parameters effecting are rock properties like minerological and physico-mechanical properties. Many studies have been realized in the research to examine the effects of the parameters. W.poloni et.al. [100] developed empirical models to detect the variation of energy, the models discussed by them can also be used to select cutting conditions. Xipeng xu et al[101] investigated forces and energy of circular sawing and grinding of granites, the calculated tangential force components were found to be much different than measured horizontal force components for sawing, but the two forces were almist identical for grinding. I.S. Buyuksagis et.al [55] investigated marble machine performances using a fully instrumented block-cutter with a diamond segmented sawblade. The operations were performed in the down cutting mode, considering specific energy as a citerian for sawing efficiency, and many parameters were investigated like depth of cut etc on seven different marble stones. H. D.Jerro et al [102], did kinematic analysis of the sawing operations and fund that the forces generated on the blade can be reduced and even optimized with respect to the machining parameter. A new material chipping geometries have been mathematically defined and derived through kinematic analysis. A review of older chipping models were performed, comparing well with the developed model. The results show an excellent agreement with the new model and older ones. A. Ersoy et al. [93], studied the performance characteristics of circular diamond saw cutting with different rocks, The effects of the operating and rock parameters on the performance of the diamond saws were examined and relations between the cutting variables are described. Co-relation between textural, physical and mechanical properties of the rocks with specific cutting energy of the saw are also highlighted. S. Turechetta [103], studied the effects of cutting conditions on cutting force and cutting energy are related to the shape of the idealized chip thickness. The empirical models were developed to predict the variation of the cutting energy. These, models can be used to guide the selection of cutting condotions. The chip generation and removal process has been quantified with the intention of assisting both the toolmaker and the stonemason in optimising the tool composition and cutting process parameters, respectively.

3.3.1.1 Models for both cutting and energy consumption

Cutting force and specific energy both play a vital role while machinig marble stone. They are related to the cutting geometry and typical geometry of the cutting chip [104]. Different chip geometries leads to different cutting behaviour. The shape and size of the idealized chip is characterized by its thickness (h_{eq}) as shown in Fig. 3.3.1.1. This equivalent thickness is given by

$$h_{eq} = \frac{dp\,.Va}{Vt} \qquad (1)$$

It is determined by the d_p is the depth of cut, Va cutting feed, and Vt cutting speed respectively. The cutting force is the summation of the individual grain forces. It may be assumed that the average cutting force on a grain is proportional to the equivalent chip thickness h_{eq} by means of a power function.

$$f_t = k_t \, . \, h_{eq}{}^{\eta}{}_t \qquad (2)$$

$$f_c = k_c \, . \, h_{eq}{}^{\eta}{}_c \qquad (3)$$

Where, ft and fc are the radial and tangential force on a grain, Kt and Kc are the cutting force coefficients, while ηc and ηt are constants. The tagential Fc and radial Ft cutting forces are the sum of the forces on individual grains. Therefore,

$$F_t = K_t \, . \, h_{eq}{}^{V}{}_t \qquad (4)$$

$$F_c = K_c \, . \, h_{eq}{}^{V}{}_c \qquad (5)$$

Where, Kt and Kc are the cutting force coefficients, V_t and V_c are constants. The above relations are valid to different values of feed and speed.

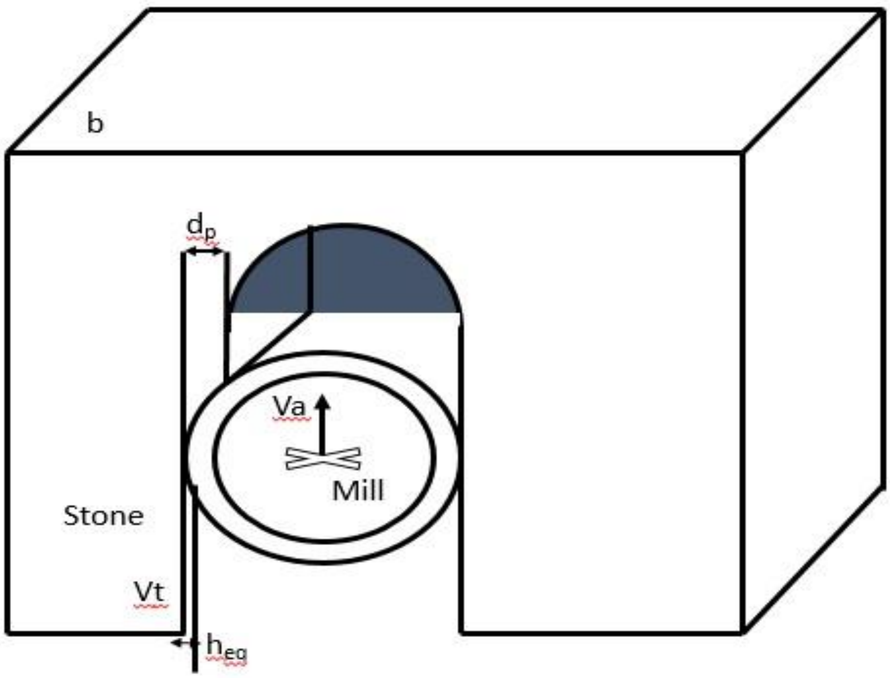


Fig. 3.3.1.1 Generation of chip through milling

Based on equations (4) and (5), the relation between cuttinng force and cutting conditions is not linear but can be expressed as an exponent. The cutting force is measured using a dynamometer, during stone machine as shown in Fig. 3.4.1.2 below

Fig. 3.3.1.2 Workpiece with dynamometer below attached

A dynamometer measures differernt components of the cutting forces, which acts on the workpiece while machining operation, along the feed rate direction and perpendicular to the feed direction. F_f and F_{fn} respectively[105][106]. The resltant forces R generated is calculated as

$$R = \sqrt{F_f^{\ 2} + F_{fn}^{\ 2}} \qquad (6)$$

The resultant R makes and angle β with the component F_f

$$\beta = \tan^{-1}\left(\frac{F_{fn}}{F_f}\right) \qquad (7)$$

The angle of contact between mill and workpiece is given by

$$\theta = \cos^{-1}\left(1 - \frac{2d_p}{d}\right) \qquad (8)$$

Thetangential Fc and radial Ft components of the cutting force can be calculated using the R

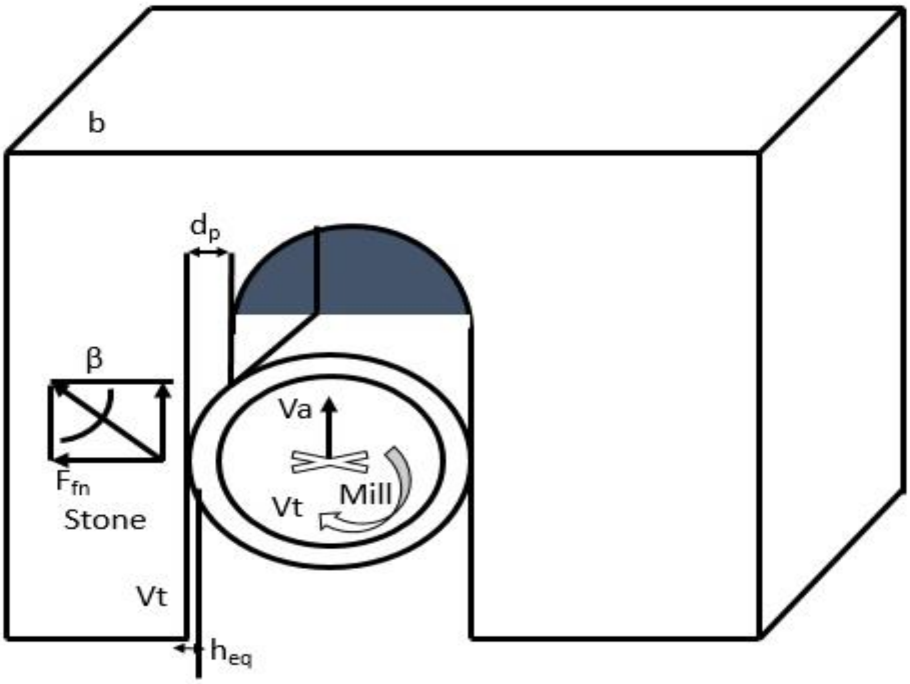


Fig. 3.3.1.3 Force measurement using dynamameter

The tangential F_c and radial F_t compoents of cutting force may be calculated by the resultant force R

$$Fc = R\sin\delta \qquad (9)$$

$$Ft = R\cos\delta \qquad (10)$$

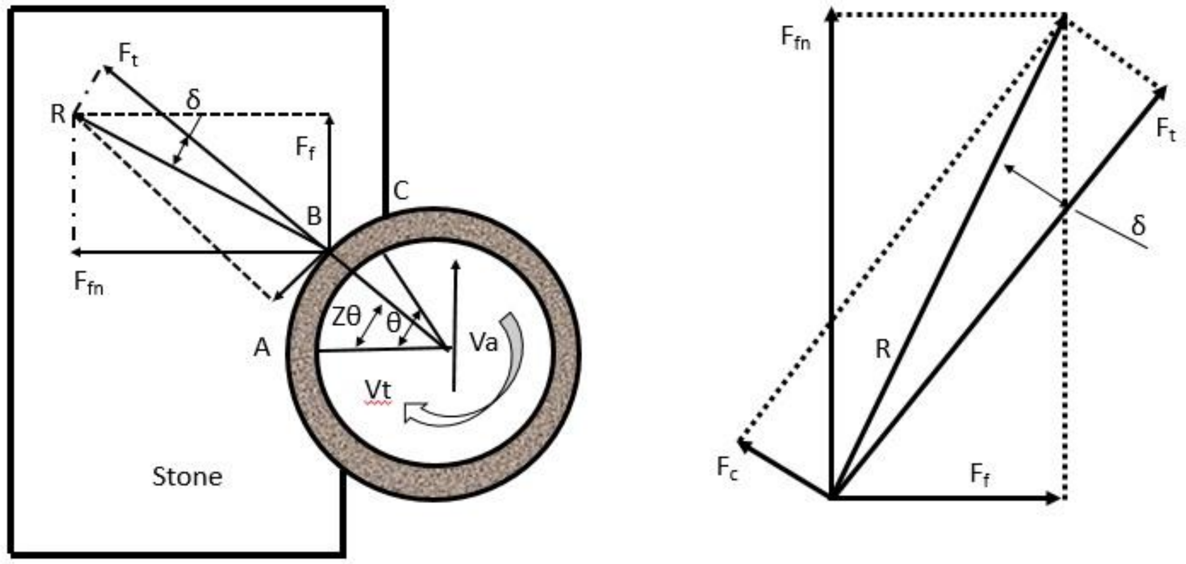


Fig. 3.3.1.4 Fc and Ft components of force

Where,

$$\delta = \beta - Z \cdot \theta \qquad (11)$$

The parameter Z depends on the location where the application point of the resultant force R on the arc of contact AC between milling tool and the workpiece. Hence,

$$Z = \frac{AB}{AC} \qquad (12)$$

Before finding the values for F_t and F_c by measuring F_f and F_{fn} . If the depth of cut is small then the tangential F_c and radial force F_t components of the cutting force will coincide. ‘b’ is the width of cut. A more detail estimate can be found by emperical investigations. Since the cutting power is the product of the tangential force and the cutting speed, a non-linear relationship exists for cutting power. The specific cutting power can be expressed as below

$$Ec = \frac{Fc\,.Vt}{Va\,.dp\,.b} \qquad (13)$$

The term which is in the numerator is the rate of power consumption, while the denominator is the time rate of stone volume removal. Specific energy is the convenient quantity in estimating the cutting forces. Substituting the values of equations (1) and (4) in equation (13)

$$Ec = \frac{Kc}{b} . h_{eq}{}^{V}{}_{c}{}^{-1} = kc . h_{eq}{}^{Ve} \quad (14)$$

Where,

$$Kc = \frac{Kc}{b} \text{ and } Ve = Vc - 1 \quad (15)$$

The material removal rate takes into account different parameters which is given below,

$$MRR = V_a . d_p . b$$

Substituting equation (1) in equation (15) we get

$$MRR = h_{eq} . Vt. b \quad (16)$$

Therefore,

$$heq = \frac{MRR}{Vt .b} \quad (17)$$

Substituting Eq. (17) in Eq . (14) the results we get are

$$Ec = \frac{Kc}{b^{Vc} \ . \ Vt^{Vc-1}}$$

Hence, by defining the four parameters (Kc, Kt, Vc, Vt) it can be possible to model both cutting force (Fc , Ft) and the specific cutting energy (Ec) by using the equations (4), (5), (14) and (18). These are the generalised equations and can be valid for different values of cutting parameters.

Energy consumption is a key factor to be reviewed in marble stone industry which directly influence the cost scrutiny and fabrication scheduling. Due to the escalation in the marble stone usage in many fields there is a tight struggle among the industrialists for revisions on optimizing the operational parameters. For this purpose, the milling factors of the stones to be sliced with CNC milling machine are vital in terms of observing the milling performance. Defining the key constraints for the physico-mechanical and mineralogical features of the stone to be milled shows a vital role in cost scrutiny, fabrication planning, merchandise excellence and choice of proper equipment for the stone to be milled.

Milling operations were performed on the sample using CNC Bridgeport Interact 1 MK-II 3-axis CNC milling machine having a maximum RPM of 4000 shown in the Fig. 3.3.1.6. Two end mill cutters of 10 and 12 mm diameter were used for the end milling operation which are coated with diamond as shown in the Figure. 3.3.1.5 which consists of 4-flutes. Marble sample used for the experimentation is of 200mm x 150mm x 40mm dimension.

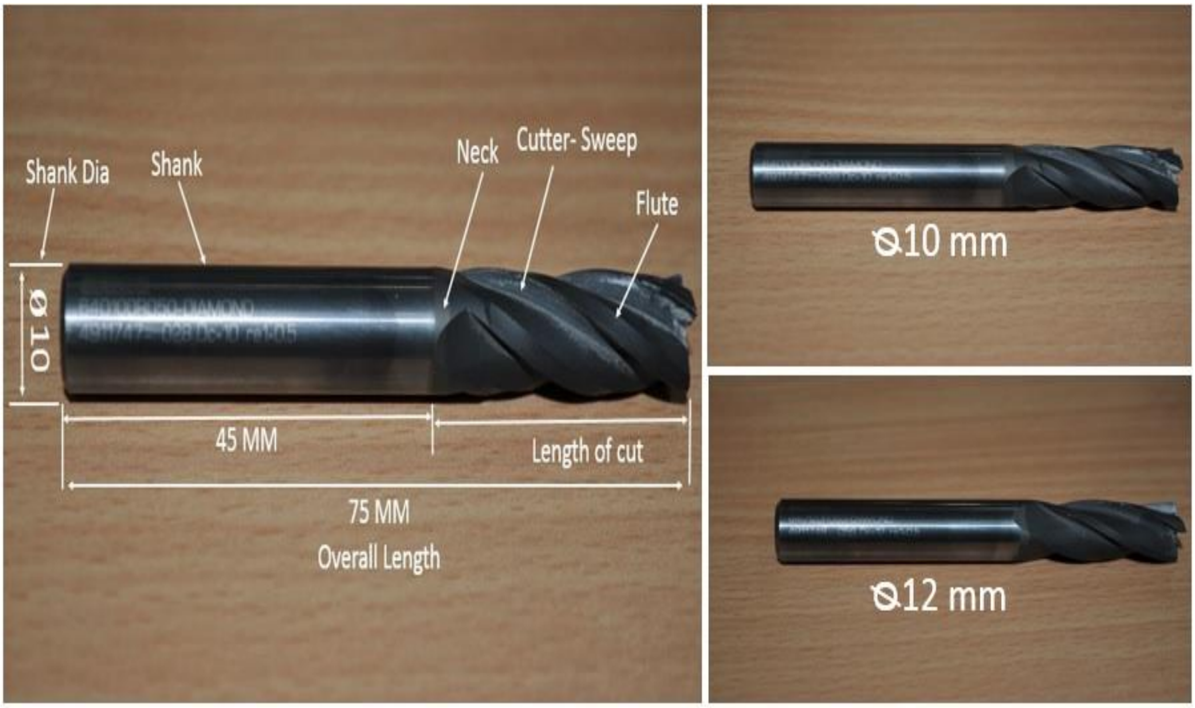


Fig. 3.3.1.5 End mill cutters

Fig. 3.3.1.6 Bridgeport Milling machine

The machine is attached with the energy meter Enertrak build (TMF 28) model to record the power input simultaneously when the milling operation is carried out shown in Fig. 3.3.1.7.

Fig. 3.3.1.7 Digital energy meter used for experimentation

The experiments were performed using Taguchi L16 orthogonal array, it is one of the important statistical method used to design a process in a view of creating it robust according to the experimental settings. Our aim is to improve the procedure by identifying the optimal input settings. To do this we use Taguchi techniques like orthogonal arrays and signal-to-noise ratio (S/N ratio) analysis are castoff. Orthogonal array aids specialists to enterprise the method by lesser rounds, hence saving the computing time and coinage in executing the extra rounds. Signal to noise ratio is a measure of a quality of the merchandise. These two approaches are accountable for the robustness of the merchandise so as to yield great quality and cost operative modules.

3.3.2 Diamond Tool Wear

Diamond tool wear is effected by the mineral composition of the stones to be cut, different segment wear states that can be found, depending on the type of segments as well as the machining parameters. Wear of segments broadly divided into matrix wear and diamond wear.

Wear mechanism effecting the diamond grains can be divided into four main forms:

1. Adhesion wear: the diamond particles stick to the stone surface and the particles are sheared off
2. Friction wear: hard grain particles of the stone scratch the diamond surface
3. Wear by diffussion: chemical reaction between the workpiece and the diamond particles decrease the strength of the bond
4. Fracture of grains: Fracture of the diamond is caused by mechanical and thermal loads of by the fatigue loads

Out of the four different diamond wear discussed above wear by adhesion and wear diffusion play a very negligible role on the process of stone. Fracture wear and fracture of grains are the major wear that effects the cause of reduction of grains.

Matrix wear is the other form of wear experinced by the diamond tools besides wear of grains, depending on the stone being cut, the bond material has to be chosen appropriately. Otherwise,

1. If the matrix wears too fast, the diamond’s capacity to is not completely used before the grain is pulled off
2. If matrix wears slowly the gap between the cutting edges and the matrix is constantly reduced, hence the segment will continously loose its ablity to cut.

A diamond segment blade used in experiment for cutting is of 110 mm diameter, which is widely used to cut the marble. The sawblade consisting of 12 slots and having dimensions (2mm thick, 32mm length, and 8mm height). A constant RPM was applied throughout the cutting process. In order to make some true comparisons of wear rate of the blade testes are performed and an area of 0.0045m2. Normal tap water was used as coolant while sawing experiments were performed and the fluid is supplied at a rate of 12 l/min. The specification of the cutting machine are 1300 Watt, 220 v, 50 Hertz and revolving at an RPM of 11,000.

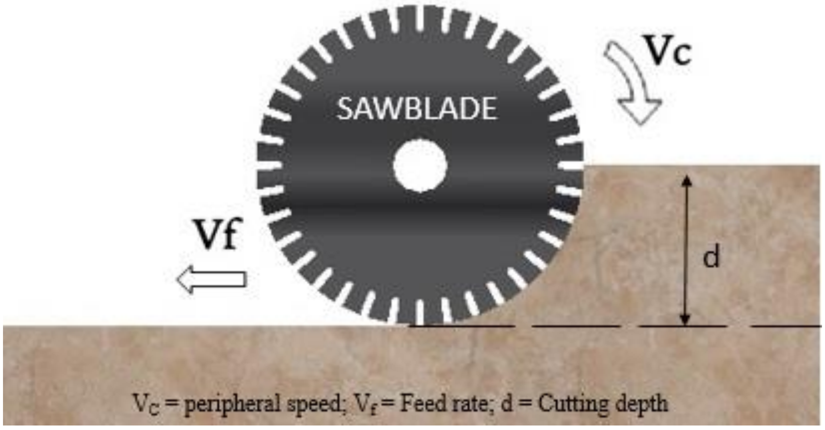


Fig. 3.3.2.1 Down cutting of marble stone

Wear of the sawblade can be assessed in terms of SWR (specific wear rate), can be expressed by formula radial wear of blade segments surface divided by sawn area which can be expressed in units as (µm/m2). The wear of sawblade radially can be calculated by measuring heights of all the individual segments of the sawblade former and after completion of all machining process [85] Before the measurements were taken the sawblade was cleaned with the ethanol so that any machining debris present on it can be cleaned up and then dried at room temperature. More and more readings were taken approximately four times for each experiments of each segment of the blade so that the error can be reduced. For the estimation of the wear radially the approach was applied twice former and after the completion of the machining process. The acquired results evaluation was carried out on excel program.

3.3.3 Rheological analysis

Rheology, defined as the science of deformation and flow has been an area of research since 1970 [107]. Fresh marble paste can be described as a particle suspension. The rheological properties of fresh marble paste are rather complex and time dependent due to powder hydration. In this approach, fresh paste could be considered as coarse aggregates suspended in liquid motar phase. Or sand particles in liquid paste. Thus, the evaluation of the paste and motar would yeild useful infromation in the optimization of mix proportions of different marble powders.

Tattersall has proposed flow properties of marble powder to be represented by the bingham model. The two characteristics of the bingham prameters are the yeild stress and plastic viscosity shown in Fig. 3.3.3.1 below

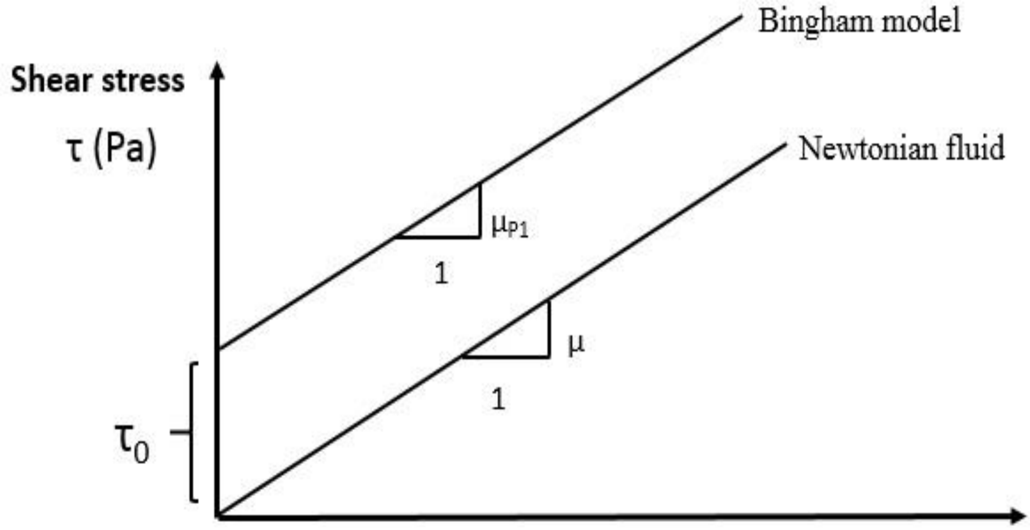


Fig. 3.3.3.1 Bingham Rheology model

According to the bingham model, fresh slurry prepared must overcome the limiting stress (yield stress, τ_0) before it can flow. Once the slurry starts to flow, shear stress increases lineraly with increasing in the strain rate as defined by plastc viscosity, μ .Thus one target rheological property of slurry is to reduce the yield stress to as low as possible so that it behaves like a newtonian fluid with zero yield stress. The other target of the property is adequate viscosity to hold all constituents evenly. The use of bingham parameters is helpful in describing the behaviour of fresh slurry and in understanding the infuence of various mix constituents. However, there is no consensus, atleast at this stage, on their limiting values appropriate for slurry. It is obvious that the appropriate bingham rheological values depend on the materials and equipment used. Thus, to get the reliable values of rheological properties for slurry, it is important to specify the type of equipment, testing procedure, and the nature of costituent materials used in mix.

Besides the linear Bingham plastic model, a more sophisticated Hershel-Bulkey maodel has been suggested with the relation between shear stress, τ, and the strain rate, γ, being non-linear and taking the following form

$$\tau = \tau_0 + a.\gamma^b$$

Where,

τ_0 = yield stress

a = Viscosity term

b = constant

The constant b, can be greater or less than unity depending on whether the fluid is characterized by shear thickening or thinning. The situation is even more complicated if the fluid exibits thixotropic behaviour.

Chapter 4: Results and discussions: Sustainability study

4.1 Life cycle assessment of marble extraction process

The LCA of the marble extraction process which is been shown in Fig. 4.1.1 is developed scientifically keeping in mind all the five components like goal definition, inventory analysis, classification, evaluation and improvement analysis [108]. Goal of the study is to reduce the waste generated at each and every stage of the extraction process. The total life cycle study of marble stone extraction process is shown in Fig. 4.1.1 the environmental innervations and substances which are effecting the environment are clearly explained. The classification of potential environment effects produced by the marble waste is also discussed as overall but not in detail.

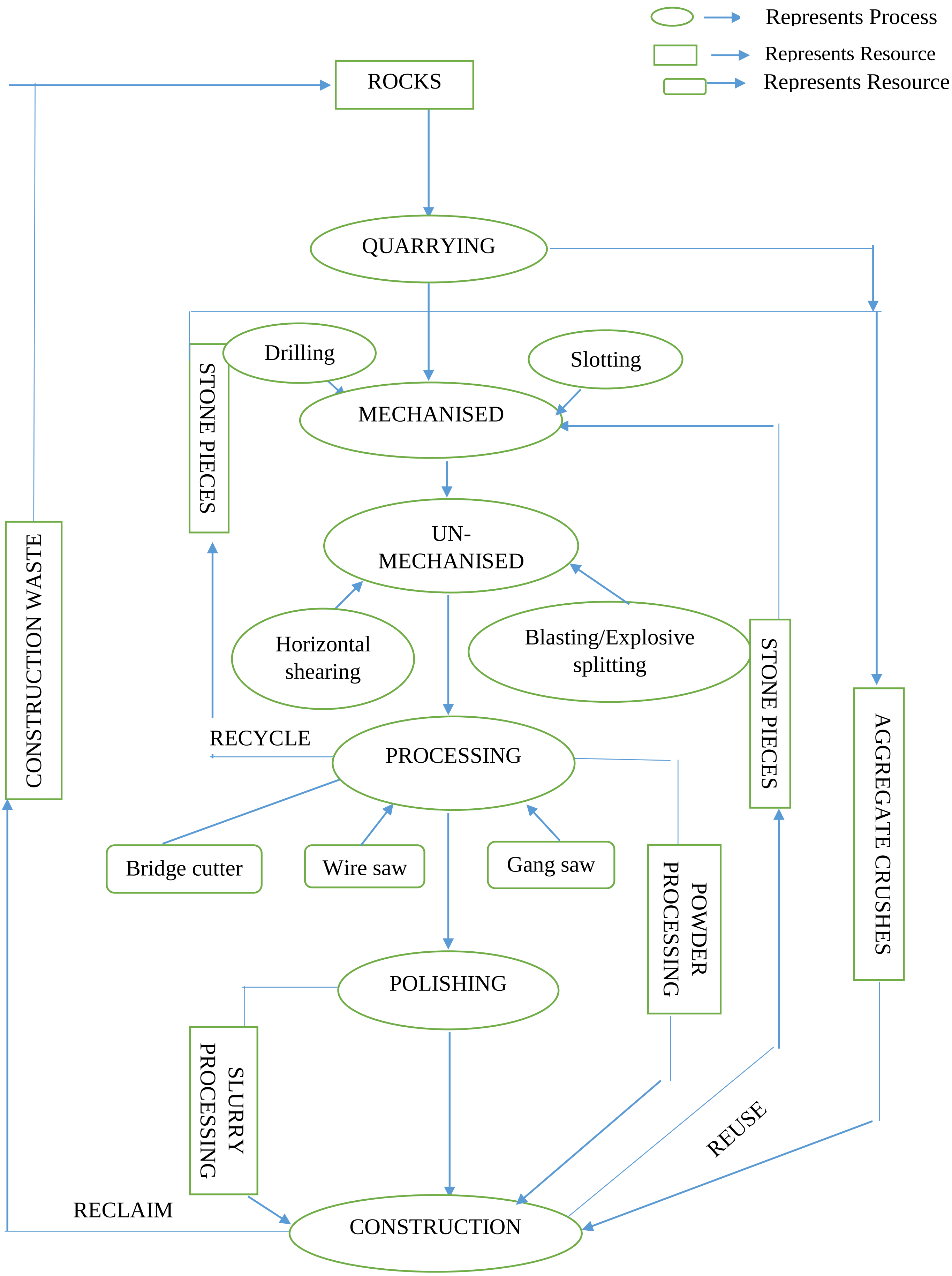


Fig. 4.1.1 Life cycle assessment of marble

The marble stone industry can be simulated for sustainability using doughnut-modelling technique. Doughnut model is used to represent the knowledge management strategies in safe and sustainable environment. This model has two rings internal and external. The internal ring corresponds to social foundation under which people can live safely away from the environmental issues, The outer ring of the model represents the environmental ceiling above which human beings will be exposed to environment hazards due to the air & climate pollution, and land changes besides other impacts that change human and nature. This ensures working under suitable conditions along by keeping an acceptable margin of profit which increases the value of contribution of the modeled process.

The doughnut model tells us the fact that as far as the size of any (process or method) is in the measured range then it is said to be sustainable. Moving towards the center of the model implies reducing the production of the system and increasing the safety of the model, while moving away from the center of the model implies increasing the environmental hazards with increasing the production & productivity. This clearly shows that the donut model is a compromise between the production and consumption which is considered as Index of sustainability or Sustainability Index.

Environment Sustainability Index (ESI) = Production/consumption

Here, we interpret as the Environment Sustainability Index (ESI) because we are more concerned about scaling down the total waste generated by improving the productivity of the diligence. So, let us consider two systems or two stages of the process quarrying and polishing and try to examine how to increase the ESI of these processes.

Let us consider the sustainability doughnut models of three activities one Sustainable quarrying, second the sustainable processing and third sustainable construction. If we see in detail the quarrying process in Fig. 4.1.2 the four activities like explosive splitting, overburden removal, bench drilling, crushing are the activities with enhancement of these will increase the productivity/production but will decrease the sustainability and increase the ESI of marble stone industry.

If we consider the rest of the activities which are the results of quarrying like accidents & risks, waste generated, health hazards and noise pollution are considered as consumables because these are the activities resulted with the expense of money for each activity. Optimization of these activities leads to increase in the sustainability of marble and stone industry. If we look at sustainability doughnut model of processing as shown in the Fig. 4.1.3 the above four activities cutting waste, polishing waste, dressing waste and transportation with the enhancement of these will decrease the sustainability or ESI. The rest of the four activities Accidents & risks, health hazards, water consumption/slurry waste and noise pollution which are the results of processing of the stones. With the optimization of these activities we can increase the ESI of the model.

If we look at sustainability doughnut model of construction as shown in Fig.4.1.4 the above four activities unloading, arranging & distribution, handling and advanced cutting with the enhancement of these will decrease the sustainability or ESI. The rest of the four activities Accidents & risks, waste generated, construction and lining which are the results of the construction. With the optimization of these activities we can increase the ESI of the model.

Fig. 4.1.2 Doughnut model for quarrying process

Fig. 4.1.3 Doughnut model for processing

Fig. 4.1.4 Doughnut model for construction

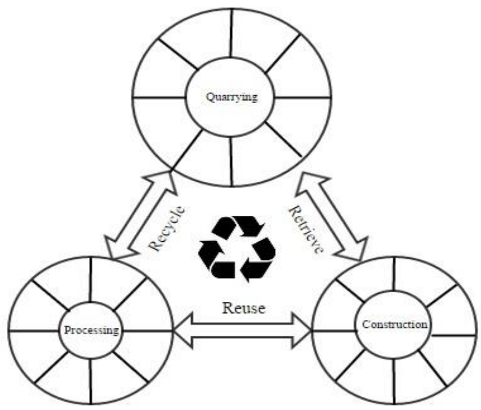


Fig. 4.1.5 Doughnut model for marble life-cycle

The three doughnut models can be connected to each other in order to represent the complete life-cycle of marble stone from quarrying to construction through processing is shown in Fig. 4.1.5

Marble stone sector can be imitated using the sustainable model for better understanding of relation between different factors effecting the sector. This model can be represented with Fig. 4.1.6 where the three different models are represented by an interfered circles namely quarrying, cutting and construction. The main task of the quarrying is to cut/slice the stones load it on to the trucks and transport it to the cutting site. Here, in quarrying skill work is required in order to minimize the waste generated at quarry. The cutting workshops are responsible for shaping, cutting and transporting the dimensional stones to the construction field. At the same time quarrying is also responsible for the supplying of aggregates of stones to the construction site. So both quarrying and construction produces waste and needs some means to recycle this produced waste.

In order to keep the sustainability, the stone waste from cutting site is sent back to the quarrying where it is crushed and transported in different sizes to construction and concrete factories. On the other hand whenever an old building is demolished the stones are sent back to cutting sites to be reshaped and reused again in new buildings. The rest of the waste from the demolished building can be retrieved and sent to abandoned quarries to fill them for reshaping the landscape.

All operations done in three sectors include all of the sustainable items: water, energy, environment and safety. As water is a scarce resource in Rajasthan, it is very important for any process to take into account recycling and reusing the water especially in cutting workshops where water consumption is high. Energy conservation is also required. The issue associated with the three sectors is the environment. This environment is represented by air and water pollution. In cutting workshops the air pollution is reduced by adding water to the cutting process but this leads to pollute the water. But modern quarries use advanced cutting technologies like water jet machining for cleaner production last but not least while working safety of the workers need to be considered which can be maintained by following standards and precautions while cutting and handling process.

Fig. 4.1.6 Sustainable model for marble stone

It is clear from the sustainability models that by increasing the production of items and decreasing the consumption of items best result between production and consumption can be achieved by taking into consideration the supplies, demands and requirements of the Rajasthan region. Here in this section the Environment Sustainability Index (ESI) was only calculated specific to the processing industries. Only the energy terms related to cutting, processing and construction was calculated. The limitation of this study is the environmental impact factors according to LCIA-CML acidification potential, climate change, eutrophication potential, human toxicity etc. were not calculated. The data available is not sufficient to carry out the results.

4.2.1 Case study of processing industries

In order to find out different tools and equipment's used by the industry it is essential to do the case study of various industries. Various input as well as output parameters influencing the energy consumption and many other factors can be known with the study.

In case of all materials the selection of tool for cutting is really important in terms of efficiency as well as tool wear. This fact can also be extended for cutting and milling operations. Diamond tools are widely used for machining hard materials and stones. During cutting or milling operation it is important to choose the appropriate dimensions like (diameter, insert cover, angle of tool). In case of marble, the properties that influence are diameter, material and type of segments/bits, concentration and size of diamond grains in the segments.

Inserts that are used for cutting marble and stone is made of two components (metal matrix + diamond grains). According to the hardness of the marble this composition can be changed. If the hardness number of any stone is less then diamond powder can be replaced with other constituents in order to reduce the cost of the tool.

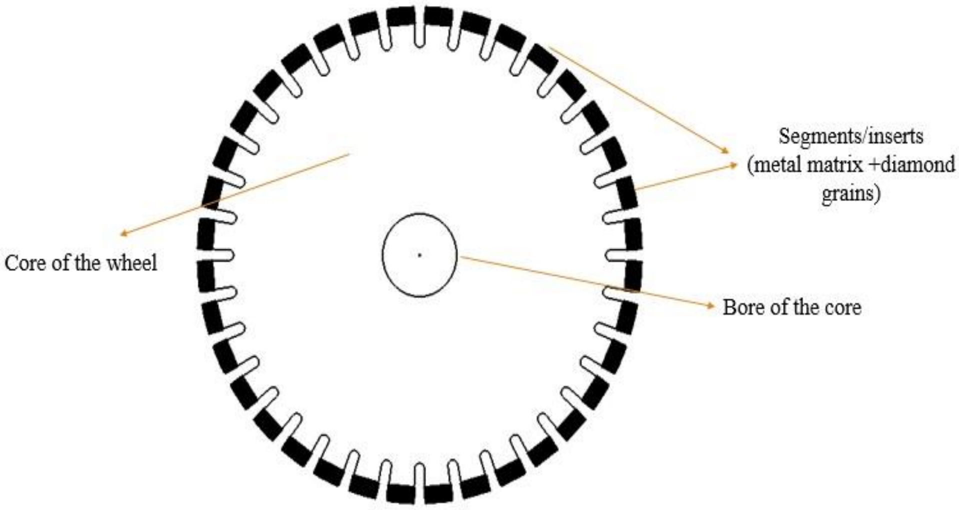
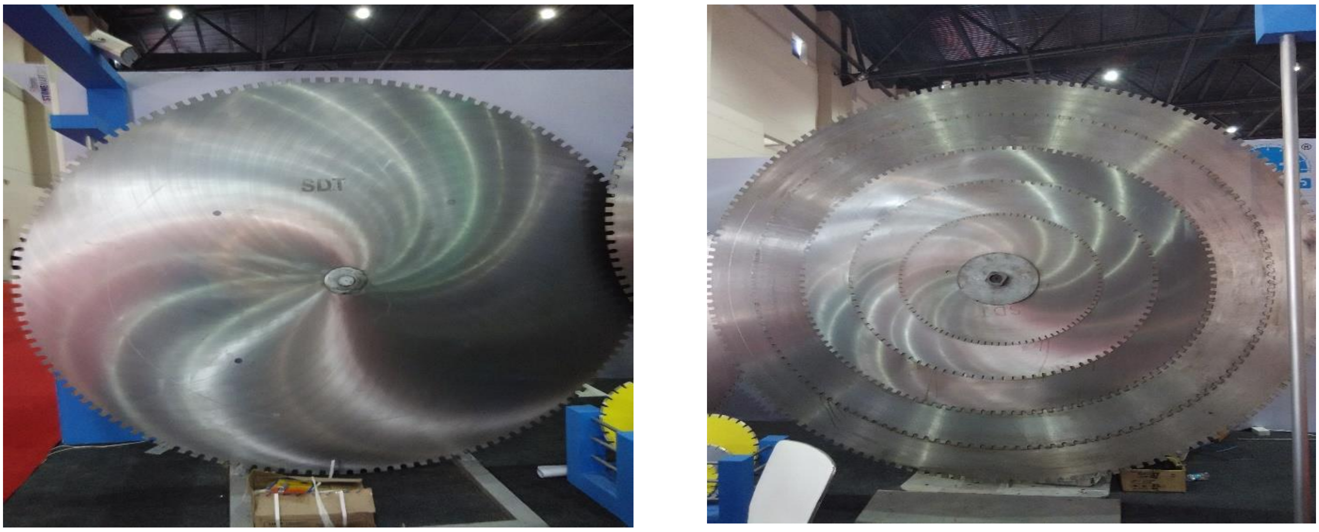


Fig. 4.2.1.1 Parts of circular diamond cutter

The following are some of the cutters/blades that are used for slicing marble stone in different regions of Rajasthan.

Single and multi-wire circular blade

The single circular blade has different diameters ranging from (800 to 3000) mm and its corresponding bore hole varies from (100 to 150) mm with different segment thickness and height as per the customer requirement. In the same way a multi circular blade is available with different diameters ranging from (35 to 1600) mm and bore hole ranging from (50 to 100) mm with different segment height and thickness as shown in Fig. 4.2.1.2



(a) (b)

Fig. 4.2.1.2 a) Single and b) multi-blade circular diamond tools

The core of the cutting tool is typically made up of different quality of steels that solely depends on whether the segments/inserts are attached to the core by soldering or welding.

Diamond wire cutter

Diamond wire sawing is a very old technique and is in use for approximately around 30 years before [22] They have indeed revolutionized cutting processing by increasing the material removal rate (MRR) and surface finish when compared to other conventional sawing methods. Now-a-days diamond segment tools are widely used for soft, hard and brittle stones. The efficiency of the tool is an important criteria to be considered while performing the experiments. The cutting ability of the wire is influenced by various parameters like cutting force, speed, feed and the configuration as (diamond grain size, its concentration and bonding) between the diamond segments of the wire saws.

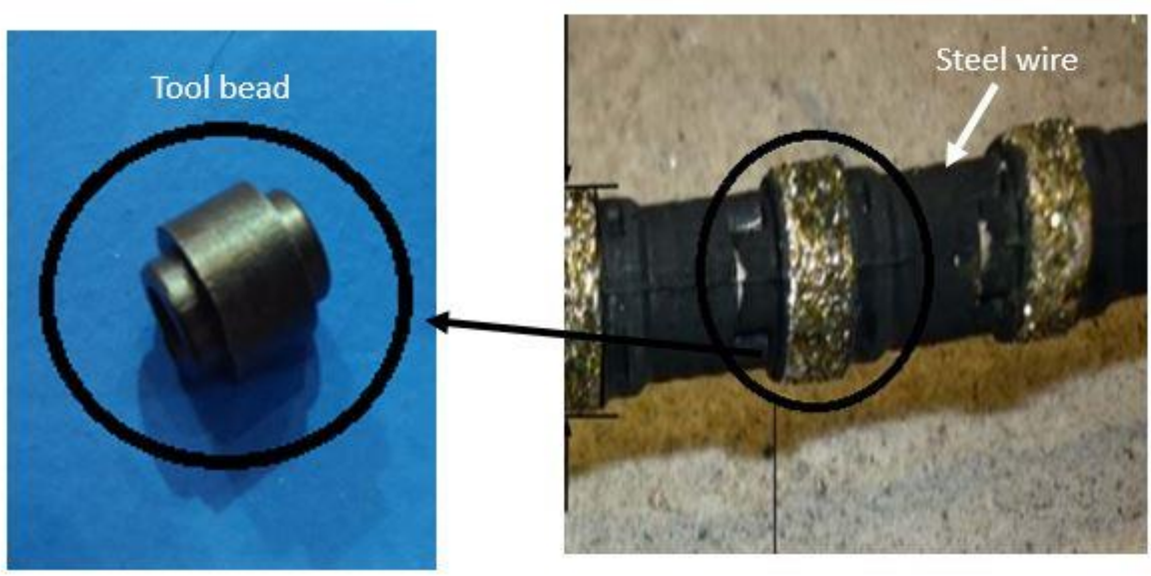


Fig. 4.2.1.3 Diamond wire beads/segments

Single blade cutting tool

The above mentioned tools are little bit expensive when compared to a straight blade cutting tool. These tools are widely used by small scale industries of Rajasthan. The blade mainly consists of a steel core of required length according to the length to be cut and the segments/beads are either sintered or welded at the end of the tool, the design of tool is shown below in Fig. 4.2.1.4

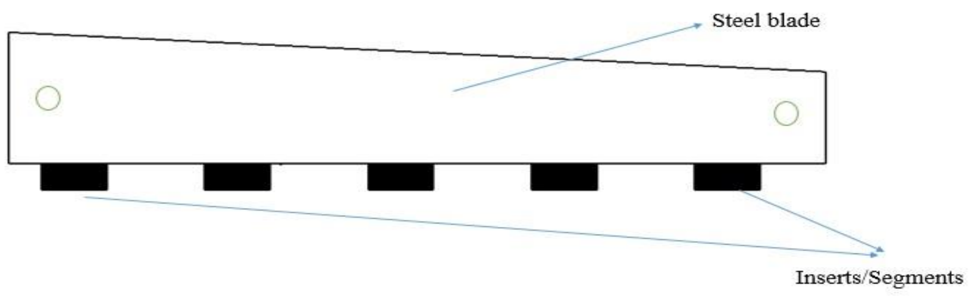


Fig. 4.2.1.4 Straight blade cutting tool with segments

The segments are mostly made of (metal matrix + diamond grains) embedded into it. These segments are fabricated locally, the composition of the metal matrix depends on the hardness of the marble to be machined. A survey was conducted in seven different industries (A, B, C, D, E, F and G) located nearby regions of Rajasthan. The segments collected were characterized using SEM, EDS to find the composition of the metal matrix. Further, their life was calculated using the tailor formulae ($VT^n = C$) where V is the velocity of cutting tool, T is the time in hours and presented in Fig. 4.2.1.7. The characterization revealed that iron and silicon powder were used as abrasives since the cost of availability of these materials are less (when compared to the circular and wire saw) for the metal matrix with diamond particles suspended in it. For a harder stone or marble to be cut then the iron or silicon particles are replaced by cobalt or nickel according to the required composition.

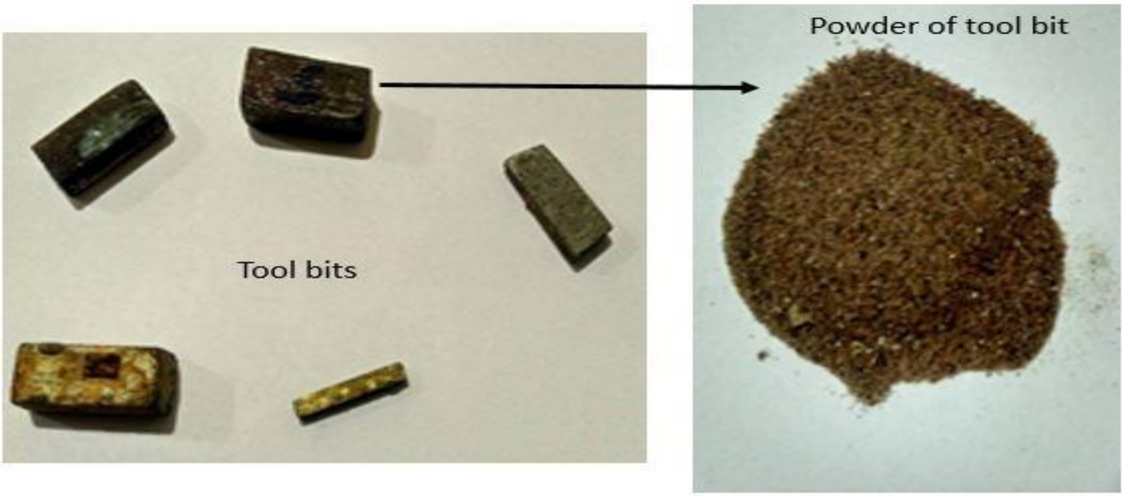
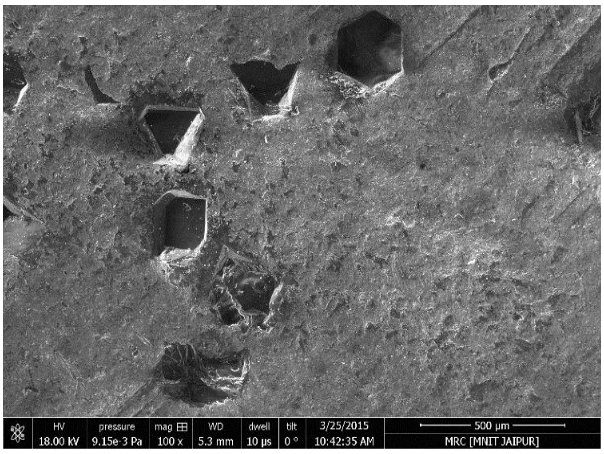
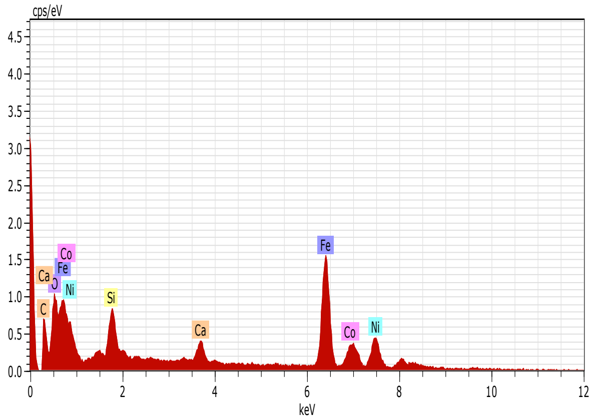


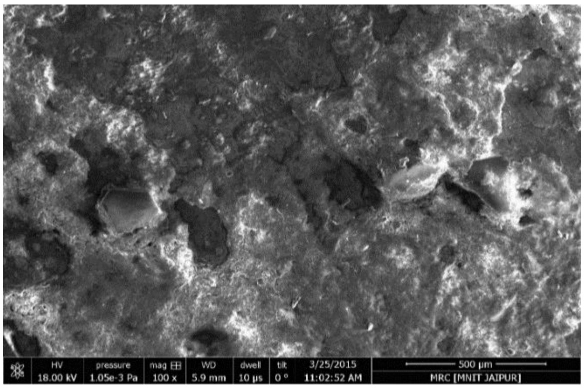
Fig. 4.2.1.5 Tool Segments/bits of straight blade and their powder

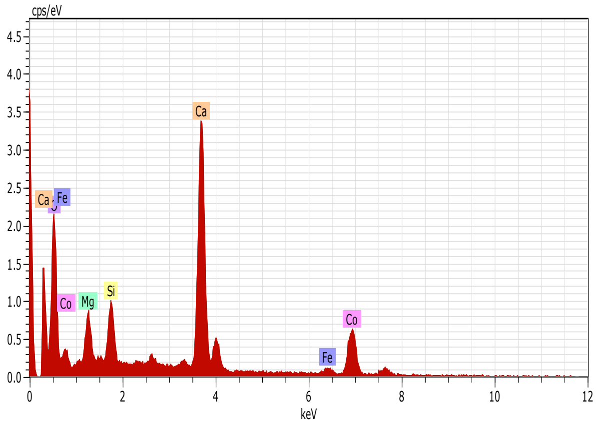




a) Industry A-tool

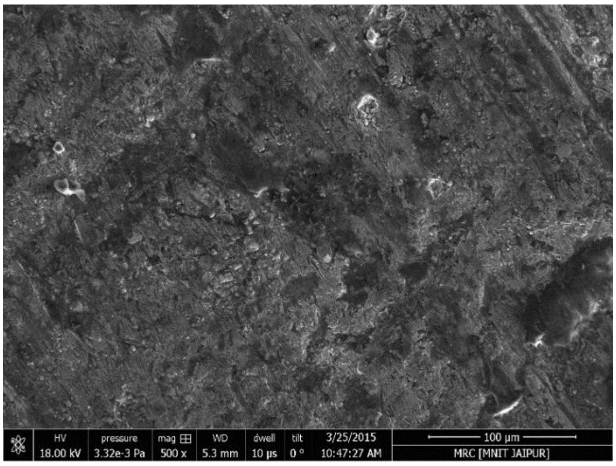
a) EDS of tool-A

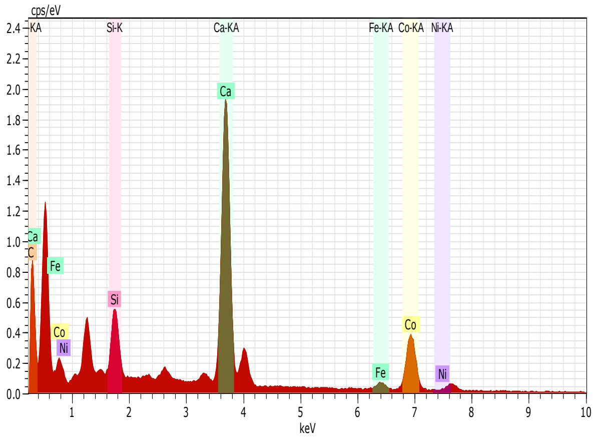




b) Industry B-tool

b) EDS of tool- B





c) Industry C-tool

d) EDS of tool- C

Fig.4.2.1.6 SEM and EDS analysis of tools of industries

The parameters of the tool effecting the cutting speed and the life of the blade is listed in the Table. 4.2.1.1

Table. 4.2.1.1 Parameters effecting the speed and life of tool

	Cutting Speed	Blade Life
Segment Bond Hardness Harder	slower	Longer
Diamond Quality Higher	Faster	Longer
Diamond grit size bigger	Faster	Shorter
Diamond Concentration Higher	Faster	Longer
Segment Width Thicker	Slower	Longer
Segment height Higher	Slower	Longer
Cutting Depth Deep	Slower	Shorter
cutting Pressure Higher	Faster	Shorter
Material Hardness Higher	Slower	Shorter
Material Abrasion More	Faster	Shorter
Aggregate Size Larger	Slower	Shorter
Cutting with coolant	Higher	Longer
Rotation speed Higher	Higher	Longer
Operator's Experience More	Higher	Longer

The survey results of different industries are listed below in Table. 4.2.1.2

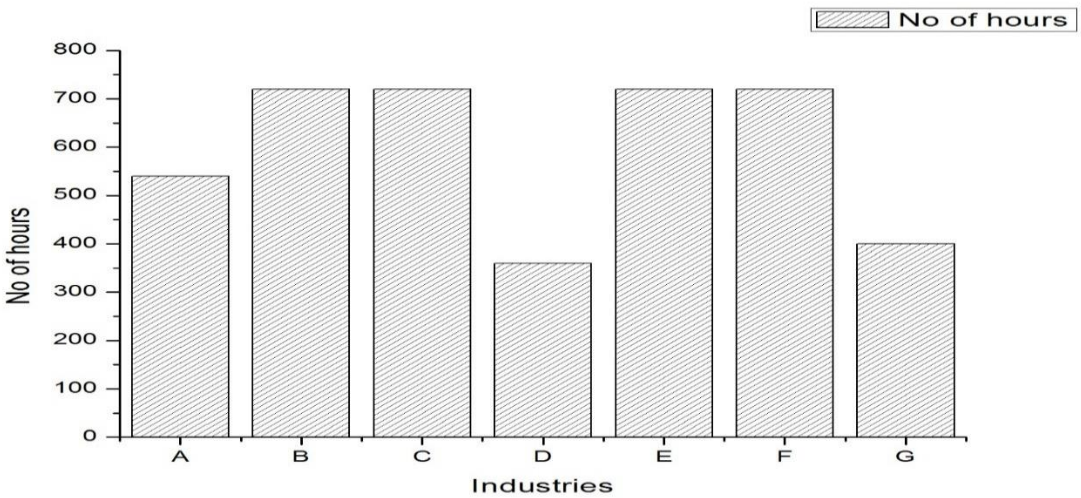


Fig. 4.2.1.7 Tool beads/segments life in hours

Table. 4.2.1.2 Specifications and parameters of various industrial machines

Industry	Machine	Stone	Material of cutter	Sludge formation	Cooling type	Safety device	lubrication
A	Gang saw	marble	iron	10-15%	WET	-	-
B	Gang saw	marble	-	25-30%	WET	Support & Safety	-
C	Block cutter	Marble & sandstone	Pure steel	33%	WET	No need, shoes only	Gear oil 180 No.
D	Water jet machine	Wood to M/S	Carbide +Iron (nozzle)	-	WET	Avoid hand on practice to nozzle	-
E	Circular single and multi-cutter	Granite	-	30%	WET	-	Grease, Gear oil 90 No.
F	Circular saw	All stones	-	4-5%	WET	-	Gear oil & grease
G	Block cutter	Quartz & Sandstone	2% Nickle + Steel	37.5%	WET	-	Gear oil

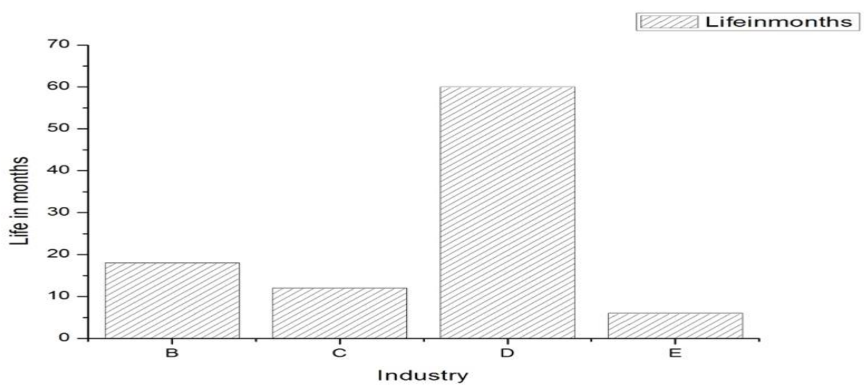


Fig. 4.2.1.8 Life of cutters

4.3.Energy audit and waste disposal of marble stone processing

Table. 4.3.1 Energy audit of different industries

Type of machine	**A**	**B**	**C**	**D**	**E**	**F**
Gangsaws	125*2hp	150hp	150	125*3hp	150*2+180hp	150*4hp
Runtime for Gangsaws	12hrs	10hrs	12hrs	12hrs	12hrs	10hrs
Dressing machine	50hp	30hp		50hp	30hp	30*3hp
Runtime for dressing	5hrs	6hrs		6hrs	6hrs	6hrs
Block cutter			50hp			
Runtime for block cutter			10hrs			
Polishing machine		30*6hp	30*3hp			30hp
Runtime for polishing machine		4hrs	4hrs			5hrs
Line polishing machine			14*14+7*2hp		12*14+7hp	
Runtime for LPM			6hrs		4hrs	
Bridge cutter			10hp			10*6hp
Runtime for bridge cutter			6hrs			8hrs
Energy consumption (kWh)	5.6225	4.152	6.8854	8.304	11.4872	12.4041
Monthly units consumed	168.675	124.56	206.562	249.12	344.616	372.123

Waste disposal practices

Stone industry has a severe impact on the environment in both sites; quarries and cutting workshops. In quarries, the rock extraction process is accompanied by dust, which pollutes air besides to the wide excavations that leave severe effect on landscape and soil. In cutting workshops, the problem of dust is partially treated by adding water to the cutting process which reduces air pollution but on the other hand, it causes water pollution and forms big basins of slurry that need to be solved. The wet slurry generated by the processing industries is diverted to a sedimentation tank. In almost 90% of the industries, the settled slurry is pumped out in to adjacent agricultural lands and left to dry there, as shown in Fig. 4.3.1 (a,b)

(a) (b)

Fig. 4.3.1 (a) sedimentation pits (b) sedimentation and filtration towers

Some of the industries do employ a mud dehydration plant for recycling of water. The filtration plants installed employ flocculation agents for quick separation of water and slurry. They help in preservation of water to a great extent. Here we found the sedimentation area of near about 6x24 m2. The filter tower as seen here is approximately 25m in height. However, they were found to be ineffective in reducing the volume of the waste to a large extent. Some of the industries pump the slurry on to tankers and transport the slurry presumably for dumping in disposal sites earmarked by the government. However, most of them dump the slurry in vacant forest areas or on the road side. There is no proper arrangement for collection of waste material in most of the processing units of marble. Except at few large processing units, segregation of waste is practically non-existent. The processing industry in Rajasthan mostly does not employ filter presses. In most of the cases there is contamination of polishing waste with the cutting waste (produced at circular raw and / or gangsaw). Large amount of marble slurry is discharged as a waste either to a vacant land or to a surface water source located in the vicinity of the units. There is a lack of seriousness towards effective disposal of the sludge and slurry to the identified/ specified site of disposal; for reasons like expenditure involved in handling the stone waste, remoteness of locations of the site of disposal, time and efforts involved in handling the waste material etc.

4.4.Life cycle energy assessment of processing using GaBi

The processing plant is located in the Rajasthan region, approximately 40 km from the quarrying area. The basic processing sequences include cutting, dressing operations (polishing, line polishing, curing, block cutting) packing of the final products and storage of them for delivering it to the customers. The total power required is 738.68 kW and its demand is supplied by an electric grid. The installed machines in the processing industry is shown in Table 4.4.1 along with their power ratings. The processing plant layout is given in Fig.4.4.1

Table.4.4.1 Installed machines with their power ratings

S.No	Machine	Power rating (kW)
1	Multi wire gang saw	441
2	Block cutter x 2	66.15,36.75
3	Line Polishing	44.1
4	Polishing and Curing	128.68
5	Water treatment	22.05

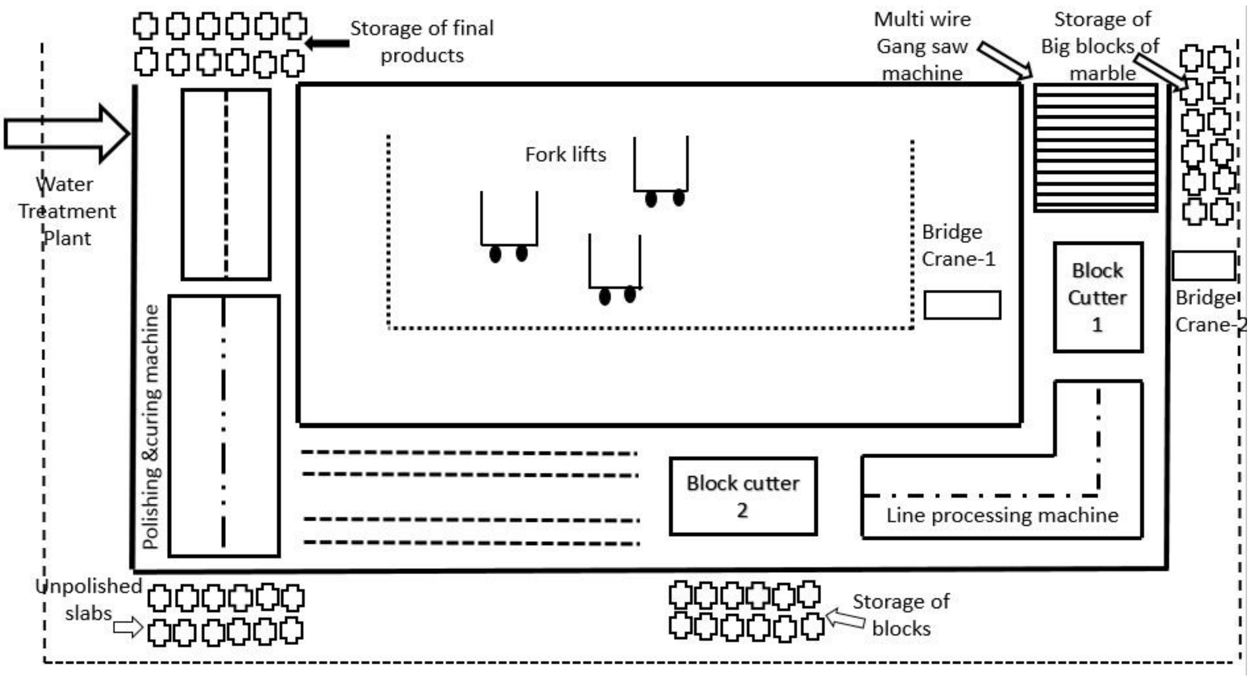


Fig. 4.4.1 Processing plant layout

The processing plant operates 365 days per year, 8 hours a day and employs roughly around 18 persons either working full time or part time.

The operations performed at processing unit can be classified into two categories for easy energy calculations: cutting equipment and finishing equipment. Multi blade Gang saw machine and bridge cutters are included in the cutting machines, whereas polishing machines and line polishing machines are included in the finishing machines. Multi wire gang saw machine has a self-propelled carriage equipped with a motor connected to a large pulley. The carriage is in turn mounted on a set of rails with a rack and is connected by a cable to the control box which is placed at a distance from the machine. The driving pulley, powered by the motor, makes the wire move. The wire is in constant contact with the rocky surface and it is the wire itself which cut the materials with the aid of water. The wire is composed of a steel cable mounted with diamond beads and small springs which separate and induce the even rotating movement of the beads. At the moment the average cutting speed is around 10-20 m^2/h for marble and 3-10 m^2/h for granite on machines with 50-70 hp engines. The diamond wire used for marble and some varieties of stone is either the traditional wire or the plastic covered wire, with electrodeposited or sintered beads cuts range from 20-30 square meters to 200 square and more. The no. of beads generating varies from 28 to 30 per linear meter for an average duration of the wire between 20 and 50 m^2/m. For granite, the plastic or rubber-covered type is used only with sintered beads (from 34 to 40 per m). In this case the wire's duration is from $38m^2$/m. In case of granite, on the other hand, the composition and shape of the diamond used are being analyzed in detail with a view to increasing the wire's capacity.

The processing plant has many auxiliary equipment to carry different operations like two bridge cranes to lift and relocate the inventory of the plant which has a capacity of about 5000 kg to 50,000 kg respectively, several fork lifts to move the blocks from place of operation to the stock room. For the cutting and finishing operations to be performed there is a requirement of large quantity of water to be supplied per minute to the whole plant, for this purpose a water treatment plant is installed. The wet slurry generated by the industry is diverted to a sedimentation tank. In almost 90% of the industries, the settled slurry is pumped out in to adjacent agricultural lands and left to dry there, but to dispose more sustainable means now a days they employ either a sedimentation pit, or sedimentation and filtration towers where water dry up over a course of time and then the dried marble slurry is utilized further by different industries like (Cement, watch manufacturing plants etc.). Some of the industries do employ a mud dehydration plant for recycling of water. The filtration plants installed employ flocculation agents for quick separation of water and slurry. They help in preservation of water to a great extent. The sedimentation area of near about 6 x 24 m^2 as shown in Fig.4.3.1 and the filtration tower is approximately 25m in height.

The efficiency of the water treatment plant that is installed in the processing unit is about 65%. The volume of the conical filtration tank is about 140 m^3, where a chemical agent is added to increase the rate of sedimentation.

Big blocks of size 2.2 m x 2.15 m x 3.2 m which are extracted from the quarry is shaped to an average slab size of 2 m x 2 m x 0.02 m in the multi wire saw blade. Subsequently, the slabs are transferred to the block cutter and are further cut to the tiles of final dimension (0.4 m x 0.4m x 0.4m). The finishing operation is performed in polishing/line polishing machines where surface finish is further reduced. In multi wire saw blade there are approximately 70 wires cutting the slabs simultaneously producing 71 pieces at a time. Further they are sliced to smaller products such as stairs, strips, claddings and tiles, of different dimensions. There are two finishing equipment's polishing and line polishing machines to further increase the smoothness of the surface of marble stones, they are cured and dried with a coating of resin to keep the quality of the marble intact and make them suitable for anti-slipping applications.

To identify and estimate the energy requirements and energy saving potentials it is necessary to adopt a methodology capable of identifying, defining, estimating energy flows in the natural processing plant. The methodology adopted in the study takes into account the energy inputs to produce a unit product, taking into account the details of the processing activities, and details of machines used at each stage of the process and their energy requirements. The first step of the process is to calculate the energy consumption at each production line and at each operation based on the efficiency values of the machinery which are obtained from the machines available nominal power.

Big blocks extracted from quarrying plant is transported to the processing plant with dimension (2.2 x 2.15 x 3.2 m) is shaped and squared to slab of dimension (2 x 2 x 0.4 m) in a multi wire saw machine, it is further cut to tile of dimension (0.4 x 0.4 x 0.02 m) using a block cutter. Finishing operation includes passing the blocks through polishing and line polishing machines where its surface roughness is reduced, they are then sent for resin processing and curing machine to increase its durability and anti-slip properties. The outline of the whole process is shown in Fig.4.4.1. The energy required for transportation of the big block from the quarrying plant to the processing plant is given in Table.4.4.1 and energy consumption to cut the block to slab using a multi wire saw is given in Table.4.4.2. Energy consumption for the finishing operation using line polishing and polishing machine is shown in Table.4.4.3 and 4.4.4 respectively.

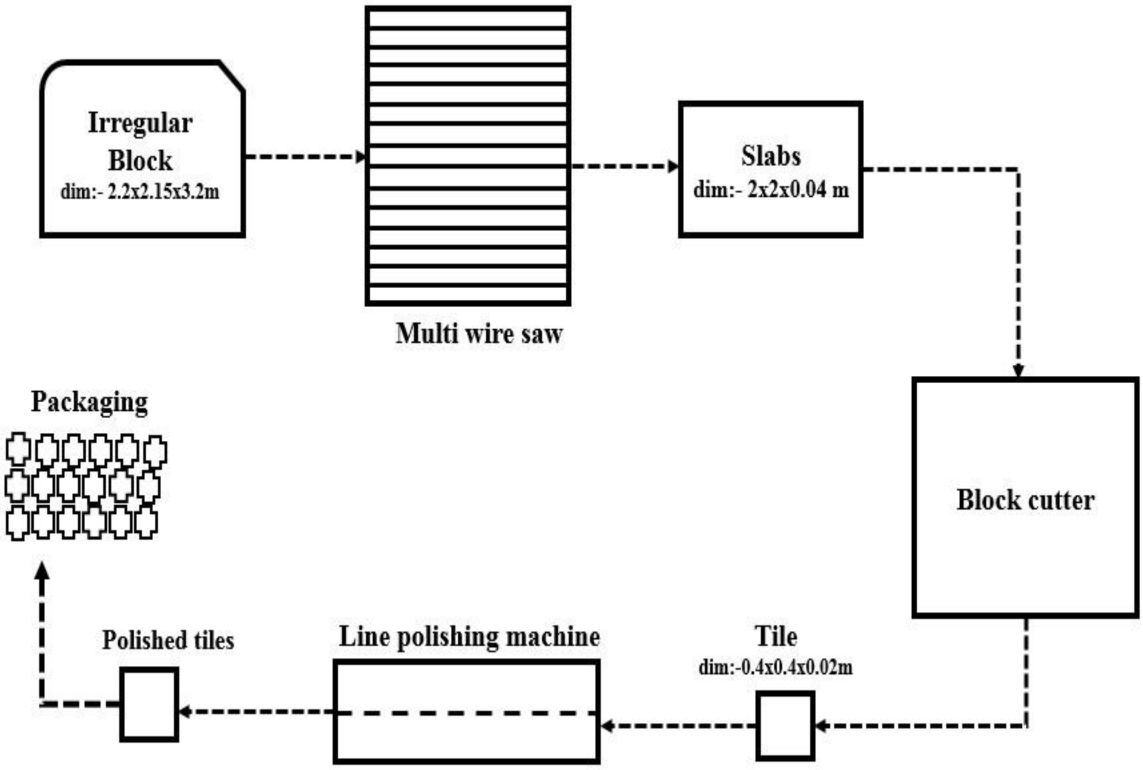


Fig. 4.4.2 Outline of the process

Table.4.4.2 Energy consumption to transport big block from quarry to processing plant

Quarry to processing plant distance	40 Km
Velocity of vehicle carrying block	45 Km/hr
Vehicle power	373 kW
Block Volume	15.14 m^3
Capacity	2
Energy Consumption	166 kWh/block 11 kWh/m^3

Table. 4.4.3 Energy consumption for block cutting to slabs using multi wire saw

Process	Time (min)	Power consumption (kW)	Efficiency	Energy Consumption (kWh)
Transferring block from trolley using bridge crane	3	2	100	0.1
Lowering crane to load block on to machine	2	8	100	0.267
Cutting operation	660	100	65	715
Raising the sliced slabs	2	2	100	0.06
Transferring to trolley	3	8	100	0.25
Total Energy consumption (kWh/block)				715.68
Energy consumption (kWh/m^3)				47.3

Table. 4.4.4 Energy consumption for block cutting to tiles using a block cutter

Process	Time (min)	Power consumption (kW)	Efficiency	Energy Consumption (kWh)
Transferring slabs from trolley using bridge crane	3	2	100	0.1
Lowering crane to load block on to machine	2	8	100	0.267
Cutting operation	175	100	65	190
Raising the sliced slabs	2	2	100	0.06
Transferring to trolley	3	6	100	0.3
Total Energy consumption (kWh/block)				190.73
Energy consumption (kWh/m^3)				15.84

Table. 4.4.5 Energy consumption in line polishing machine for 2 x 2 x .02 m slabs

Machine length, L	12,500 mm
Belt speed, V	5000 mm/min
Process time, t (L/V)	2.5 min
Power	122 kW
Efficiency	0.65
Energy P x t	3.30 kWh
Number of slabs	25
Energy consumption	0.132 kWh/slab
Slab area	4 m^2
Energy consumption	0.0323 kWh/slab/m^2

Table. 4.4.6 Energy consumption in polishing and resin treatment machine for tiles

Machine length, L	6000 mm
Belt speed, V	1250 mm/min
Process time, t (L/V)	4.8 min
Power	60 kW
Efficiency	0.65
Energy Px t	4.8 kWh
Number of slabs	10
Energy consumption	0.48 kWh/slab
Slab area	0.16 m^2
Energy consumption	3 kWh/slab/m^2

The energy consumption in the cutting process is related to the block cutting and the final product dimensions. As a result no significant energy improvement can be suggested in the process, but the modification and replacement of the existing machines may increase the efficiency or decrease the energy consumption. The energy consumed for cutting, polishing and transportation is plotted in the Fig. 4.4.3 and Fig. 4.4.4 pie graph shows the percentage of energy consumption at each stage of the process.

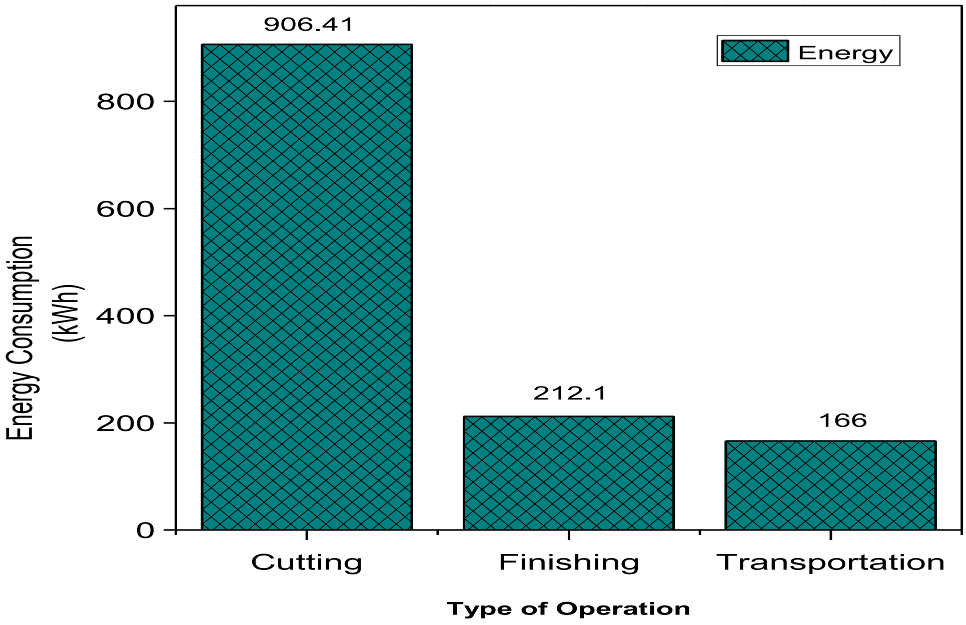


Fig. 4.4.3 Energy consumption

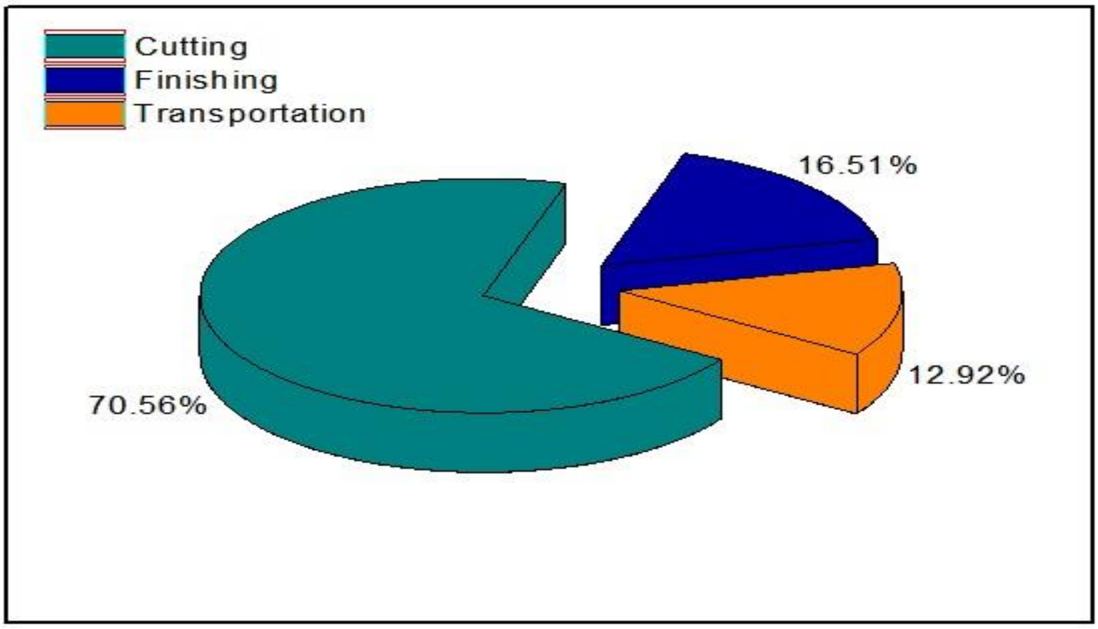


Fig. 4.4.4 Percentage of energy consumption

The impact analysis of the process on the environment is discussed in detail with different tables.

Table. 4.4.7 Calculation of various potentials using LCIA-CML 2001

Impact category	Characterized (Units)	Amount
Global warming 100a	kg CO_2 eq	8.28E005
Acidification potential	kg SO_2 eq	4.34E003
Eutrophication potential	kg Phosphate eq	1.12E003
Ozone layer depletion	kg R11 eq	9.58e-6
Abiotic depletion	kg Sb eq	0.121
Freshwater aquatic Eco toxicity	kg DCB eq	4.98E003
Human toxicity potential	kg DCB eq	2.82E004

Table. 4.4.8 Calculation of various potentials using ReCipe

Impact category	Characterized (Units)	Amount
Climate change	kg CO_2-eq	8.49E005
Terrestrial acidification	kg SO_2-eq	1.75E005
Fresh water eutrophication	kg P-eq	5.97
Fossil depletion	kg oil-eq	2.72E005
Ionising radiation	kg U235-eq	1.63E004
Marine Eco toxicity	kg 1,4-DB eq	111
Particulate matter formation	kg PM10 eq	767

Chapter 5: Results and Discussions: Characterization and grading of marble stones

5.1 Characterization of marble stones

The selected marble samples were characterized physico-mechanically as well as petro graphically whose procedure is described in chapter 3, the results are given below:-

5.1.1 Physico-mechanical characterization

So, according to the testing done the different physico-mechanical properties are listed below in the Table. 5.1..1.1

Table. 5.1.1.1 Results of physico-mechanical properties

S.No	Type of Stone	Water absorption (Weight %)	Density (g/mm^3)	Modulus of Rupture (N/mm^2)		Compressive Strength (N/mm^2)		Abrasion	Flexural Strength (N/mm^2)	Hardness (HRC)
				Dry	Wet	Dry	Wet			
1	Makarana	0.04	2.69	15	17	96	85	2.7	17	42
2	Bhainslana	0.03	2.72	22	19	70	57	4.3	21	45
3	Andhi	0.08	2.83	14	17	94	114	4.1	16	42
4	Sea green	0.07	2.66	42	35	286	194	1.1	35	48
5	Agaria	0.06	2.84	17	16	106	102	4.0	15	43

Chemical composition

A titration test was carried out on the five samples to determine their chemical composition. For carrying out the test marbles were crushed in the form of fine powder and 500g was taken for analysis. Titration is a laboratory method of qualitative analysis which it is used to determine the unknown concentration of known substances such as quartz (SiO_2), Lime (CaO), Priclase (MgO), Hematite (Fe_2O_3), Corundum (Al_2O_3). In titration method a known volume of titrant reacts with a solution of analyse to determine concentration. The different compositions of the marble are listed in Table. 5.1.1.2.

Table. 5.1.1.2 Chemical composition of marble samples

S.No	Composition	Makarana	Bhainslana	Andhi	Sea green	Agaria
1	SiO_2, Quartz	1.36	9.12	3.17	traces	0.01
2	CaO, Lime	51.58	47.74	43.89	47	43
3	MgO, Periclase	0.20	0.7	8.91	16	1
4	Fe_2O_3, Hamatite	Traces	1.99	0.3	Traces	Traces
5	Al_2O_3, Corundum	Traces	Traces	Traces	Traces	traces
6	LOI	46.76	40.20	43.71	37	44

5.1.2 Thin section analysis results

Thin section analysis was done in order to find out the various minerals that are present in different marble samples. SEM-EDX is generally done to know the chemical composition of the marble stone. The experimentation procedure and the machine specification is described briefly in chapter 3.2.1.1. The various composition is listed in the tables below:-

Table. 5.1.2.1 Mineral composition of marble stones

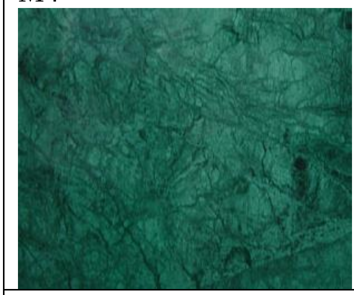
Sample	q (%)	L (%)	P (%)	H (%)	LOI
M1	1	52	1	-	46
M2	9	48	1	2	40
M3	3	44	9	1	43
M4	0	47	16	-	37
M5	0	43	1	-	44

Q: Quartz; L: Lime; P: Priclase; H: Hematite; LOI: Loss of ignition

Table. 5.1.2.2 Distribution of grain size in marbles

Sample no	Q		L		P		H	
	Mean	Max	Mean	Max	Mean	Max	Mean	Max
M1	0.28	1.6	1.12	7.5	0.39	0.44	-	-
M2	0.50	4.0	0.51	5.0	0.57	1.11	0.14	.23
M3	0.42	1.0	0.37	1.0	0.35	0.40	0.9	0.12
M4	0.58	3.5	0.23	2.5	0.43	0.80	-	-
M5	0.60	0.4	0.73	5.0	0.64	0.85	-	-

Table. 5.1.2.3 Petrographic interpretations

Sample no	Petrographic interpretations based on images shown in Fig. 5.1.2.2
M1 	Marble name: Makarana white marble, the nature of the stone is hard and compact essentially composed of dolomite and calcite. A medium to fine grained termolite marble with strong post crystalline deformation at low temperature conditions than 200 degree celcius. Therefore, the strong interlocking grains show clearly bent twin lamellae. The irregularly distributed brown haze of the grain structure suggests an incipient weathering out (Fe-hydroxide). Amphibole (actinolite-tremolite) occurs as accessory. Dolamite/calcite shows rhombohedral cleavage, polysynthetic twinning occurs as polygonal grains. The rock is medium to coarse grained and shows granoblastic texture
M2 	Marble name: Bhainslana black, the nature of the stone is hard and compact essentially composed of calcite. A fine grained calcite marble with strong foliation and accordingly flattered calcite grains. The calcite grains show internal pressure twin lamellae. From this it can be deduced that weak deformation followed after completion of the calcite recrystallization. Tourmaline, opaque and amphibole (termolite-actinolite) is present as accessory. Calcite grains shows a perfect rhomboheral cleavage and polysynthetic twinning at places. Fine dust of opaque minerals is distributed over the carbonates.
M3 	Marble name: Andhi white, this is a fine grained termolite-dolamite marble with polygonal dolomite aggregates. The euhedral termolite are porphyroblast a primary component of the rock. Twin lamellae indicate a weak post crystalline deformation. The metamorphic grade corresponds to amphibolite facies conditions. The nature of the stone is hard and compact essentially of calcite. Amphibole (actinolite-tremolite) occurs as accessory. Calcite shows rhombohedral cleavage, polysynthetic twinning and occurs as polygonal grains.
M4 	Marble name: Sea green, a fine grained mixture of antigorite and carbonate with dendric grain shapes, calcite is a secondary product of the replacement offer antigorite. Calcite in connection with antigorite is not stable under greenschist facies to amphibolite facies conditions. The nature of the stone is hard and compact essentially of antigorite and lizardite. Opaque and amphibole are present as accessory. Secondary calcite veins are common as criss-cross veins, asbestos veins is also observed. The rock is fine grained with plenty of antigorite. The rock shows mesh texture. The sample on evaluation is identified as altered ultramafic (serpentinite)
M5 	Marble name: Agaria white marble, a fine grained calcite-dolamite marble with polygonal to slightly interlocked grain structure. Twin lamellae indicate weak deformation after completion of the crystallization of calcite and dolomite. The nature of the stone is hard and compact essentially composed of dolomite and calcite, amphibole (actinolite-tremolite) occurs as accessory. Dolamite/calcite shows rhombohedral cleavage, polysynthetic twinning occurs as polygonal grains. The rock is medium to coarse grained and shows granoblastic texture

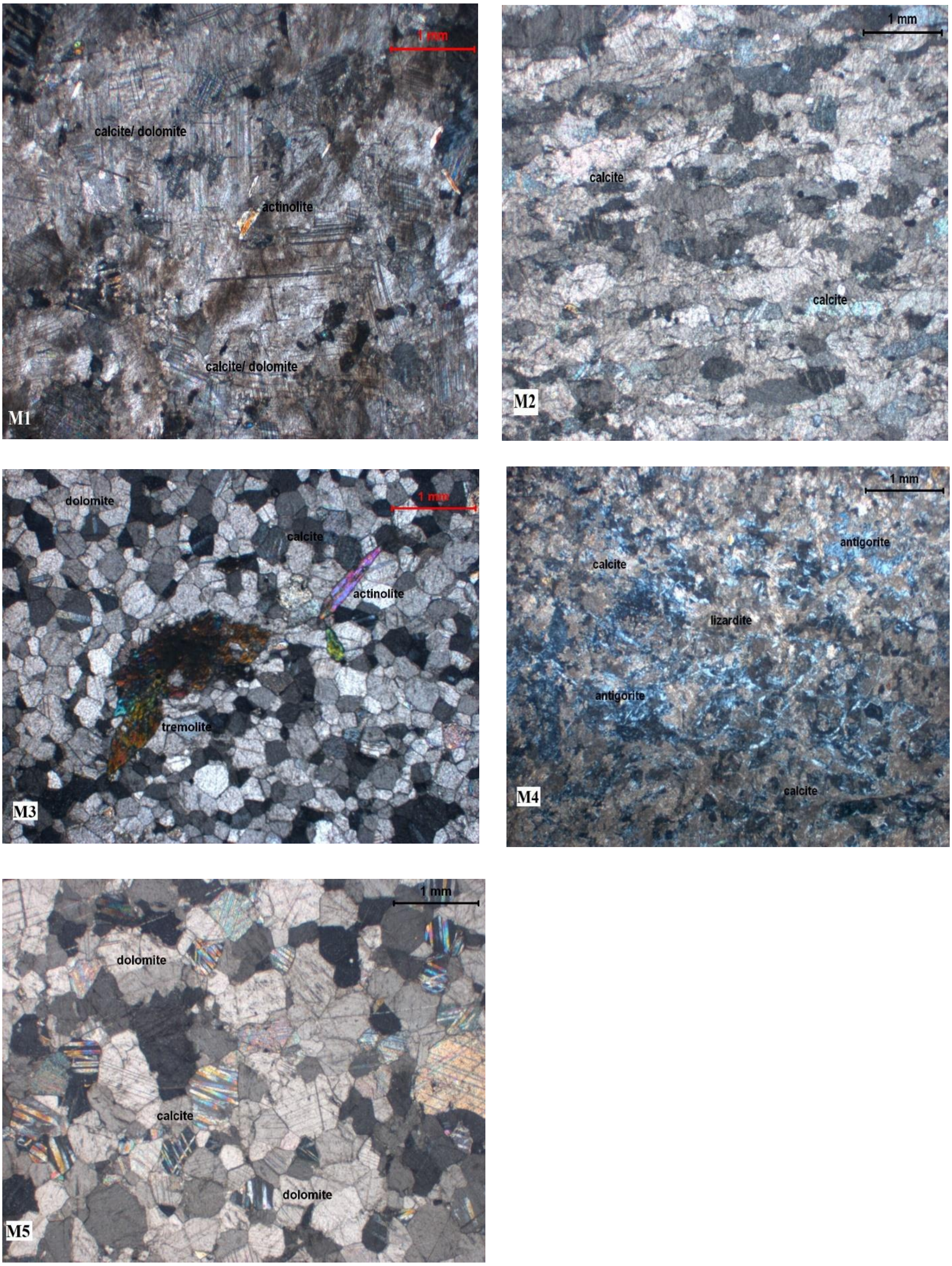


Fig. 5.1.2.1 Photomicrographs of studied marble samples

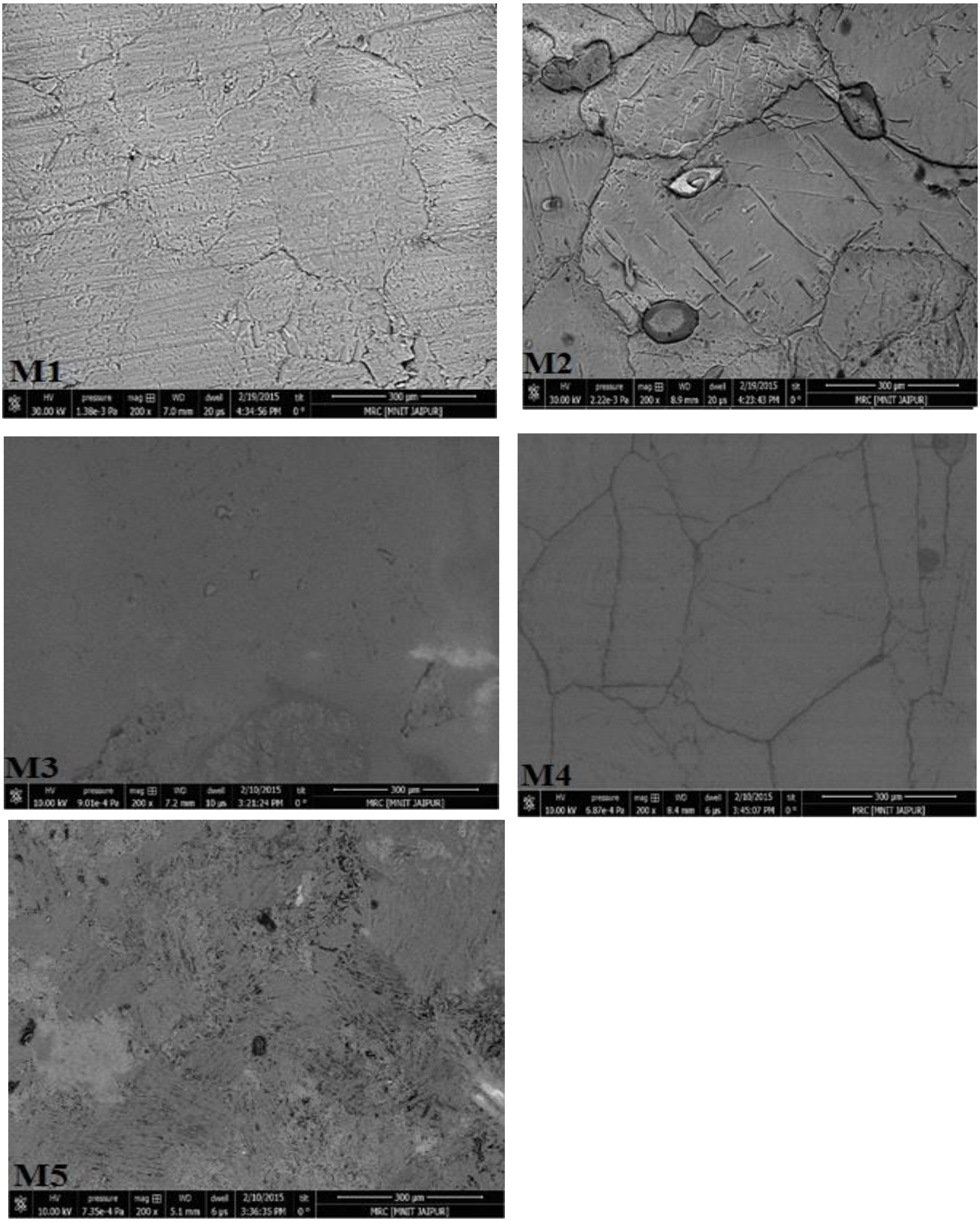


Fig. 5.1.2.2 SEM pictures of marble samples

5.1.3.X-ray diffraction analysis

To characterize the samples X-ray diffraction test were conducted for five selected samples. Diffraction occurs when waves interact with a regular structure whose repeat distance is about the same as the wavelength of X-ray waves. X-rays have wavelengths of the same order of a few angstroms, the same as typical interatomic distances in crystalline solids so they can interact with the atoms and can gain the information at the atomic level. For this powders of different samples were collected and placed in the machine, the 2-Theta readings were taken from 20 degrees to 120 degrees where all the available deflection can be noted within the wavelengths.

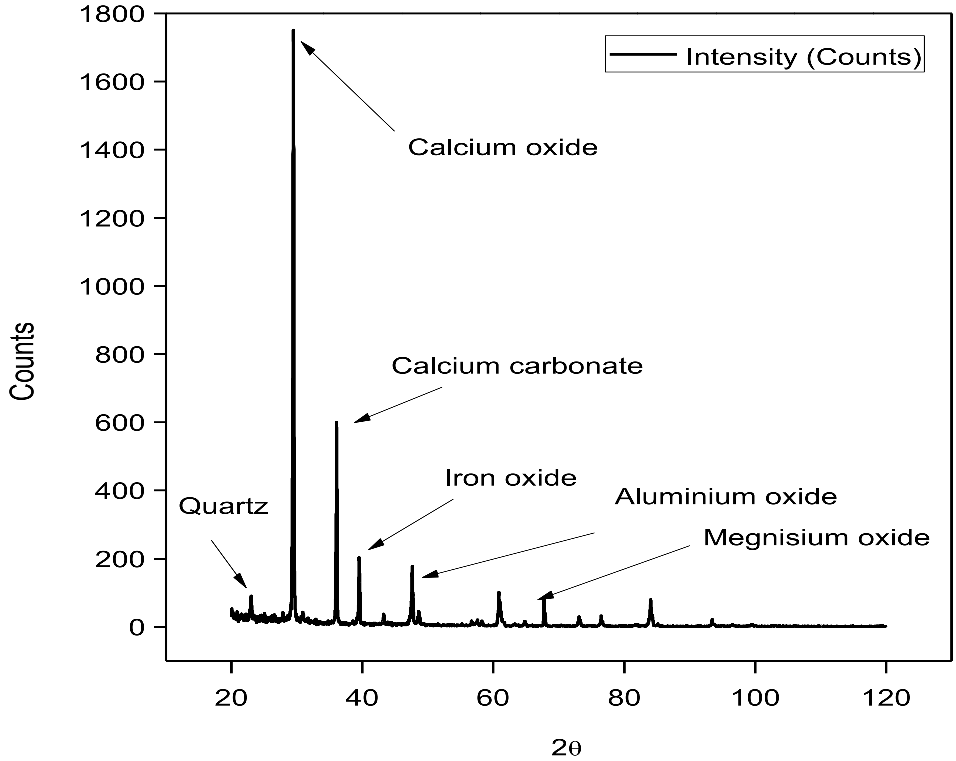


Fig. 5.1.3.1 XRD pattern for the M1 sample

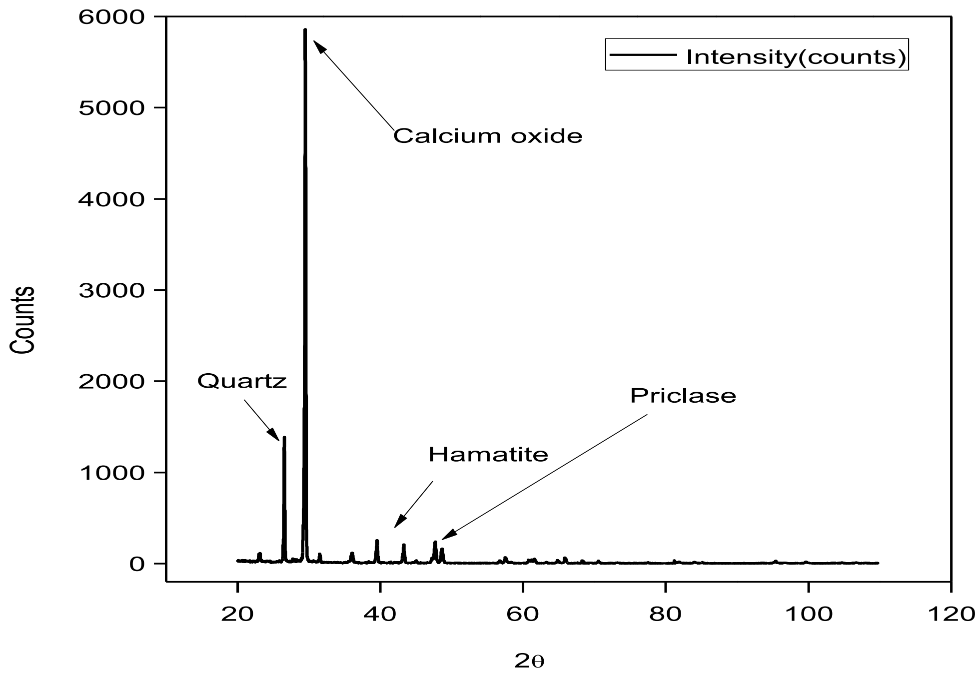


Fig. 5.1.3.2 XRD pattern for M2 sample

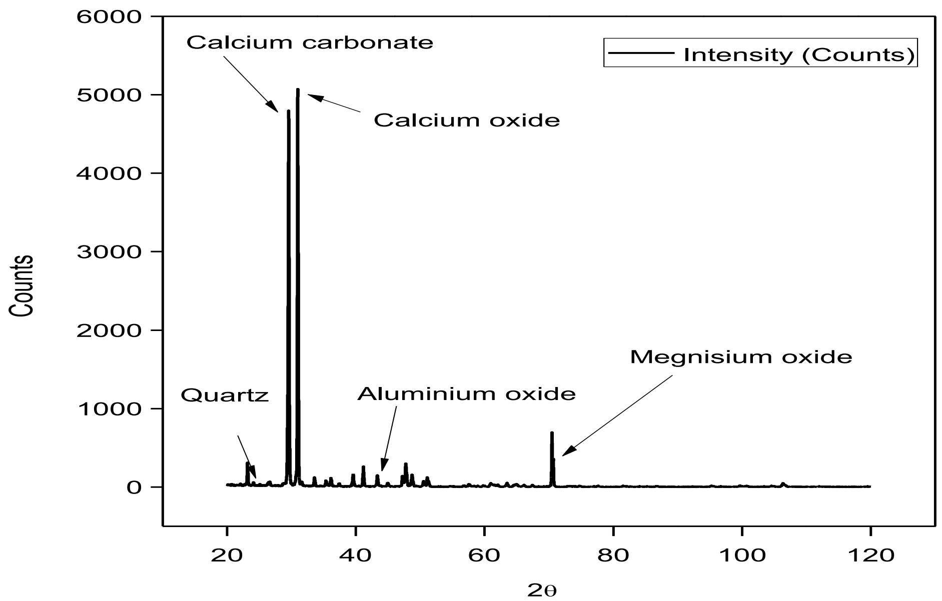


Fig. 5.1.3.3 XRD pattern for M3 sample

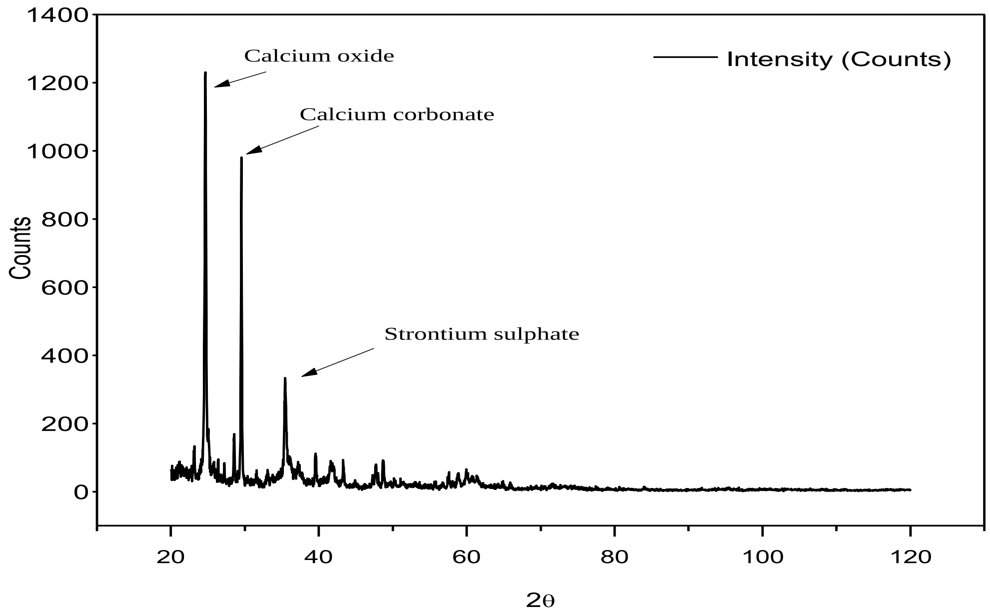


Fig. 5.1.3.4 XRD pattern for M4 sample

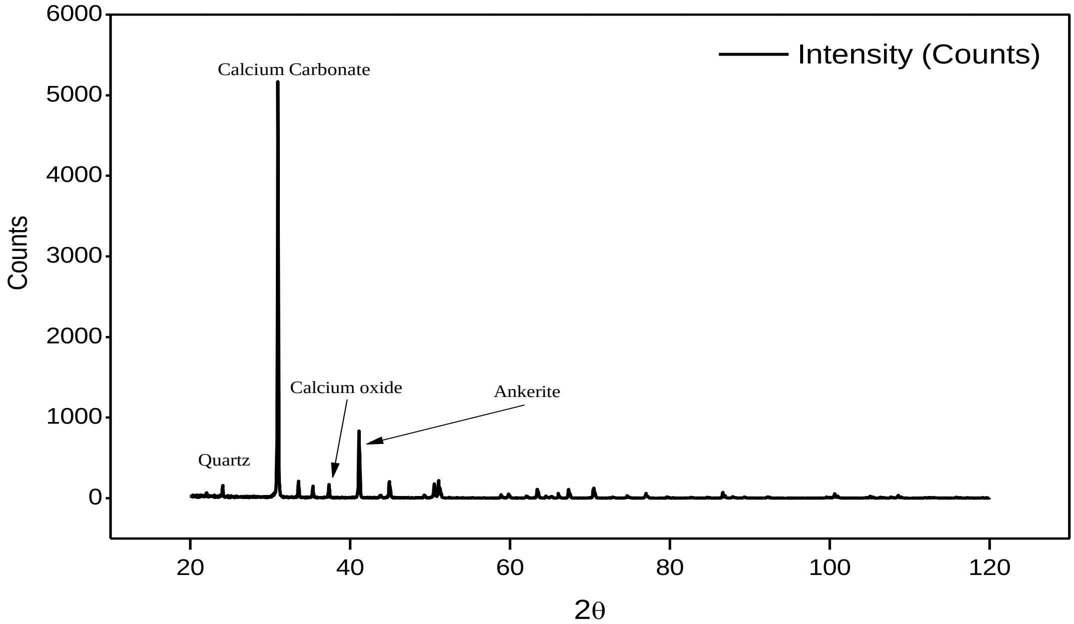


Fig. 5.1.3.5 XRD pattern for M5 sample

5.1.4.TGA analysis

Thermo-gravimetric analysis was done for selected five samples to find out the peak temperature at which the mass of the product is totally decomposed. TGA measures the amount and rate of change in the weight of a material as a function of temperature or time in a controlled atmosphere. Measurements are used prilimnary to determine the composition of materials and predict the thermal stability at temperatures 1000^0C. The technique can characterize materials that exhibit weight loss or gain due to decomposition, oxidation, or dehydration. In thermal gravimetric analysis a continous graph of mass change against temperature is obtained when a substance is heated at a uniform rate or kept at constant temperature. The results of the five samples are depicted in figures below. The experiment was started at room temperature and a temperature rate of 5^0C was added as the heat rate per minute and is heated till 1000^0C.

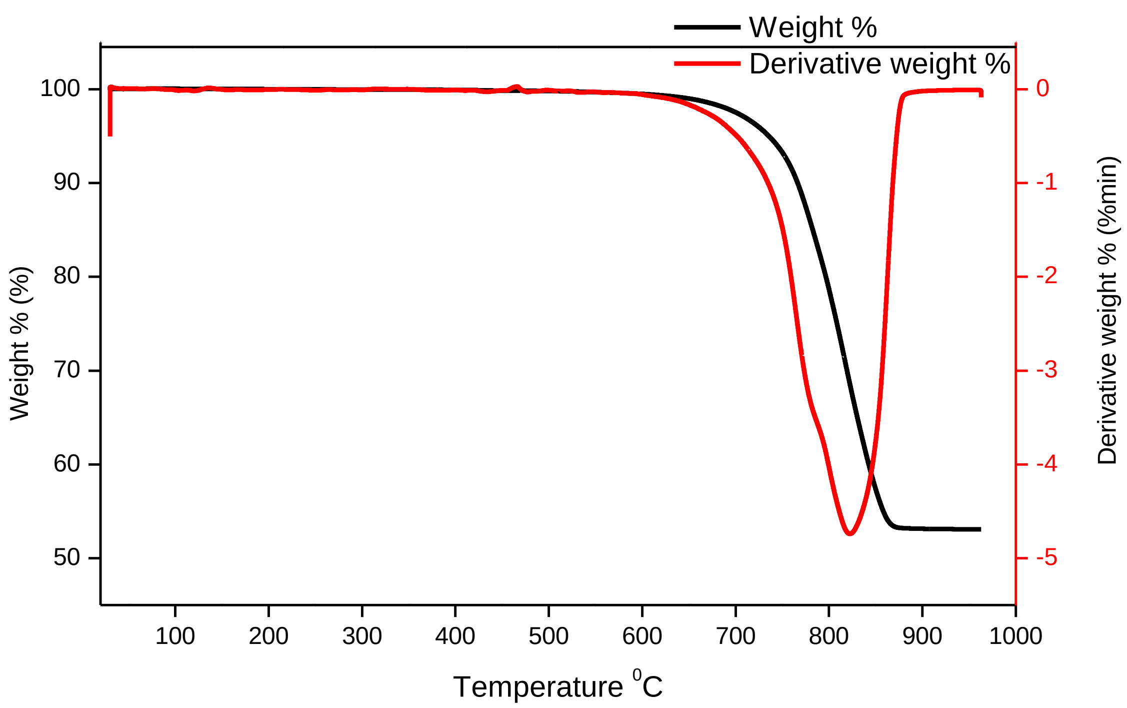


Fig. 5.1.4.1 TGA plot for sample M1

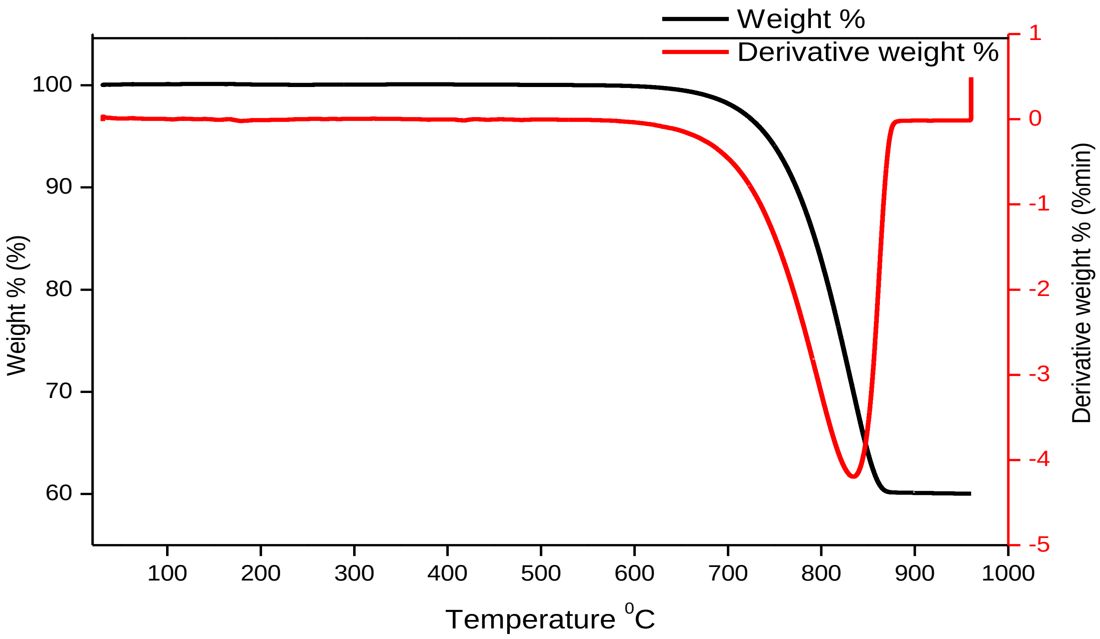


Fig. 5.1.4.2 TGA plot for sample M2

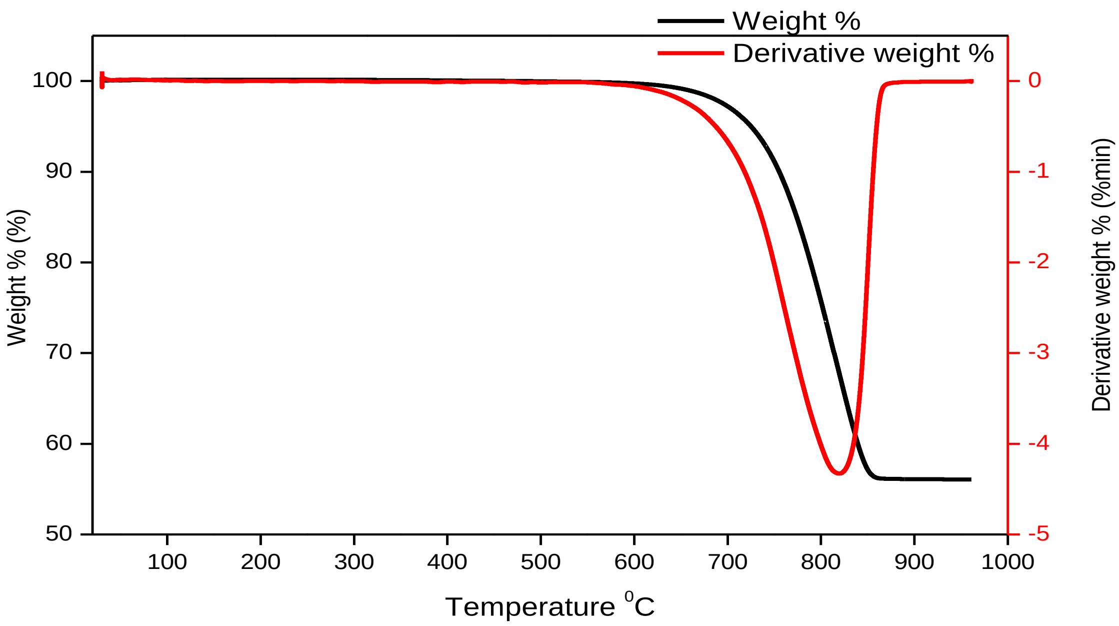


Fig. 5.1.4.3 TGA plot for sample M3

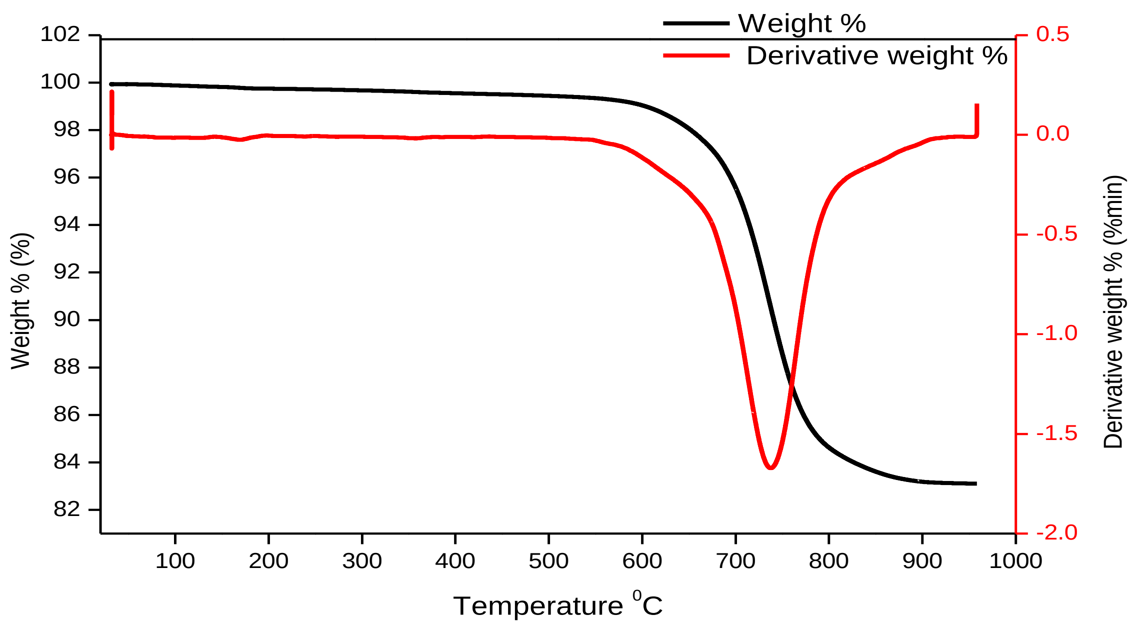


Fig. 5.1.4.4 TGA plot for sample M4

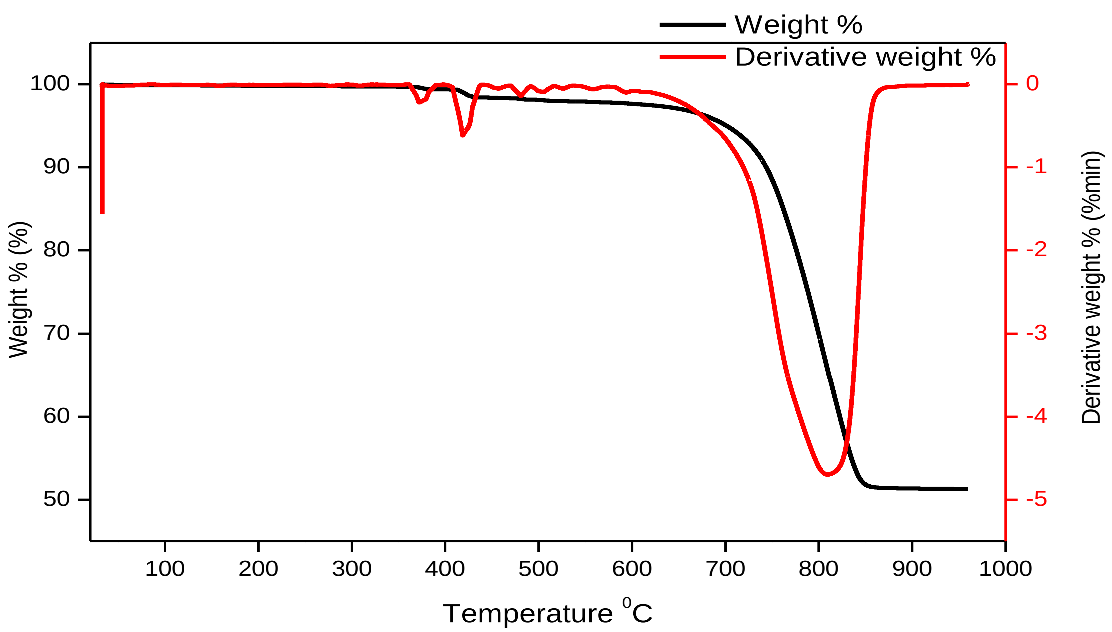


Fig. 5.1.4.5 TGA plot for sample M5

The TGA temperature plots look similar when we look at the figures it's difficult to identify with the normal picture depicted in the figures above, so to clearly identify the individual peak temperature in a separate Table. 5.1.2.4 given below.

Table. 5.1.4.1 Peak temperatures of samples

S.No	**Sample Name**	**Peak Temperature(^{0}C)**	**Weight % (%/min)**
1	Makarana	816.84	-4.68
2	Bhainslana Black	834.43	-4.19
3	Aandhi	824.80	-4.30
4	Udaipur green	739.13	-1.67
5	Agaria white	810.41	-4.69

5.2 Grading of marble stones

The five samples that the current study is classified as given below in Table.5.2.1

Table.5.2.1 Various textural properties of marble stones

S.No	Type of Stone	Hardness (HRC)	Nature of the stone	Colour of the stone	Granularity	Identified Sample as Classification Or Grading	MOH Number
1	Makarana	42	Hard and compact	White	Fine grained	Marble Grade C	2.5
2	Bhainslana	48	Hard and compact	Dark gray	Fine grained	Altered Ultrafamic (Serpentinite) Grade A	3
3	Andhi	42	Hard and compact	White	Fine grained	Marble Grade C	2.5
4	Sea green	45	Hard and compact	Dark green	Fine grained	Quartzite Grade B	4
5	Agaria	43	Hard and compact	White	Fine grained	Marble Grade C	2.5

There are 4 classifications of marbles. Class A, being the most resistant to breakage and having the least amount of natural inclusions, veins, and inconsistencies. Class B, Class C, and finally Class D, which is the most likely to break because of the above reasons. Normally, the class A materials are more consistent looking while the Class D marbles are more ornate. Class A marbles would usually be harder and more dense, while Class D marbles would be softer and more porous.

5.3 Rheological characterization using different coolants

Rheological investigations with different coolants were tested to check the behavior of the fluid. The rheological study of marble slurry is a vital characteristic for the calculation of marble characteristics, and for the parameter optimization. To achieve this, four marble sample pastes were made ready by keeping the powder to coolant ratio constant i.e. 0.5 the preparation process is given in Fig. 5.3.1 and the apparatus used to check the rheology is given in Fig.5.3.2. The powder is weighed according to the ratio and then the coolant is measured and added according to the ratios and mixed with hands until a paste is prepared. All rheological experiments were carried at room temperature (25°C).The amounts of these slurry mixtures are shown in Table. 5.3.1

Fig.5.3.1 Sample preparation with different coolants

Fig.5.3.2 Rheometer setup

The rheological study of these marble pastes were carried out at every 15 min after components mixing, and carried out till one hour. The apparatus used for the experimentation is a rotational rheometer built on coaxial rotary chambers with gradually increasing shear rate (D), extending from 1 to 100 s^{-1}, the setup is shown in Fig. 5.3.2, the rheometer is Anton par build with model number C- LTD80/QC having max pressure of 0.5 bar.

Bui et al. [11] experimented and determined that the shear rate of 1–100 s^{-1} was the best appropriate for rheological study of cement mixes, while large shear rates were considered too fast and rates limited to 50 s^{-1} did not yield constant results. The time requisite for the up-curve was one and half minute, for it to reach maximum shear rate of 100 s. The walls of the rotating rheometer is made of concentric chambers (the gap between camber walls is kept 5 mm) and the inner surface is coarsened in order to decrease (if not completely remove) the ‘‘slip” phenomenon; i.e., the progress of water-rich layer close to the inner surface of the rotating cylinder, is to produce a greasing effect, making flow easier, for the bulk material [109].

Rheological behaviour is usually defined by means of the Bingham flow model. This model assumes the marble paste behaves like a rigid body before a critical shear stress value is reached, called the yield point, beyond which it behaves like a Newtonian fluid. The shear stress at this yield point is defined as the yield stress (y, a critical value at which the properties change from rigid solid to a viscous liquid. The yield stress obtained from this model is dynamic yield stress, which is the intercept of the high shear rate asymptote with the shear stress axis. The shear stress vs. shear rate (relationship according to Bingham Plastic model is expressed as follows:

$$\tau = \tau y + \eta \dot{\gamma} \qquad \text{for } \tau > \tau y \qquad \text{where } \eta \text{ is the viscosity of the fluid.}$$

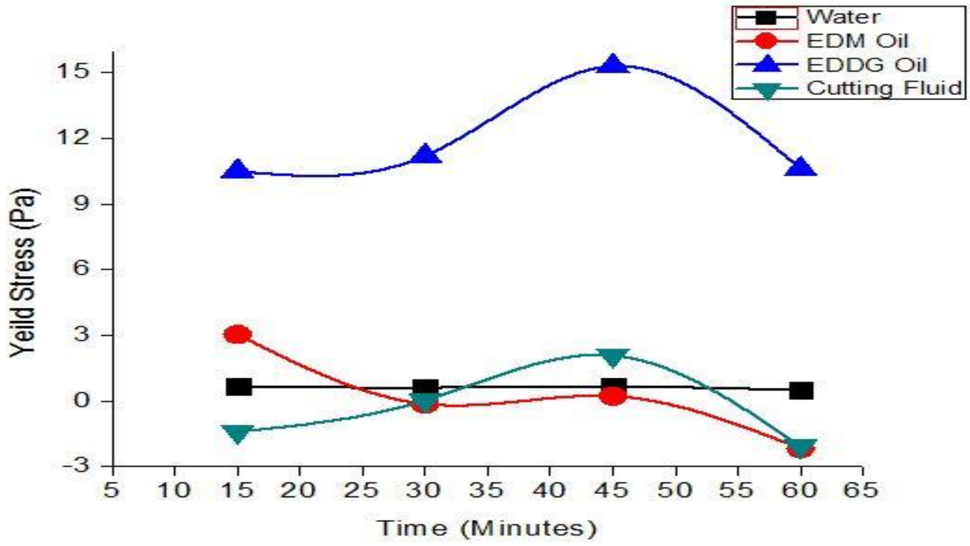


Fig. 5.3.3 Yield stress values plotted against function of time

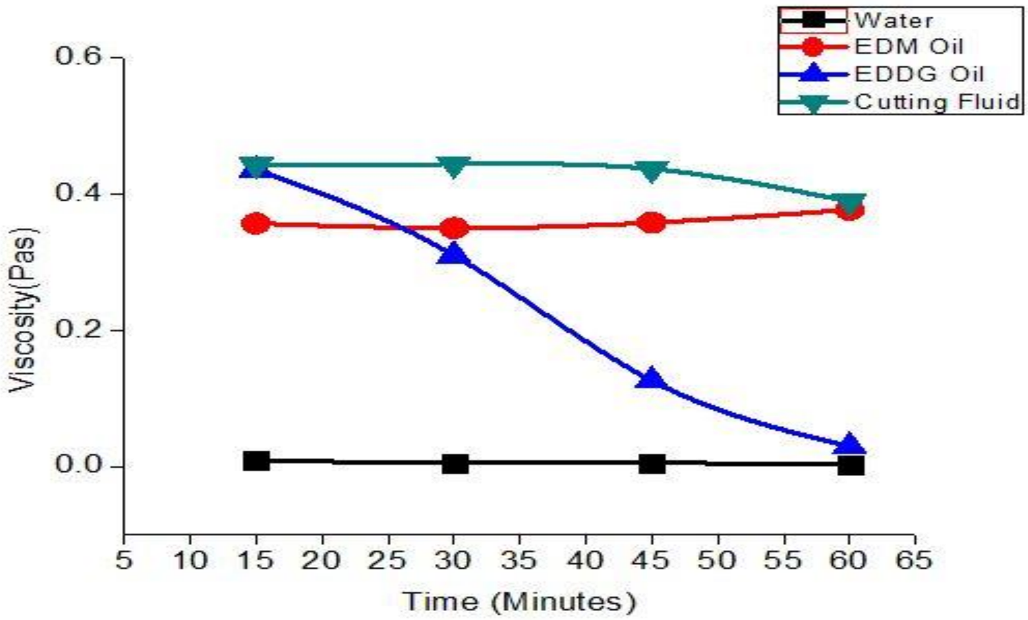


Fig. 5.3.4 Mean values of plastic viscosity vs function of time

In Fig. 5.3.3 the mean rate of the yield stress values on four samples are represented as a function of time. The behavior of real materials never shows a flow curve with only these two performances. at the same time than the yield stress there is a Newtonian plateau that is mostly hidden by the yield stress at low shear rates. this means that 95 % of the samples will not show a shear stress at low torques. they will show a shear stress with a lower slope versus shear rate. so, I can happen that the extrapolation to 0 shear rate in a log log plot give us negative values. It is obvious that the paste made of marble powder, and Electric Discharge diamond Grinding (EDDG) oil of 0.5 exhibited the highest values of the yield stress, in the range of 10.5 to 15.3 Pa. Quite large values were acquired for the pastes made with fine powder and water ratio below 0.5 ratios. On the other hand, when the water to marble ratio was kept 0.5, even at the low value (0.5% by weight of marble), the yield stress was found to be uniform on each time interval, thus inferring low cohesiveness of the related marble. Lowest yield stress values -2.179 Pa was observed for marble to Electric Discharge Machine (EDM) oil mixture. In Fig. 5.3.4 mean values of the plastic viscosity of four samples were plotted against time. A uniform plastic viscosity at different time intervals was observed in the paste prepared with water as coolant. In this study a higher value of viscosity 0.444 Pa-sec is observed with cutting fluid paste, and lowest value of viscosity of 0.0027 Pa-sec was observed in the paste prepared with water as coolant.

Harshal Bukley Model

Marble pastes prepared for experimentation behaves as Non-Newtonian fluid and the behavior of the fluid when tested shear thinning affect is caused for the fluid. The same phenomenon is exhibited by the Harshal Buckley Model which is a generalized model for a Non-Newtonian fluid, in which the strain exhibited by the fluid is associated to the stress in an intricate, non-linear way. Three factors used to characterize their association: the consistency k, the flow index n, and the yield shear stress (τ_0). The uniformity is a simple constant of proportionality, while the flow index measures the degree to which the fluid exhibits shear-thinning or shear-thickening.

The main equation of the Herschel-Bulkley model is commonly written as

$$\tau=\tau_0+k\dot{\gamma}^n$$

$$Y=a+b.Xp$$

a = Yield Stress, Y=Shear stress

X= Shear rate

b consistency index and p flow index

For $p<1$ the fluid is shear-thinning, whereas for $p>1$ the fluid is shear-thickening.

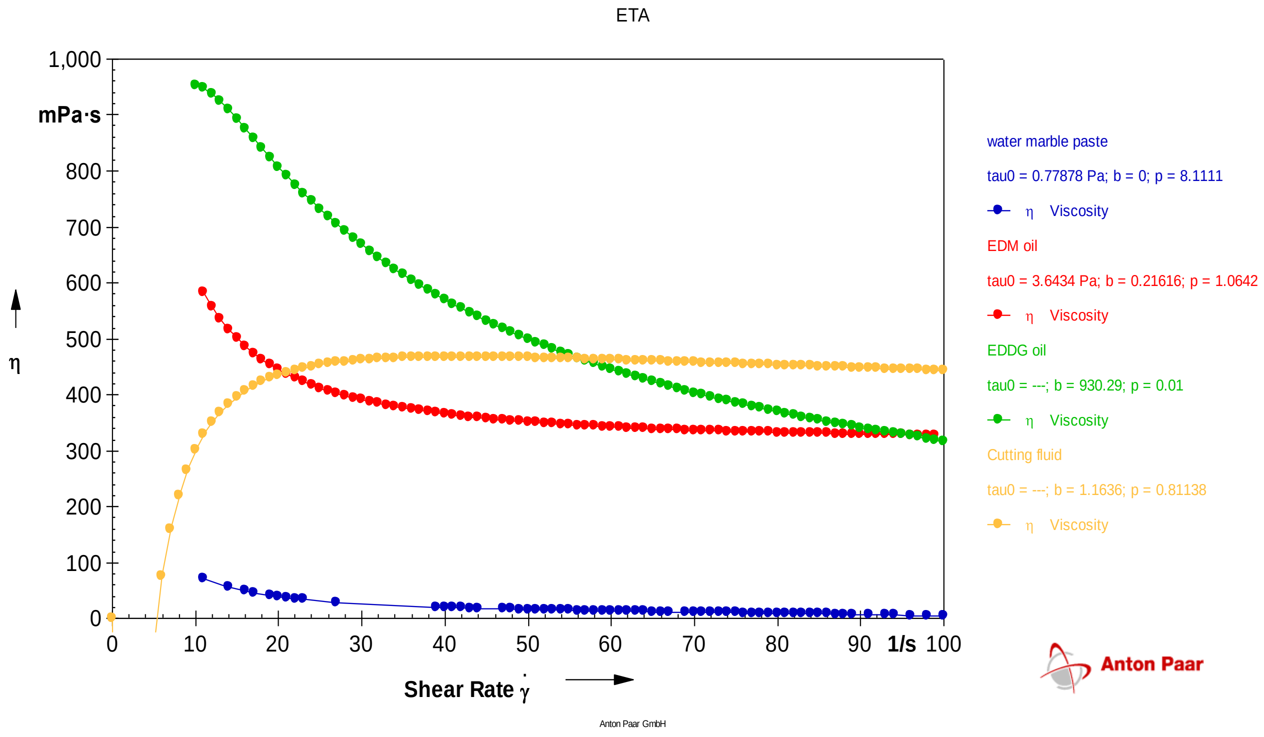


Fig. 5.3.5 Comparative for Harshal Bukley behavior of marble paste at different coolants and temperature

Fig. 5.3.5 shows the comparative graphs of shear thinning nature of paste mixed with different coolants. Highest change in viscosity with shear rate is observed in EDM oil and marble powder. Whereas, other coolants if we observe we can see a trend of shear thickening.

Chapter 6: Results and Discussions: Machinability of marble stones

Machinability is defined as how easily the material can be machined using a cutting tool. Machinability is a term indicating how work material responds to the cutting process. In most general cases machinability means the material is cut with good surface finish, long tool life, low force and power requirement and low cost.

The cutting performances of circular diamond sawblades are effected by the interaction of many effective parameters listed and discussed in chapter 3 with its mathematical equations. Let us look in detail to the results obtained for different wear phenomenon.

6.1 Diamond tool wear calculation

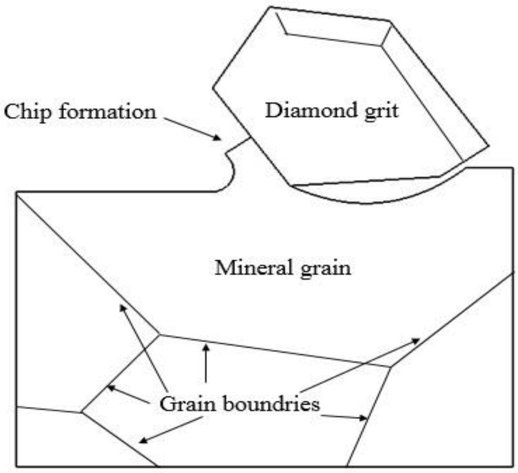
Specific wear rate (SWR) is defined as volume loss of material per unit meter per unit load. Its units are (m^3/Nm). A regression and correlation analysis was done in order to find out the relations between marble properties and SWR. Significance of the relations were checked statistically and validity of the relations were also evaluated by using some statistic tests. The R-squared value which is also termed as the co-efficient of determination, it's the segment of variance of dependent parameter which could be predicted by any independent parameter. Standard error which is denoted by Std is its standard deviation for error, and is the square root of the mean squared residual. Significance of the level observed for the experiment is denoted by probability P-value. The conventional 5 percent significance level is followed in this study. Therefore, any result which has a P-value of less than (0.05) are examined to be statistically significant with a level of confidence 95 percent [110]. Statistical evaluation and relation between physico-mechanical and specific wear rate (SWR) of the experimental data is presented in Table. 6.1.1 which clearly specify that, normally it is not possible to relate statistically dependable correlations among mechanical properties and the SWR. A partial correlation [R2 = 0.671] was seen among hardness (H) and SWR. Since, the P-value in Table-5 shows significant statistical link between the two variables at 95 percent level of confidence. The outcome supports the views of some of the researchers [103] which says that hardness can be used as a normal criteria for prediction of blade wear performance.

Table. 6.1.1 Correlation equations relating the mechanical properties and SWR

S.No	Regression equations	R^2	Std.	F	P
1	$SWR = 0.63 + 0.005\ \sigma_c$	0.139	1.456	0.452	0.550
2	$SWR = -1.04 + 0.115\ \sigma_b$	0.4961	1.109	2.953	0.184
3	$SWR = 2.18 – 0.253\ A_b$	0.644	1.510	0.206	0.680
4	$SWR = 2.72 – 24.244W_a$	0.1381	1.449	0.481	0.538
5	$SWR = 29.60 – 10.277\rho_0$	0.390	1.219	1.925	0.259
6	$SWR = -17.76 + 0.434H$	0.671	0.895	6..121	0.090

Lower correlation among individual mechanical properties of marble and SWR have also been addressed by some of the researchers. This phenomenon can be clearly explained by chip forming mechanism of marble, as suggested by, in the course of sawing operation of marble, minerals that make the marble are not totally displaced as whole grain from the matrix, but are shattered out in to small bits of minerals i.e. the chip formed are much smaller in size when compared to that of the individual mineral grain as shown in Fig. 6.1.1

The chip formation from machining of the marble is shown in Fig. 6.1.2 typically a SEM (Scanning electron microscope) image showing the size distribution of sample M2. The particle size is ranging from 63µm to 119 µm with a mean size of 90µm as shown in Fig. 6.1.2 . When we compare these figures with the grain lengths of the minerals they are too small which makes up the marble. Hence, it would be sensible to recommend that, rather than the mechanical properties of the marble, mineral properties could be fundamentally responsible for the tool wear performance. The moderate relation between hardness and SWR seems to support the argument that mineral grains and their textural properties effect the wear significantly. Some other relations between the mechanical properties like fracture toughness and young's modulus of marble samples were not examined in this part of the research which may affect the tool wear performance as reported by recent research [111]



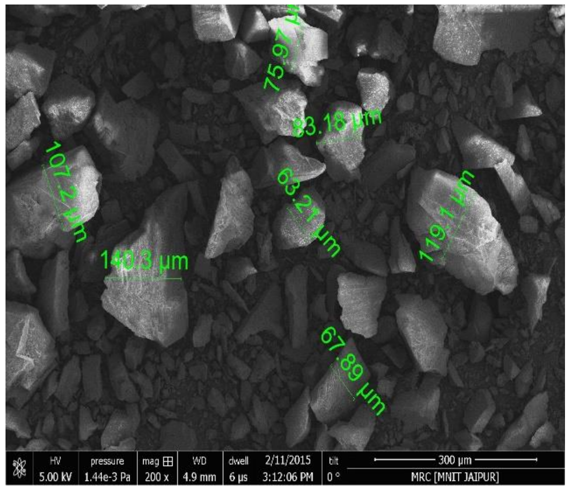


Fig. 6.1.1 Formation of chip while machining Fig. 6.1.2 SEM picture of formed chips

Correlation between SWR and petrographic properties

In this research, percentage of volume and grain size of the marble stones constituting the minerals of marble, often affecting the saw blade wear performance are also considered as main factors for petrographic parameters. Therefore, volume percentage of Lime, quartz, priclase and hematite were evaluated and statistical analysis with grain size distributions (mean and max) in mm were calculated. All the investigations are represented in Table 6.1.2 together with their statistical relations which are found to be best fit. The regression curves are also represented by Fig. 6.1.4 which shows the relation between the mineral percentage and volume percentage of individual mineral with SWR which shows a poor relation, specifying that the wear of tool is not much affected by these factors. Although the correlation of [R^2 = 0.335] was seen among the volume percentage of the quartz and SWR, this is not statistically significant at the 95 percent confidence level, since value of p is greater than 0.05. These findings can also be found in which says that the quartz content alone is not responsible for wear of sawblade, and accordingly remaining petrographic variables could be investigated to find the factor of influence.

Table. 6.1.2 Correlation analysis between petrographic properties and SWR

S.No	Regression equation	R^2	Std.	F	P
1	$SWR = 0.82 + 0.21\ v_Q$	0.335	1.273	1.514	0.306
2	$SWR = -2.68 + 0.08V_L$	0.05	1.520	0.164	0.71
3	$SWR = 1.05 + 0.05V_P$	0.07	1.501	0.246	0.654
4	$SWR = 0.89 + 0.78V_H$	0.269	1.335	1.104	0.371
5	$SWR = -0.39 + 0.83Q_g$	0.947	0.359	53.48	0.005
6	$SWR = 1.58 – 0.05L_g$	0.980	1.554	0.029	0.874
7	$SWR = -1.06 + 3.36P_g$	0.55	1.046	3.68	0.151
8	$SWR = 0.89 + 6.63H_g$	0.257	1.346	1.038	0.383
9	$SWR = -0.48 + 3.87Q_m$	0.140	1.448	0.489	0.535
10	$SWR = 2.56 – 2.02L_m$	0.270	1.334	1.112	0.370
11	$SWR= 0.31 + 2.20P_m$	0.04	1.529	0.126	0.745
12	$SWR = 1.57 – 1.02H_m$	0.08	1.491	0.290	0.627

V_Q = Quartz volume percentage; V_L = Lime volume percentage; V_P = priclase volume percentage; V_H = Hematite volume percentage; Q_g = Quartz max grain size; L_g = Lime max grain size; P_g = Priclase max grain size. H_g = Hematite max grain size; Q_m= Quartz mean grain size; L_m = Lime mean grain size; P_m = Priclase mean grain size; H_m = Hematite mean grain size

Statistical test results presented in the Table. 6.1.2 shows the quartz grain size Qg max and lime (Lg) max grain size are the most important factors effecting petrographic parameters influencing the SWR of the tool. The correlation between them is illustrated in the Fig. 6.1.6 with a graphical representation. Table. 6.1.2 also shows that though statistically it is valid at 95 percent level of confidence, mean grain size of quartz and lime mean grain size are correlated less when compared to that of the maximum grain size. The worn out surfaces of the tool were tested under scanning electron microscope (SEM) as shown in the Fig. 6.1.5. It clearly shows the engagement edges of the circular saw as well as the pull outs due to the machining operations the diamond grain size in the tool varies from 100 µm to 200 µm.

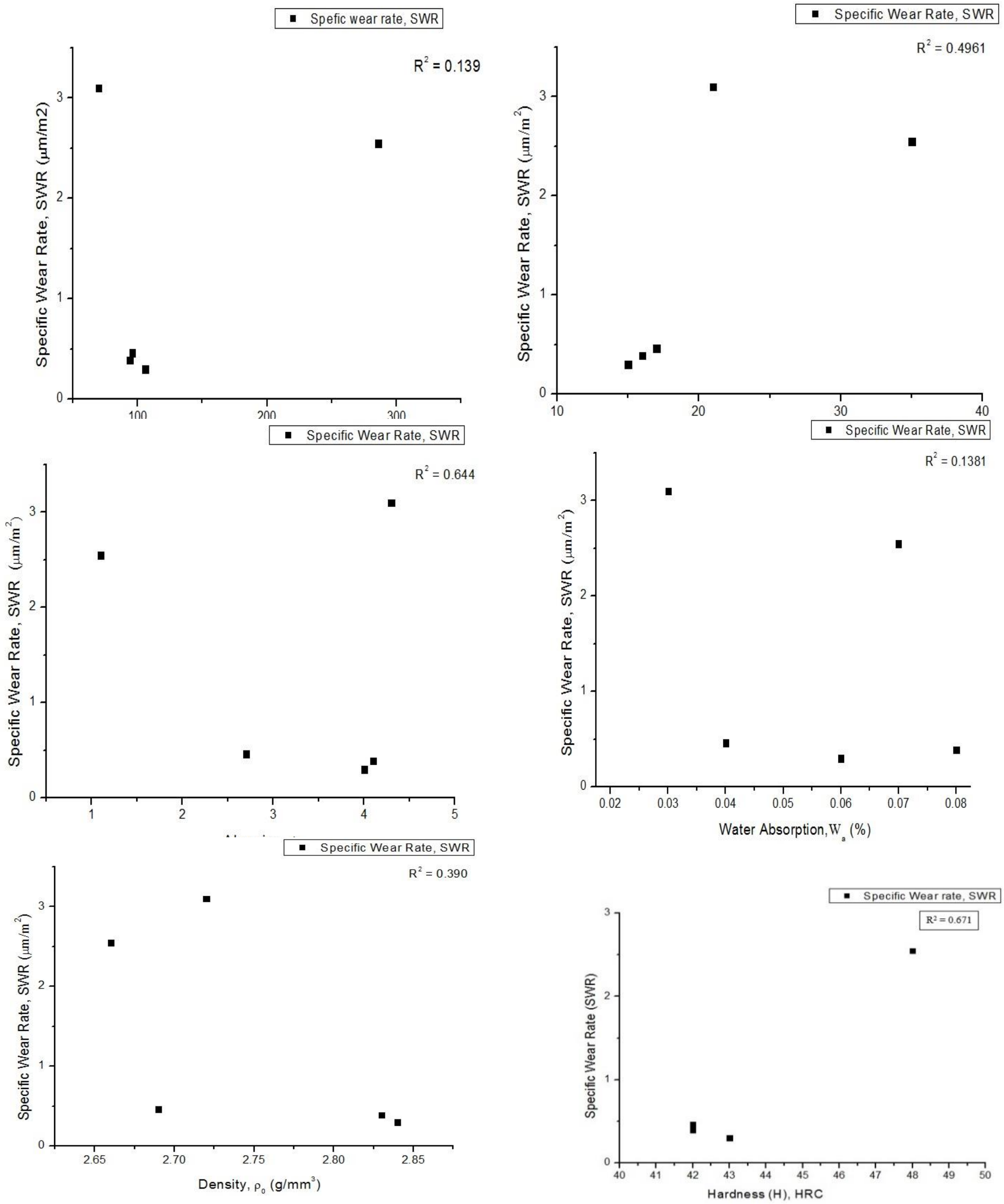


Fig. 6.1.3 Relation among mechanical marble properties and SWR

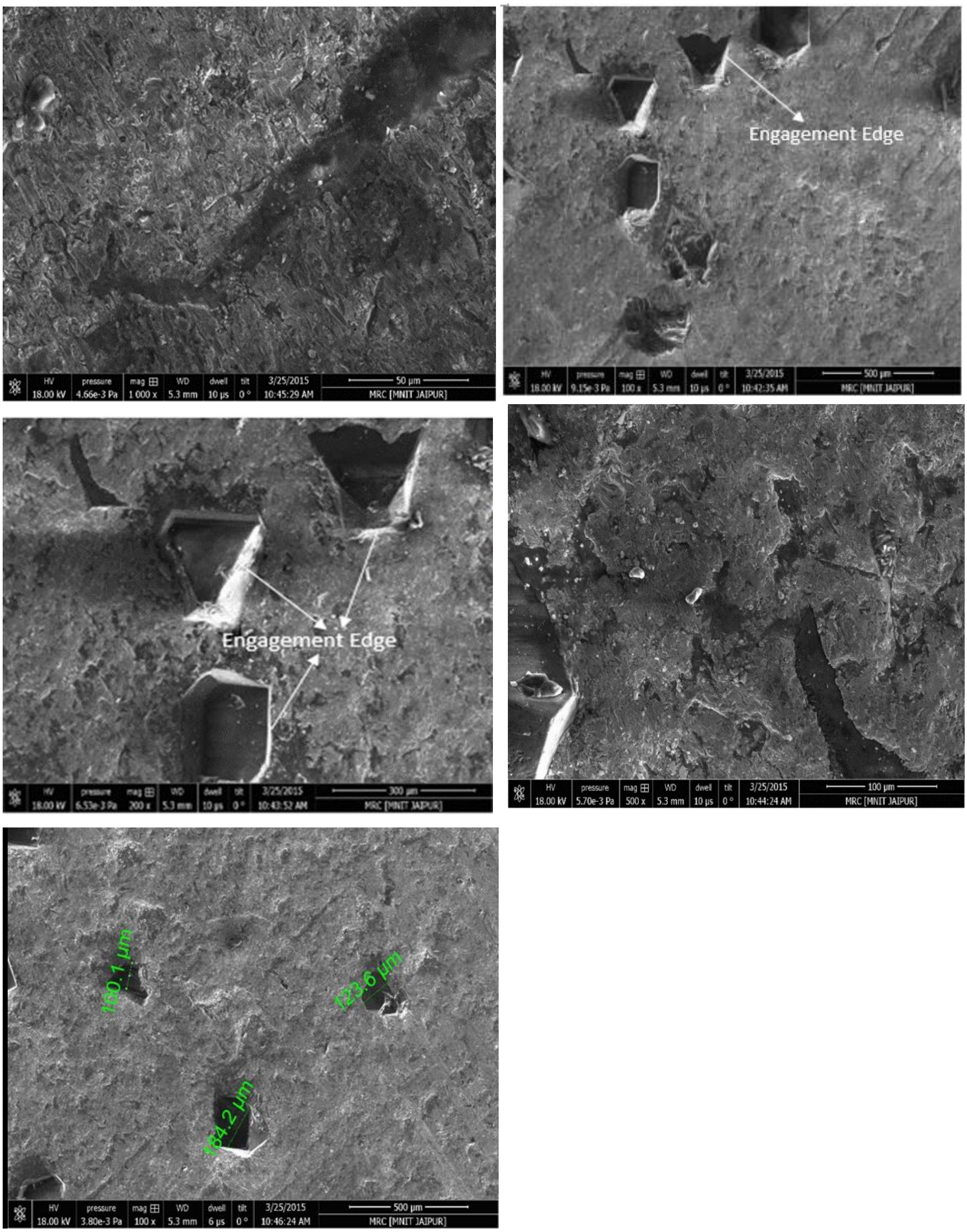


Fig. 6.1.4 SEM pictures of the worn surface of the tool after the wear test

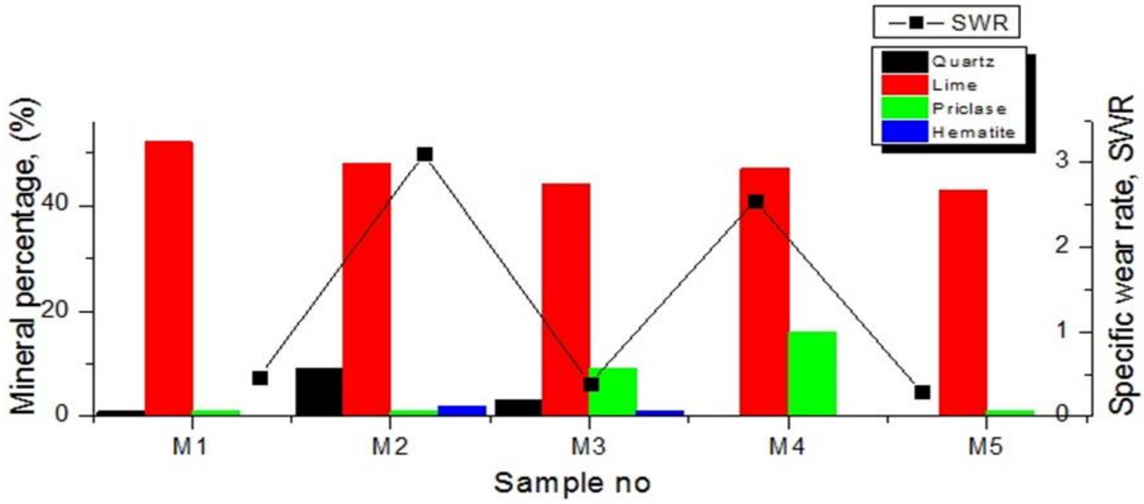
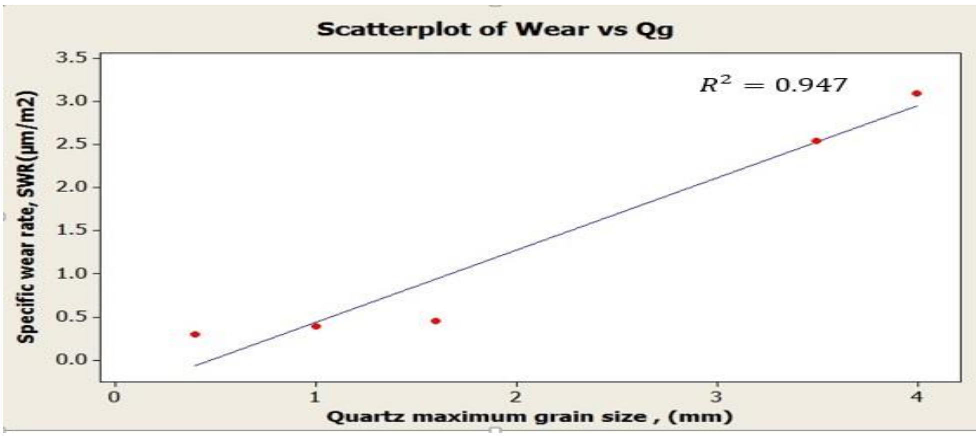
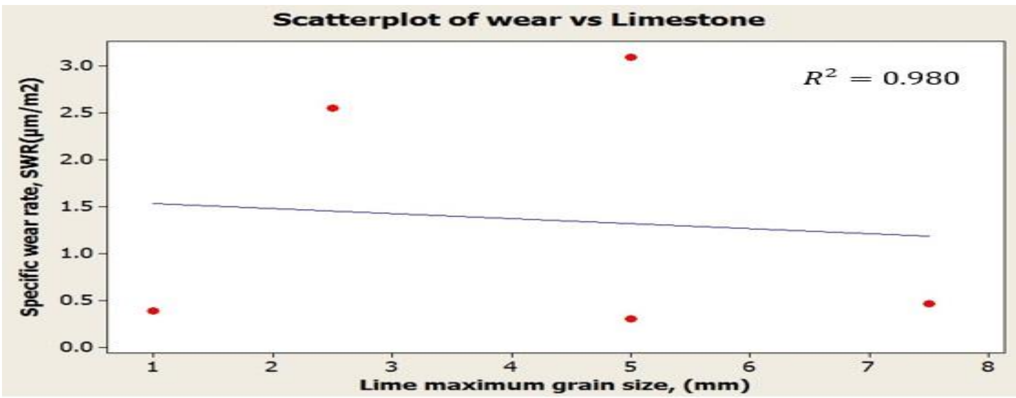


Fig. 6.1.5 Bar graph explaining the relation among mineral %, samples and SWR



(a) Quartz max grain size, mm



(b) Lime max grain size, mm

Fig. 6.1.6 Correlation among max grain size and SWR (a) Lime (b) Quartz

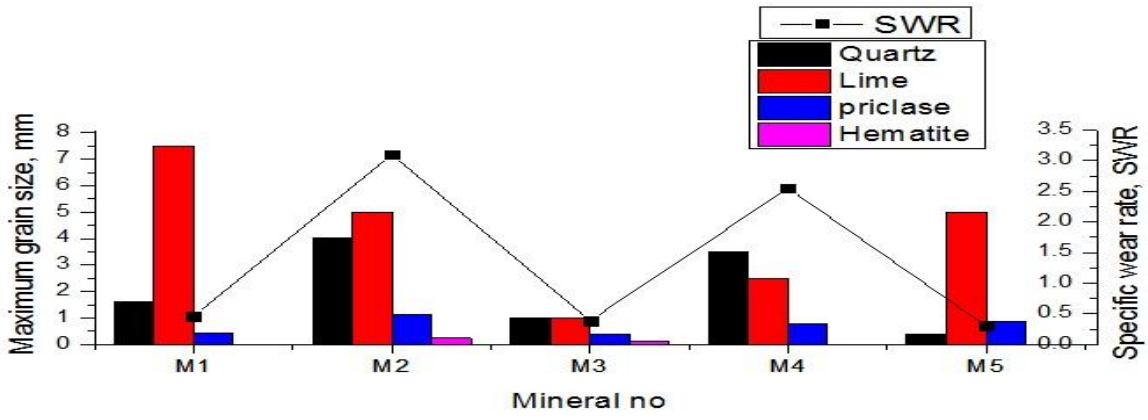


Fig. 6.1.7 Bar graph showing the relation among mineral max grain size and SWR

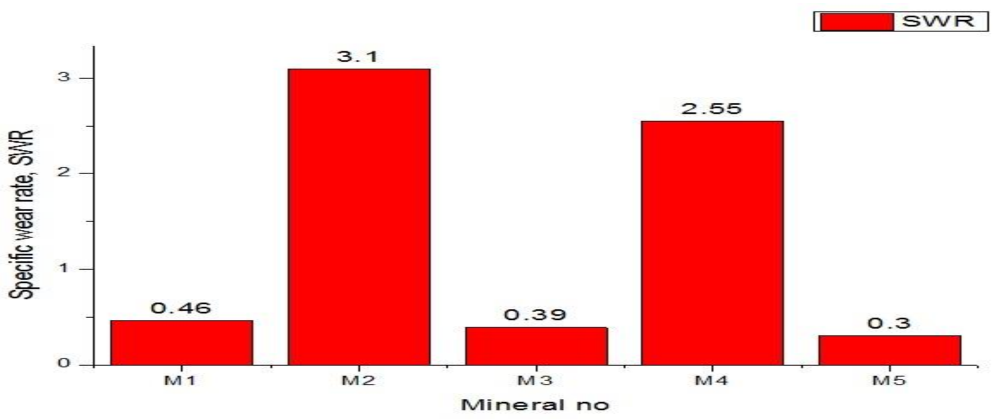


Fig. 6.1.8 Specific wear rate of measured marble

This observation clearly outlines that the erosion effect of the tool is more prominent in the case of larger grain sizes. As seen in the Fig. 6.1.6 marble samples having relatively large grain size predominantly maximum grain size of lime and quartz generate higher wear rates. The Regression curves shown in Fig. 6.1.7 clearly shows the strong correlation between the SWR and the grain size of quartz and limestone. The bar graph in the Fig. 6.1.8 shows the relation between the maximum grain size, specific wear and minerals. The SWR of different marbles is presented in a bar graph in Fig. 6.1.8. As per the literature review that has been observed by a reasonable number of papers relation between wear and mean grain size performance of diamond segment circular blades were not being considered as a direct input variable by the models developed for predicting the wear performance. These outcomes presented in this paper, indicate that inclusion of these variables could contribute in developing better models for SWR

6.2 Energy consumption while performing milling operation

Experimental procedure and the design of experiments for the energy consumption were clearly discussed in chapter 3.3.1. The results are given in tables below:-

Table. 6.2.1 Input parameters and its levels

Machine Parameters	Symbol	Units	Level 1	Level 2	Level 3	Level 4
Speed	S	RPM	800	1200	1600	2000
Feed	F	mm/min	100	150	200	250
Depth of cut	DOC	mm	1	2	3	4

Table. 6.2.2 Experimental matrix for (10 and 12 mm) diameter tool for M1 sample

S.No	Speed (RPM)	Feed (mm)	DOC (mm)	SE_{cut} (J/mm^3) (10 mm) Dia	SE_{cut} (J/mm^3) (12 mm) Dia	S/N ratio values for 10 mm Dia	S/N ratio values for 12 mm Dia
1	800	100	1	2.199	1.998	-6.740	-6.012
2	800	150	2	0.753	0.672	2.464	3.448
3	800	200	3	0.371	0.345	8.614	9.236
4	800	250	4	0.217	0.204	13.153	13.814
5	1200	100	2	1.204	0.900	-1.611	0.913
6	1200	150	1	1.659	1.402	-4.397	-2.934
7	1200	200	4	0.310	0.269	10.164	11.394
8	1200	250	3	0.329	0.299	9.634	10.461
9	1600	100	3	0.900	0.666	0.908	3.520
10	1600	150	4	0.462	0.360	6.712	8.872
11	1600	200	1	1.379	1.016	-2.788	-0.145
12	1600	250	2	0.551	0.417	5.175	7.587
13	2000	100	4	0.710	0.417	2.973	7.578
14	2000	150	3	0.688	0.363	3.248	8.788
15	2000	200	2	0.767	0.411	2.305	7.710
16	2000	250	1	1.180	0.705	-1.443	3.028

Table 6.2.3 Experimental matrix for (10 and 12 mm) diameter tool for M2 sample

S.No	Speed (RPM)	Feed (mm)	DOC (mm)	SE_{cut} (J/mm^3) (10 mm) Dia	SE_{cut} (J/mm^3) (12 mm) Dia	S/N ratio values for 10 mm Dia	S/N ratio values for 12 mm Dia
1	800	100	1	2.8587	2.597	-9.12337	-8.28944
2	800	150	2	0.9789	0.874	0.185233	1.169771
3	800	200	3	0.4823	0.448	6.333655	6.97444
4	800	250	4	0.2821	0.265	10.99194	11.53508
5	1200	100	2	1.5652	1.17	-3.8914	-1.36372
6	1200	150	1	2.158	1.823	-6.68103	-5.21573
7	1200	200	4	0.403	0.35	7.893899	9.118639
8	1200	250	3	0.428	0.388	7.371125	8.223365
9	1600	100	3	1.17	0.866	-1.36372	1.249642
10	1600	150	4	0.6	0.468	4.436975	6.595083
11	1600	200	1	1.793	1.321	-5.07161	-2.41806
12	1600	250	2	0.716	0.542	2.90174	5.320014
13	2000	100	4	0.923	0.542	0.695966	5.320014
14	2000	150	3	0.89	0.472	1.0122	6.52116
15	2000	200	2	0.997	0.534	0.026097	5.449175
16	2000	250	1	1.534	0.92	-3.71651	0.724243

Table 6.2.4 Experimental matrix for (10 and 12 mm) diameter tool for M3 sample

S.No	**Speed (RPM)**	**Feed (mm)**	**DOC (mm)**	**SE_{cut} (J/mm^3) (10 mm) Dia**	**SE_{cut} (J/mm^3) (12 mm) Dia**	**S/N ratio values for 10 mm Dia**	**S/N ratio values for 12 mm Dia**
1	800	100	1	2.64	2.398	-8.43208	-7.59698
2	800	150	2	0.904	0.81	0.876631	1.8303
3	800	200	3	0.445	0.414	7.0328	7.659993
4	800	250	4	0.26	0.245	11.70053	12.21668
5	1200	100	2	1.44	1.08	-3.16725	-0.66848
6	1200	150	1	1.991	1.68	-5.98143	-4.50619
7	1200	200	4	0.372	0.323	8.589141	9.81595
8	1200	250	3	0.395	0.36	8.068058	8.87395
9	1600	100	3	1.08	0.799	-0.66848	1.949064
10	1600	150	4	0.554	0.432	5.129805	7.290325
11	1600	200	1	1.655	1.219	-4.37596	-1.72007
12	1600	250	2	0.661	0.5	3.595971	6.0206
13	2000	100	4	0.852	0.5	1.391208	6.0206
14	2000	150	3	0.826	0.436	1.660399	7.21027
15	2000	200	2	0.92	0.493	0.724243	6.143062
16	2000	250	1	1.42	0.85	-3.04577	1.411621

Table 6.2.5 Experimental matrix for (10 and 12 mm) diameter tool for M4 sample

S.No	Speed (RPM)	Feed (mm)	DOC (mm)	SE_{cut} (J/mm^3) (10 mm) Dia	SE_{cut} (J/mm^3) (12 mm) Dia	S/N ratio values for 10 mm Dia	S/N ratio values for 12 mm Dia
1	800	100	1	3.298	2.997	-10.365	-9.53373
2	800	150	2	1.13	1.01	-1.06157	-0.08643
3	800	200	3	0.56	0.52	5.036239	5.679933
4	800	250	4	0.326	0.306	9.735648	10.28557
5	1200	100	2	1.806	1.35	-5.13435	-2.60668
6	1200	150	1	2.49	2.103	-7.92399	-6.45679
7	1200	200	4	0.465	0.404	6.650941	7.872373
8	1200	250	3	0.494	0.449	6.125461	6.955073
9	1600	100	3	1.35	0.999	-2.60668	0.00869
10	1600	150	4	0.693	0.54	3.185335	5.352125
11	1600	200	1	2.069	1.524	-6.31521	-3.6597
12	1600	250	2	0.83	0.626	1.618438	4.068513
13	2000	100	4	1.065	0.626	-0.54699	4.068513
14	2000	150	3	1.032	0.545	-0.27359	5.27207
15	2000	200	2	1.15	0.617	-1.21396	4.194297
16	2000	250	1	1.77	1.058	-4.95947	-0.48971

Table 6.2.6 Experimental matrix for (10 and 12 mm) diameter tool for M5 sample

S.No	**Speed (RPM)**	**Feed (mm)**	**DOC (mm)**	**SE_{cut} (J/mm^3) (10 mm) Dia**	**SE_{cut} (J/mm^3) (12 mm) Dia**	**S/N ratio values for 10 mm Dia**	**S/N ratio values for 12 mm Dia**
1	800	100	1	2.42	2.197	-7.67631	-6.8366
2	800	150	2	0.828	0.739	1.639393	2.627111
3	800	200	3	0.41	0.379	7.744323	8.427216
4	800	250	4	0.24	0.224	12.39578	12.99504
5	1200	100	2	1.324	0.99	-2.43776	0.087296
6	1200	150	1	1.825	1.542	-5.22526	-3.76169
7	1200	200	4	0.341	0.296	9.344912	10.57417
8	1200	250	3	0.362	0.329	8.825829	9.656082
9	1600	100	3	0.99	0.733	0.087296	2.697921
10	1600	150	4	0.51	0.396	5.848596	8.046096
11	1600	200	1	1.52	1.118	-3.63687	-0.96884
12	1600	250	2	0.61	0.459	4.293403	6.763746
13	2000	100	4	0.781	0.459	2.146979	6.763746
14	2000	150	3	0.756	0.399	2.429564	7.980542
15	2000	200	2	0.843	0.452	1.483449	6.897231
16	2000	250	1	1.298	0.776	-2.26549	2.202766

Signal to noise ratio is important to calculate because our main focus is on signal but during transmission it got effected by some random noise. At the receiving end we want to have same transmitted signal, to achieve this noise should be reduced and here SNR plays a important role Noise cannot be avoided but can be kept as low as possible. In cutting and milling operations there are many parameters like speed, feed, depth of cut and the noise of the tool, our aim is to keep the SNR as low as possible by achieving good energy consumption.

Energy essential to eliminate unit volume of stone is termed as the SE_{cut}. SE_{cut} is the function of machine variables, physico-mechanical, mineral properties of the stone to be sliced. With the aid of the experiments performed and facts obtained the SE_{cut} was calculated as

$$SE_{cut} = E_{cut}/V_{cut} \quad (1)$$

Where SE_{cut} is the specific cutting energy (J/mm^3), E_{cut} is the total energy expended during cutting process (J), and V is the volume of the conduit cut by end mill (mm^3). The power values are recorded when the cutter is in contact with the stone while calculating the SE_{cut}.

The energy consumption initially increases due to the energy required to start the spindle motor from zero to specified RPM and fluctuates in between while performing milling operation and then increases due to the rapid traverse of the tool at the end of the operation and to move back to the initial position. The graph of energy consumption vs time is plotted as shown in the figure below. The data points in the graph represents where the end mill cutter enters and leaves the stones, these points help in calculating the mean cutting energy of the end mill and also represents the time through which it is in contact with the stone. The product of the quantity of the power and time expended discloses the quantity of energy expended during milling operation (E_{cut}). The SE_{cut} of each cut can be obtained by quantity of energy required for a cut divided by the volume of the conduit sliced by the milling cutter.

$$SE_{cut} = (P \times t)/ (F \times t \times DOC \times WOC) \quad (2)$$

Where P is the power consumption during milling in (W), t is the time required to perform a single cut (s), F is the feed rate in (mm/min), DOC is depth of cut (mm), and

WOC is the width of cut (mm). The input levels and factors for the experimentation is given in Tables.

ANOVA analysis used to examine the capability of the proven models, for the results of the SE_{cut} for 10 mm and 12 mm Diameter end mill are given in the Tables, main effect plots for SE_{cut} are also shown in the Figures. The test for significance of model was tested using Regression analysis using the Minitab 16 software. The adequate measures of the model like R^2, Adjusted R^2 and predicted R^2 are also tabulated. The wellness of the model can be checked by the coefficient of determination R^2. R^2 is the statistical measure of how adjacent the data points are to the fitting regression line. The adjusted R^2 is always less than R^2, and it always reproduces the number of factors in the model. The value of the determinant coefficient $(R^2)_{SE}$ for (10 mm and 12 mm diameter) is indicated in tables it clearly indicates the model is closely determined. Even the large values of the adjusted R^2 values also guarantees the significance of the models.

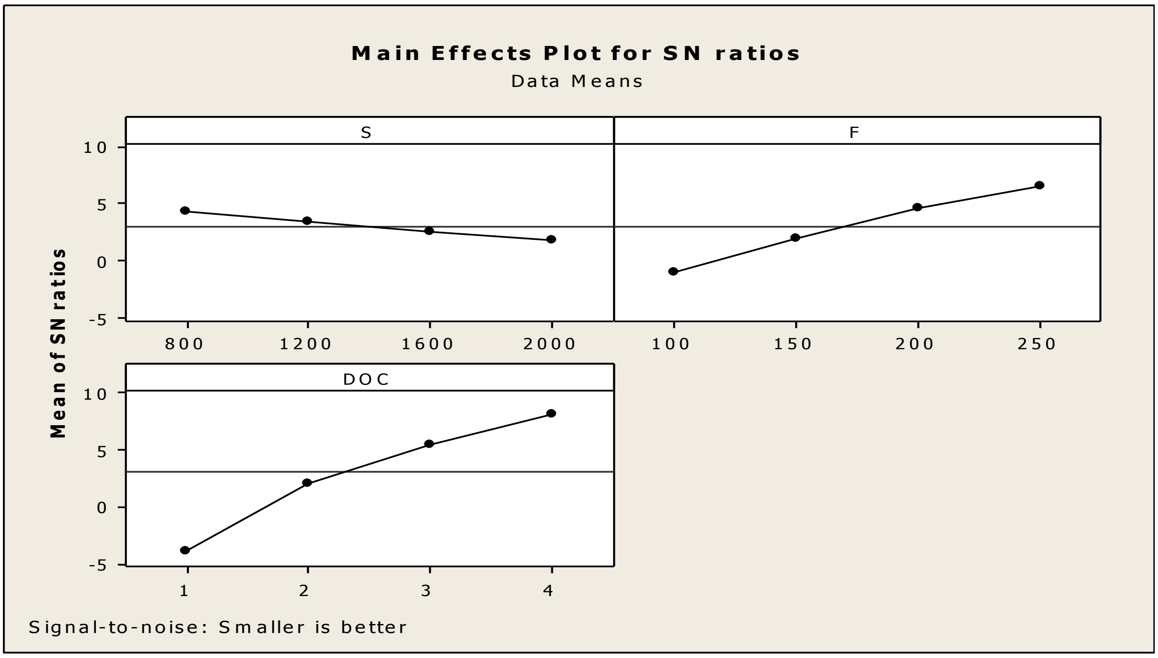


Fig. 6.2.1 Main effect plot for SEcut of sample M1 for tool Dia 10 mm

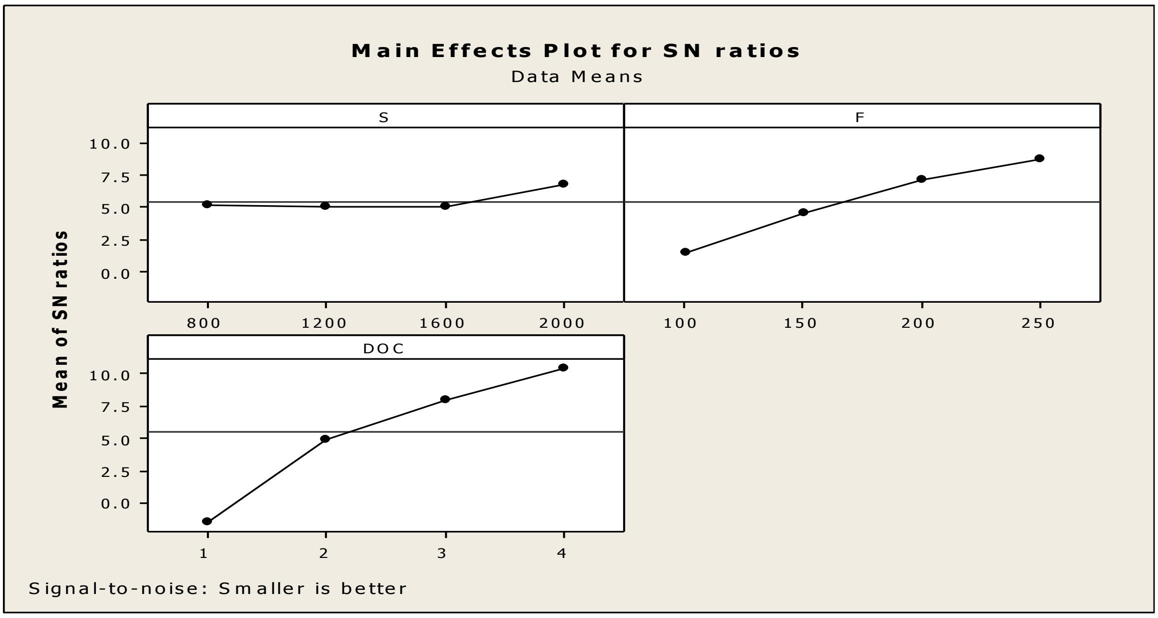


Fig. 6.2.2 Main effect plot for SEcut of sample M1 for tool Dia 12 mm

Table. 6.2.7 ANOVA results for SEcut of sample M1 for tool Dia 10 mm

Source	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F Value	P Value
Model	3	3.872	1.2909	25.25	0.000
S	1	0.007	0.007	0.155	0.700
F	1	0.999	0.999	19.54	0.000
DOC	1	2.865	2.865	56.070	0.000
Residual error	12	0.6133	0.0511		
Total	15	4.4863			
PRESS = 1.266	R^2 = 86.33, Adjusted R^2 = 82.91, Predicted R^2 = 71.77				

Table. 6.2.8 ANOVA results for SEcut of sample M1 for tool Dia 12 mm

Source	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F Value	P Value
Model	3	2.907	0.969	20.535	0.00
S	1	0.239	0.239	5.064	0.044
F	1	0.765	0.765	16.210	0.001
DOC	1	1.903	1.903	40.332	0.000
Residual error	12	0.566	0.047		
Total	15	3.473			
PRESS = 1.143	R^2 = 83.70, Adjusted R^2 = 79.62, Predicted R^2 = 67.09				

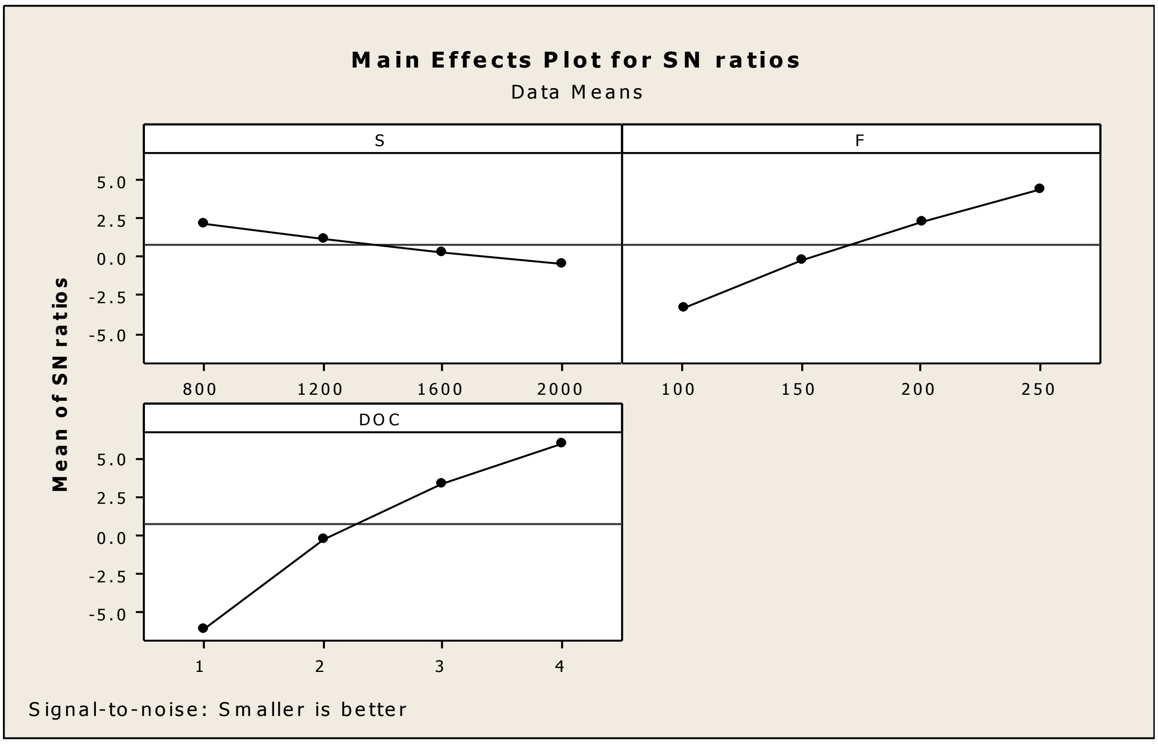


Fig. 6.2.3 Main effect plot for SEcut of sample M2 for tool Dia 10 mm

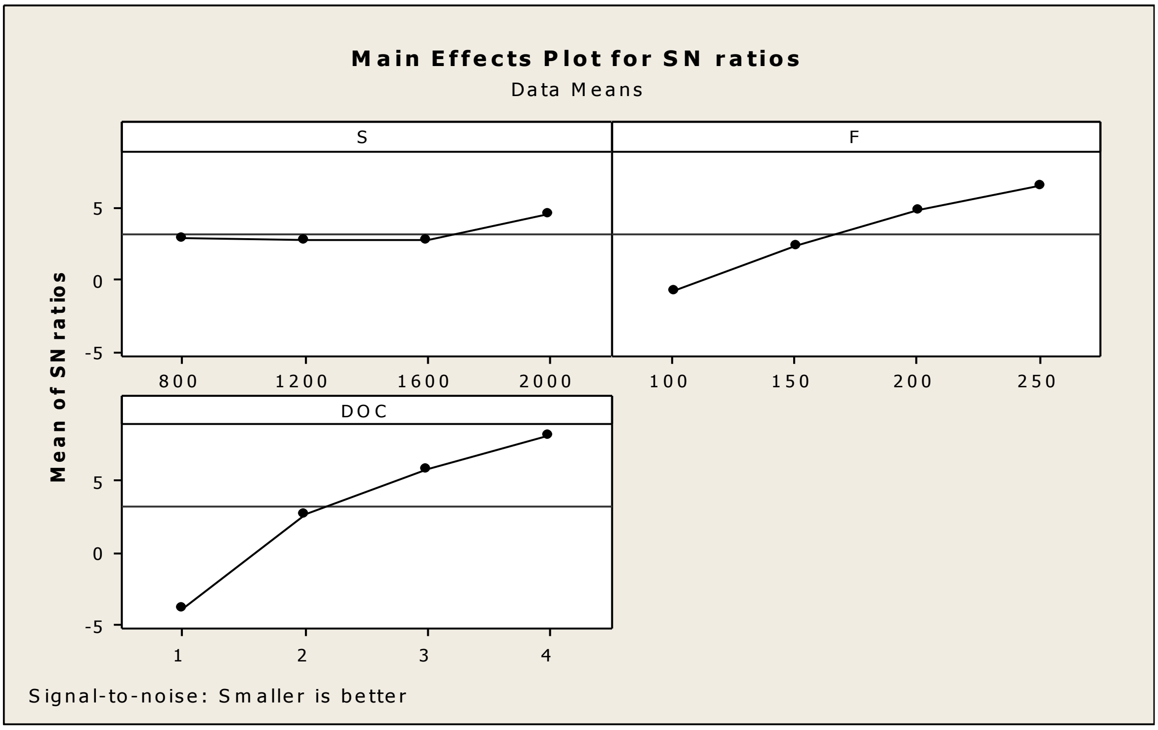


Fig. 6.2.4 Main effect plot for SEcut of sample M2 for tool Dia 12 mm

Table. 6.2.9 ANOVA results for SEcut of sample M2 for tool Dia 10 mm

Source	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F Value	P Value
Model	3	6.550	2.183	25.284	0.00
S	1	0.013	0.013	0.159	0.696
F	1	1.688	1.688	19.550	0.000
DOC	1	4.847	4.847	56.140	0.000
Residual error	12	1.036	0.086		
Total	15	7.586			
PRESS = 2.138	R^2 = 86.34, Adjusted R^2 = 82.93, Predicted R^2 = 71.81				

Table. 6.2.10 ANOVA results for SEcut of sample M2 for tool Dia 12 mm

Source	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F Value	P Value
Model	3	4.961	20.532	0.000	0.000
S	1	0.403	0.403	5.056	0.044
F	1	1.291	1.291	16.178	0.001
DOC	1	3.221	3.221	40.362	0.000
Residual error	12	0.957	0.079		
Total	15	5.874			
PRESS = 1.933	R^2 = 83.69, Adjusted R^2 = 79.62, Predicted R^2 = 67.08				

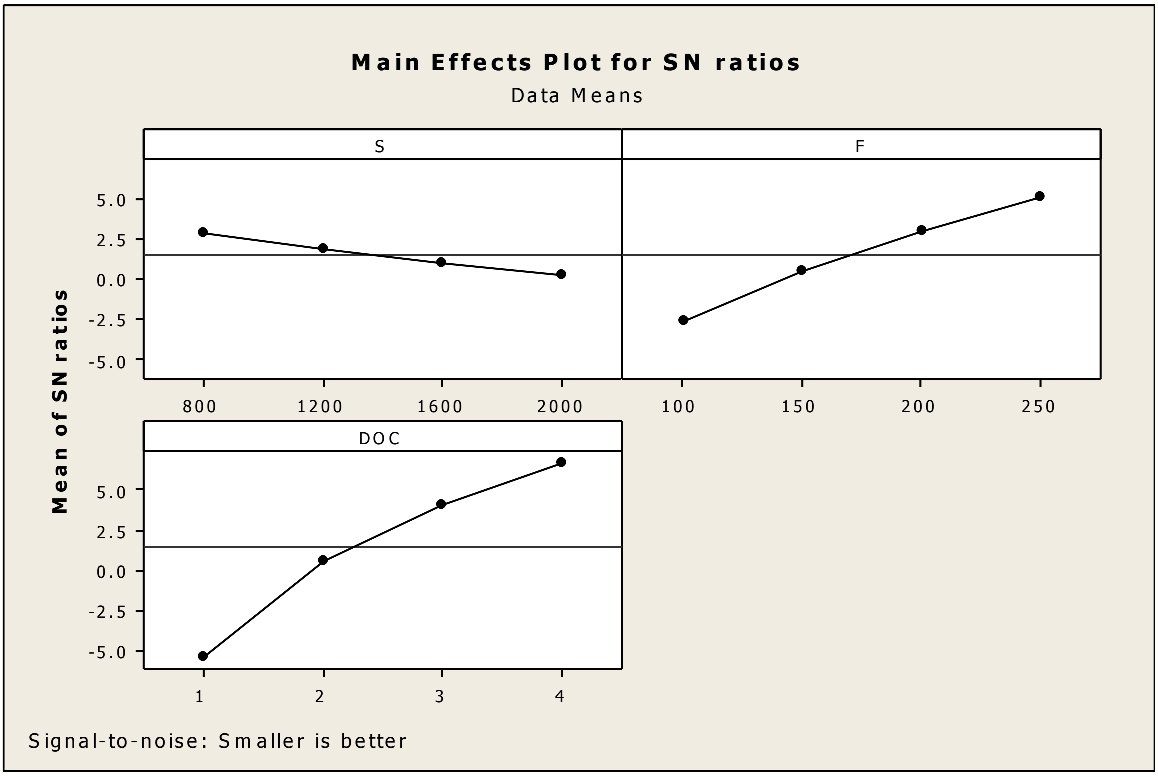


Fig. 6.2.5 Main effect plot for SEcut of sample M3 for tool Dia 10 mm

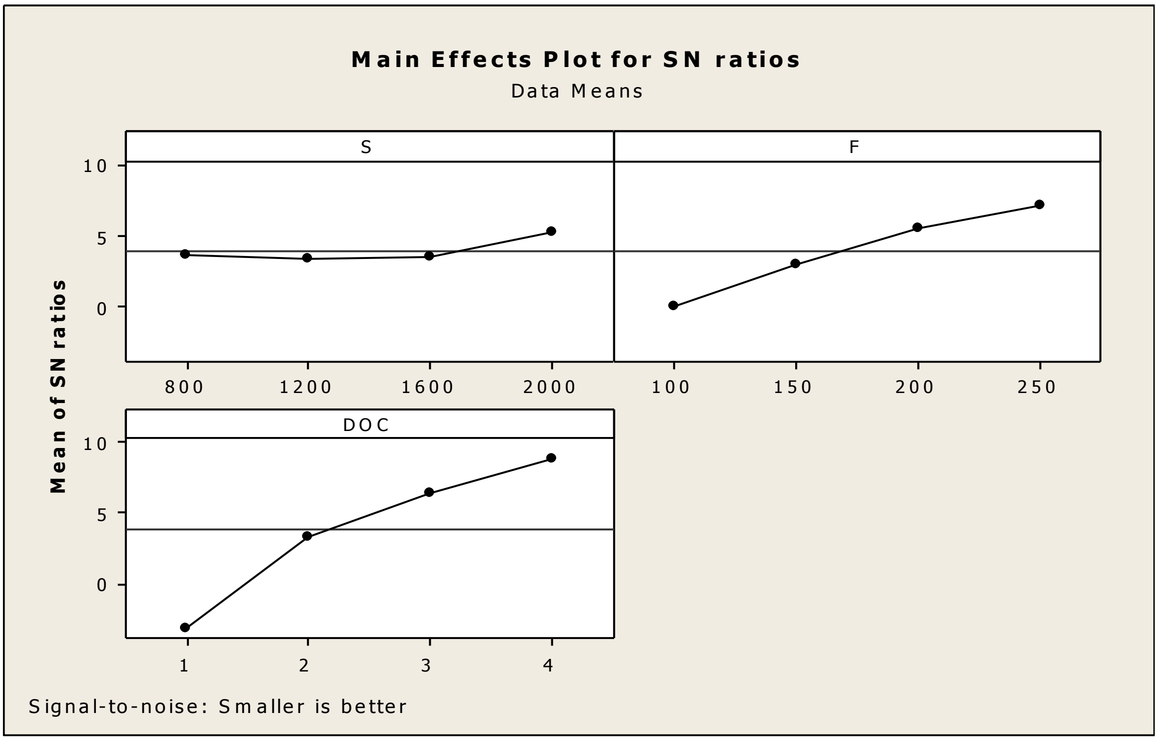


Fig. 6.2.6 Main effect plot for SEcut of sample M3 for tool Dia 12 mm

Table. 6.2.11 ANOVA results for SEcut of sample M3 for tool Dia 10 mm

Source	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F Value	P Value
Model	3	5.577	1.859	25.179	0.000
S	1	0.011	0.011	0.149	0.705
F	1	1.434	1.434	19.420	0.000
DOC	1	4.132	4.132	55.967	0.000
Residual error	12	0.886	0.073		
Total	15	6.464			
PRESS = 1.830	R^2 = 86.29, Adjusted R^2 = 82.86, Predicted R^2 = 71.68				

Table. 6.2.12 ANOVA results for SEcut of sample M3 for tool Dia 12 mm

Source	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F Value	P Value
Model	3	4.187	1.395	20.603	0.000
S	1	0.345	0.345	5.099	0.043
F	1	1.098	1.098	16.216	0.001
DOC	1	2.743	2.743	40.495	0.000
Residual error	12	0.812	0.067		
Total	15	5.000			
PRESS = 1.643	R^2 = 83.74, Adjusted R^2 = 79.68, Predicted R^2 = 67.14				

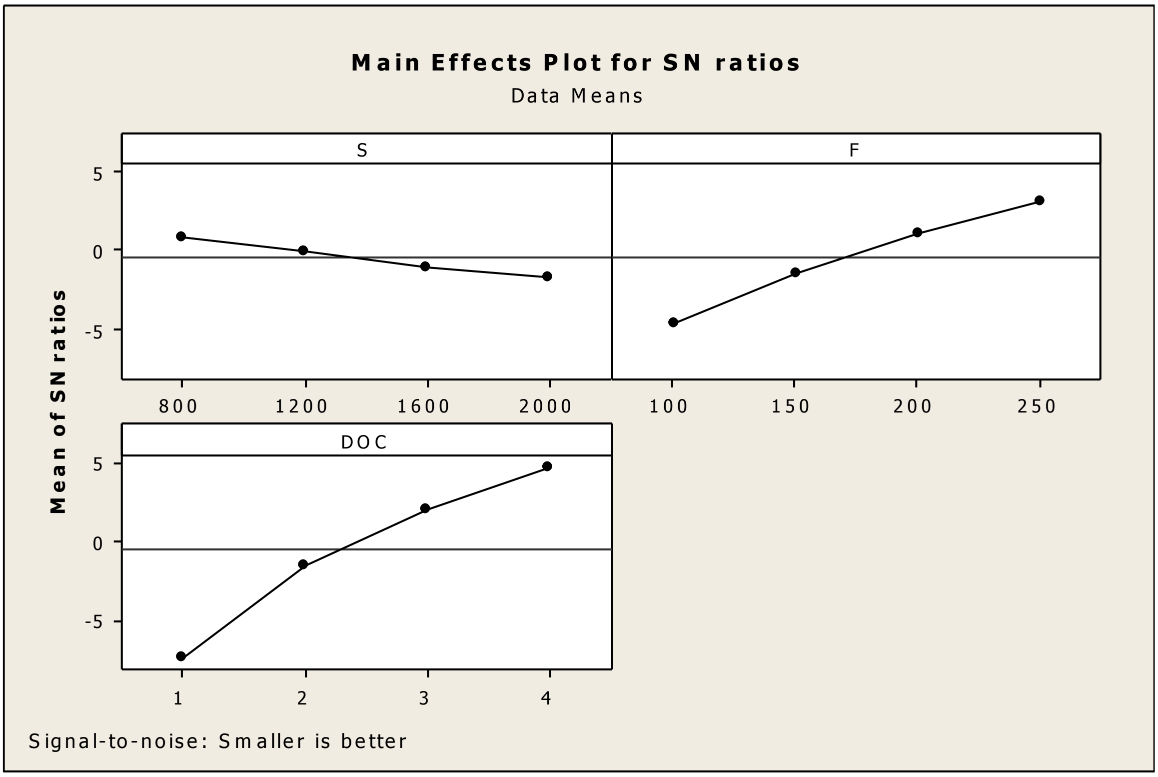


Fig. 6.2.7 Main effect plot for SEcut of sample M4 for tool Dia 10 mm

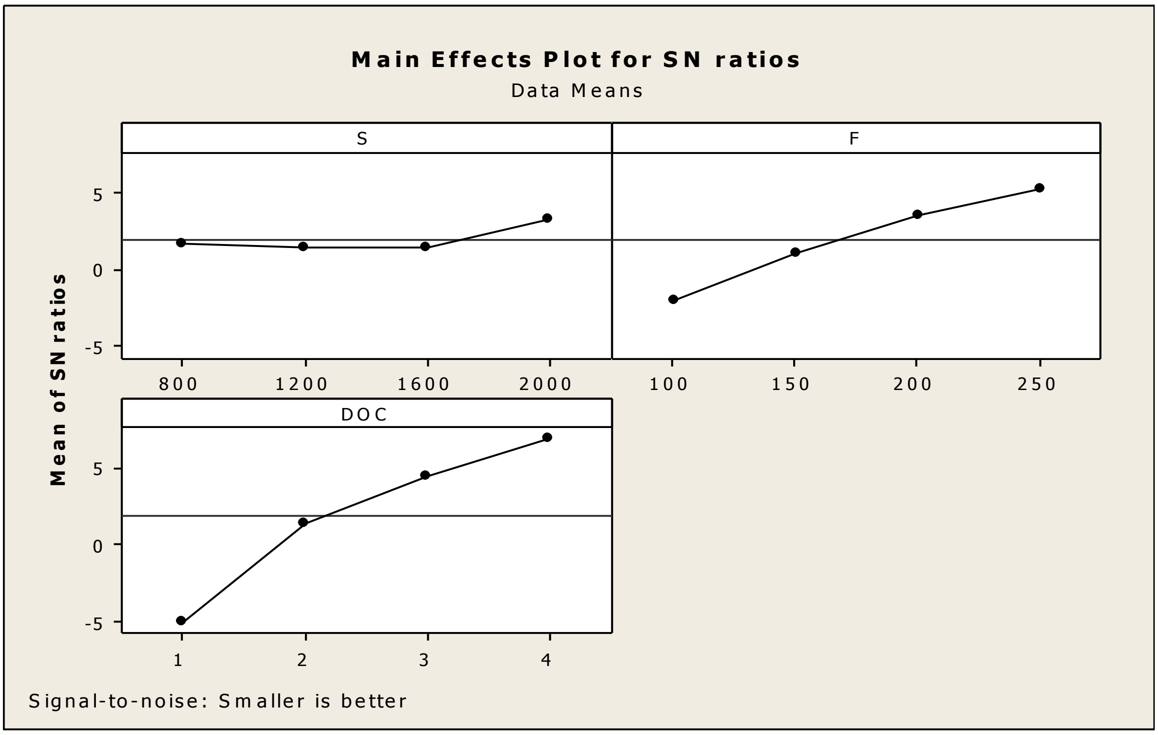


Fig. 6.2.8 Main effect plot for SEcut of sample M4 for tool Dia 12 mm

Table. 6.2.13 ANOVA results for SEcut of sample M4 for tool Dia 10 mm

Source	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F Value	P Value
Model	3	8.711	2.903	25.356	0.000
S	1	0.018	0.018	0.158	0.697
F	1	2.243	2.243	19.594	0.000
DOC	1	6.449	6.449	56.316	0.000
Residual error	12	1.374	0.114		
Total	15	10.085			
PRESS = 2.836	R^2 = 86.37, Adjusted R^2 = 82.97, Predicted R^2 = 71.87				

Table. 6.2.14 ANOVA results for SEcut of sample M4 for tool Dia 12 mm

Source	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F Value	P Value
Model	3	6.543	2.181	20.588	0.000
S	1	0.540	0.540	5.105	0.043
F	1	1.720	1.720	16.240	0.001
DOC	1	4.281	4.281	40.418	0.000
Residual error	12	1.271	0.105		
Total	15	7.814			
PRESS = 2.566	R^2 = 83.73, Adjusted R^2 = 79.67, Predicted R^2 = 67.15				

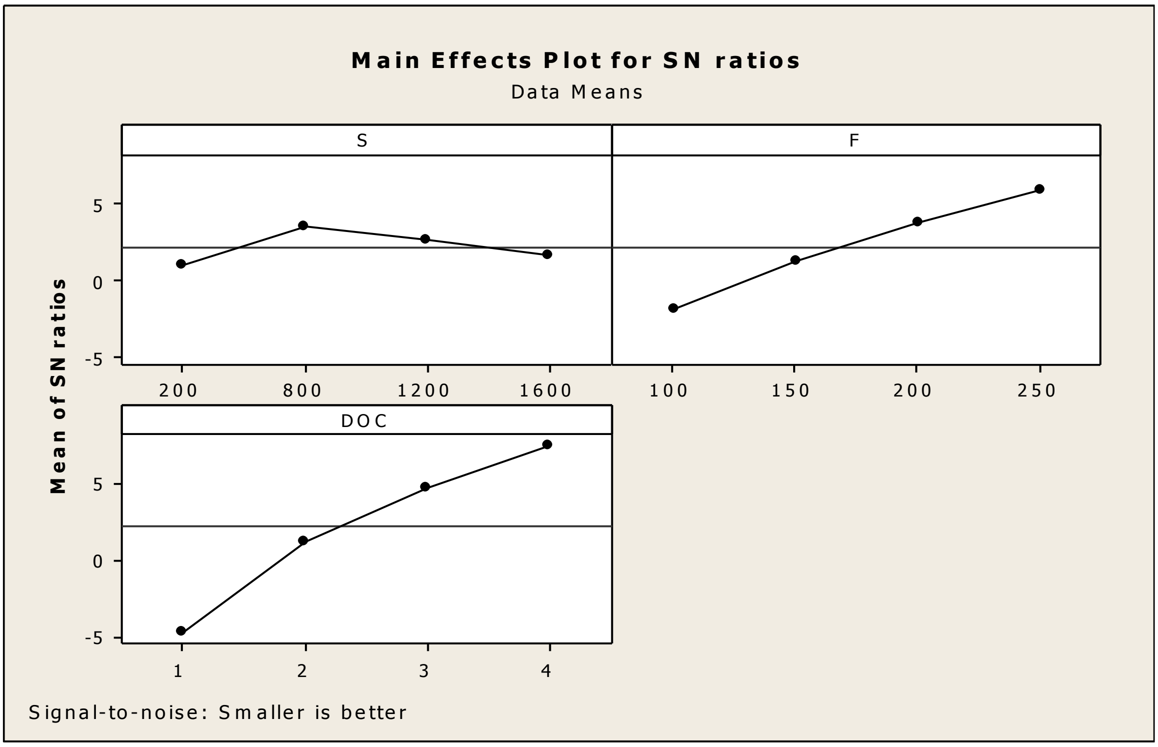


Fig. 6.2.9 Main effect plot for SEcut of sample M5 for tool Dia 10 mm

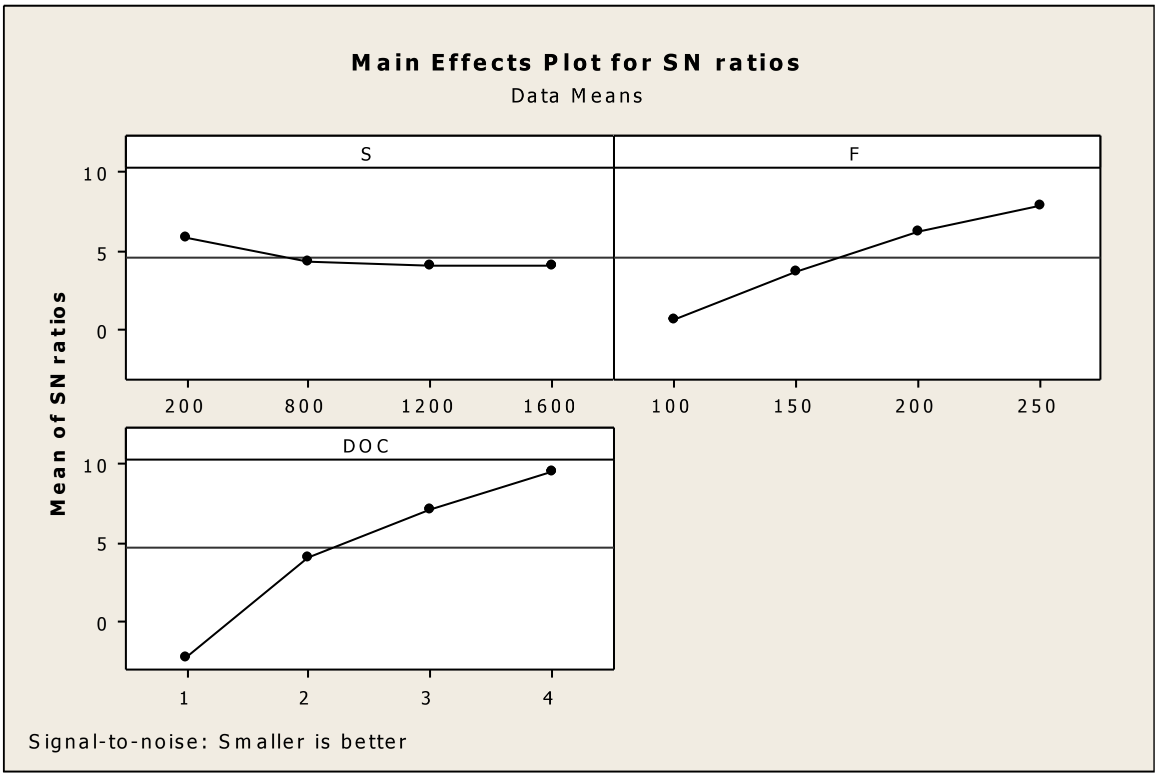


Fig. 6.2.10 Main effect plot for SEcut of sample M5 for tool Dia 12 mm

Table. 6.2.15 ANOVA results for SEcut of sample M5 for tool Dia 10 mm

Source	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F Value	P Value
Model	3	4.674	1.558	24.871	0.000
S	1	0.000	0.000	0.001	0.968
F	1	1.205	1.205	19.239	0.000
DOC	1	3.469	3.469	55.374	0.000
Residual error	12	0.751	0.062		
Total	15	5.426			
PRESS = 1.281	R^2 = 86.15, Adjusted R^2 = 82.68, Predicted R^2 = 76.38				

Table. 6.2.16 ANOVA results for SEcut of sample M5 for tool Dia 12 mm

Source	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F Value	P Value
Model	3	3.276	1.092	14.142	0.000
S	1	0.047	0.047	0.620	0.446
F	1	0.925	0.925	11.982	0.004
DOC	1	2.303	2.303	29.823	0.000
Residual error	12	0.926	0.077		
Total	15	4.203			
PRESS = 1.716	R^2 = 77.95, Adjusted R^2 = 72.44, Predicted R^2 = 59.15				

Regression study is one of the extensively used, most common arithmetical tool since it delivers simple process for instituting a functional association between variables. It has broad applications in numerous subject areas. In the current study general regression is made use of to find the relation between the SE_{cut} with other variables like speed, feed and depth of cut. The equations obtained after the analysis is represented by equations given below for different samples using 10mm and 12 mm end mill cutters. This equation help in predicting the values of SE_{cut} in future.

Regression equations for sample M1

$$SE_{cut} = 2.63 - 0.000045\ S - 0.00443\ F - 0.376\ DOC \qquad (1)$$

$$SE_{cut} = 2.49 - 0.000273\ S - 0.00391\ F - 0.308\ DOC \qquad (2)$$

Regression equations for sample M2

$$SE_{cut} = 3.45078 - 6.5575e\text{-}005\ S - 0.005811\ F - 0.49234\ DOC \qquad (3)$$

$$SE_{cut} = 3.23865 - 0.000355125\ S - 0.005082\ F - 0.40135\ DOC \qquad (4)$$

Regression equations for sample M3

$$SE_{cut} = 3.18193 - 5.88125e\text{-}005\ S - 0.0053555\ F - 0.454575\ DOC \qquad (5)$$

$$SE_{cut} = 2.98993 - 0.000328563\ S - 0.0046875\ F - 0.370375\ DOC \qquad (6)$$

Regression equation for sample M4

$$SE_{cut} = 3.9803 - 7.525e\text{-}005\ S - 0.006699\ F - 0.56785\ DOC \quad (7)$$

$$SE_{cut} = 3.7385 - 0.000411125\ S - 0.005866\ F - 0.4627\ DOC \quad (8)$$

Regression equation for sample M5

$$SE_{cut} = 3.9803 - 7.525e\text{-}005\ S - 0.006699\ F - 0.56785\ DOC \quad (9)$$

$$SE_{cut} = 3.7385 - 0.000411125\ S - 0.005866\ F - 0.4627\ DOC \quad (10)$$

6.3 Force Measurement while performing end milling operation

Cutting force and specific energy both play a vital role while machinig marble stone. They are related to the cutting geometry and typical geometry of the cutting chip. Different chip geometries leads to different cutting behaviour. Energy consumption is a key factor to be reviewed in natural stone industry which directly influence the cost scrutiny and fabrication scheduling. Due to the escalation in the natural rock usage in many fields there is a tight struggle among the industrialists for revisions on optimizing the operational parameters. For this purpose, the milling factors of the stones to be sliced with CNC milling machine are vital in terms of observing the milling performance. Defining the key constraints for the physico-mechanical and mineralogical features of the stone to be milled shows a vital role in cost scrutiny, fabrication planning, merchandise excellence and choice of proper equipment for the stone to be milled.

Milling operations were performed on the samples using CNC milling machine having a maximum. Two end mill cutters of 10 and 12 mm diameter were used for the end milling operation which are coated with diamond as shown in the Fig.5.3.1 which consists of 4-flutes. Marble sample used for the experimentation is of 200mm x 150mm x 40mm dimension.

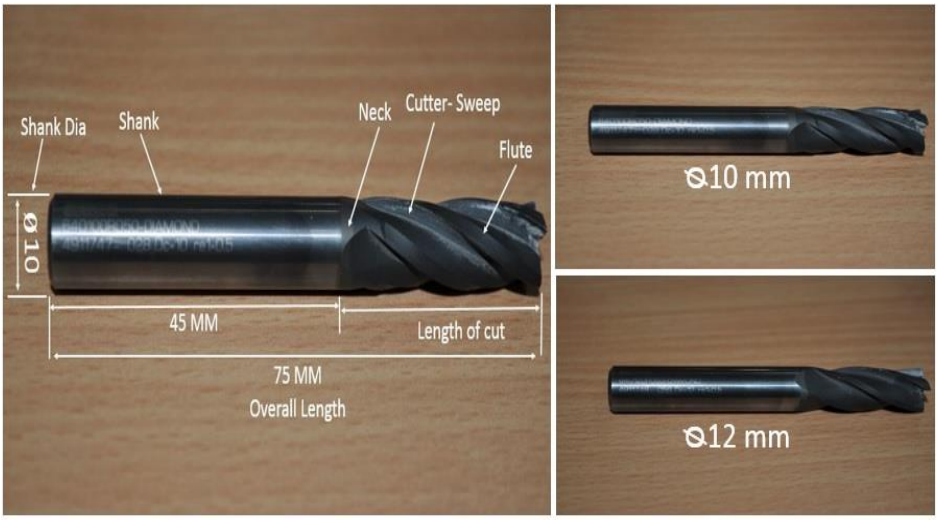


Fig.6.3.1 End mill cutters

Taguchi L16 orthogonal array is applied to calculate the different forces that are generated while milling the samples whose details are given in the Table. 6.3.1

Table.6.3.1 Various levels and factors applied for milling experiments

S.No	**Speed (RPM)**	**Feed (mm)**	**DOC (mm)**
1	800	100	1
2	800	150	2
3	800	200	3
4	800	250	4
5	1200	100	2
6	1200	150	1
7	1200	200	4
8	1200	250	3
9	1600	100	3
10	1600	150	4
11	1600	200	1
12	1600	250	2
13	2000	100	4
14	2000	150	3
15	2000	200	2
16	2000	250	1

A Kistler 9257B Type multi component dynamometer is used to measure the forces, this dynamometer consists of four three-component force sensors fitted under high preload between base plate and top plate. Each sensor contains three pairs of quartz plates. One sensitivity to pressure in Z direction and the other two responding to shear in the x and y directions respectively.

The outputs of the four built-in force sensors are connected inside the dynamometer in a way to allow multicomponent measurements of forces and moments to be performed. The eight output signals are available at the 9-conductor flange socket.

Various forces and their readings are displayed in the figures below, ANOVA analysis underlined that both feed rate and depth of cut significantly influence the force components, even the depth of cut seems to be the most significant variable. An increase of both the depth of cut and the feed, speed causes an increase of both force components.

Regression analysis of the experimental data was carried out to the constant values in (1) – (10) The R^2 values are between 85 – 95 %, while, the hypothesis (normality and homogeneity of variance) about the residuals were satisfied. Also, the cutting force components depend on the maximum thickness of chip removed. The obtained models are effective, simple and general. They represent a first step towards the optimization of the stone machining parameters.

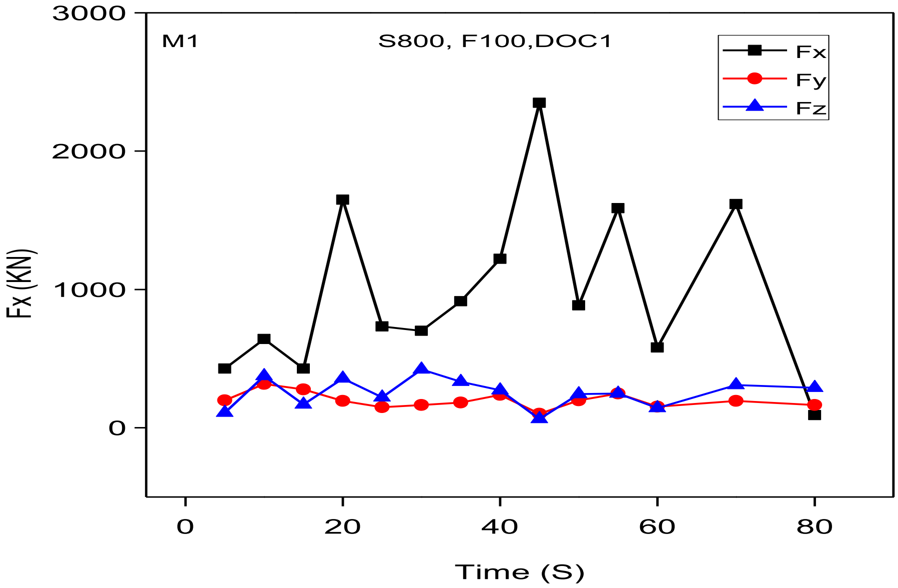


Fig. 6.3.2 Force Vs Time (S800,F100,DOC1)

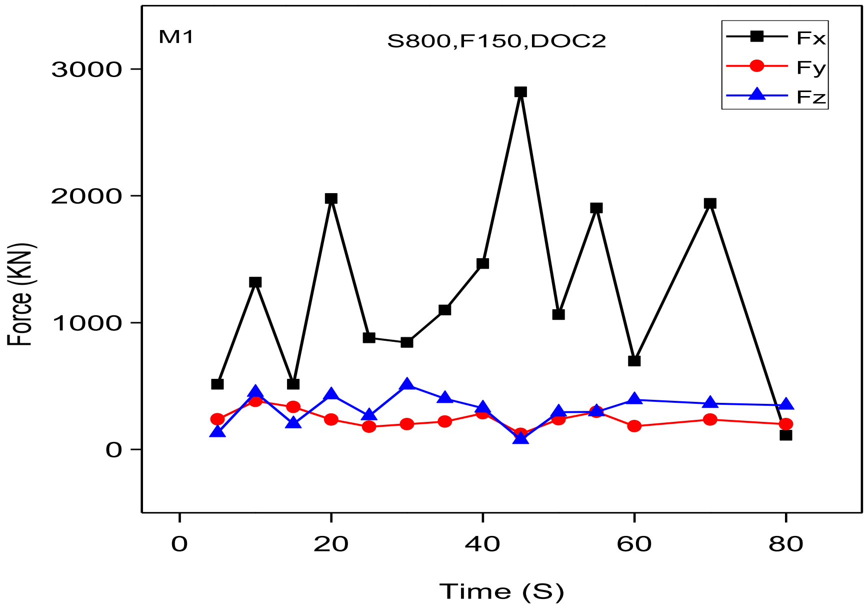


Fig. 6.3.3 Force Vs Time (S800,F150,DOC2)

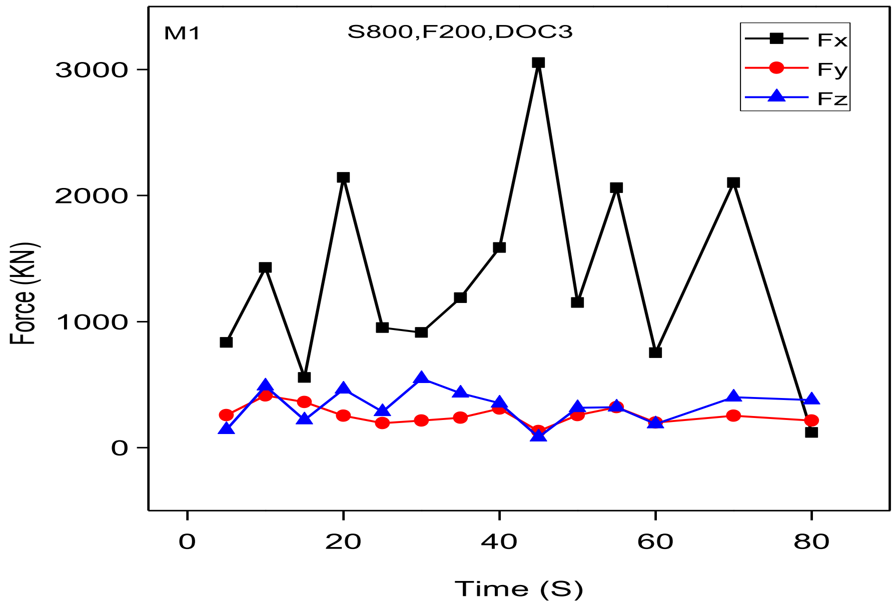


Fig. 6.3.4 Force Vs Time (S800,F200DOC3)

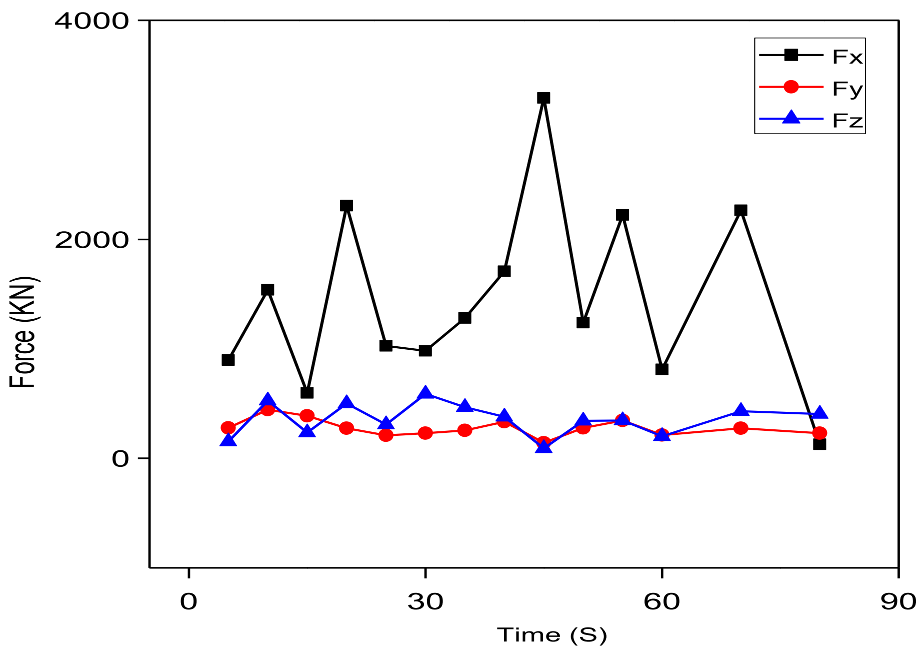


Fig. 6.3.5 Force Vs Time (S800,F250,DOC4)

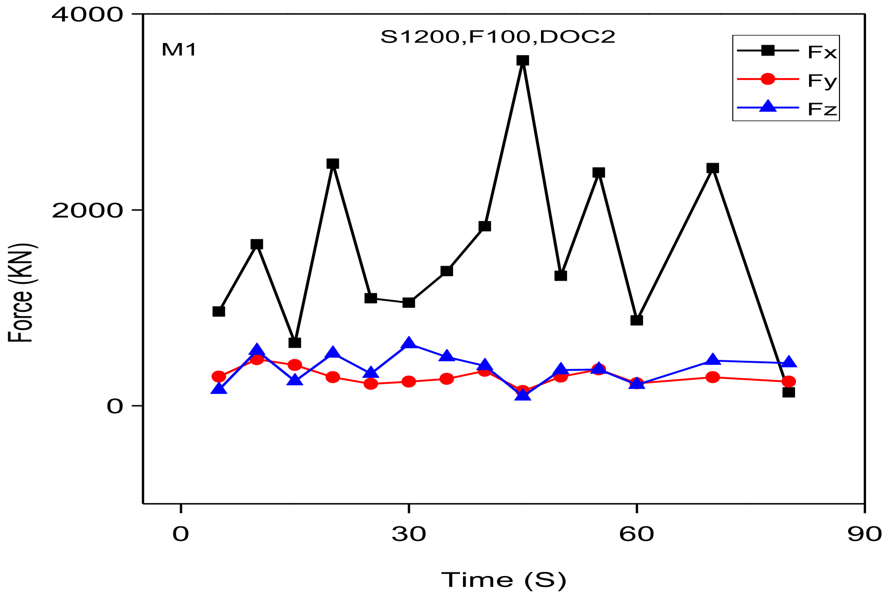


Fig. 6.3.6 Force Vs Time (S1200,F100,DOC2)

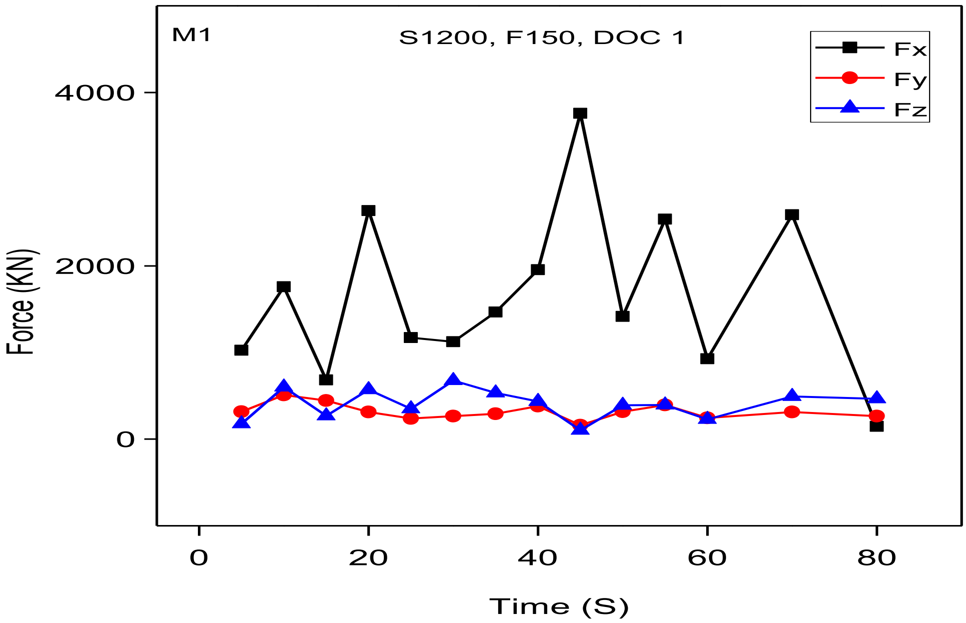


Fig. 6.3.7 Force Vs Time (S1200, F150, DOC1)

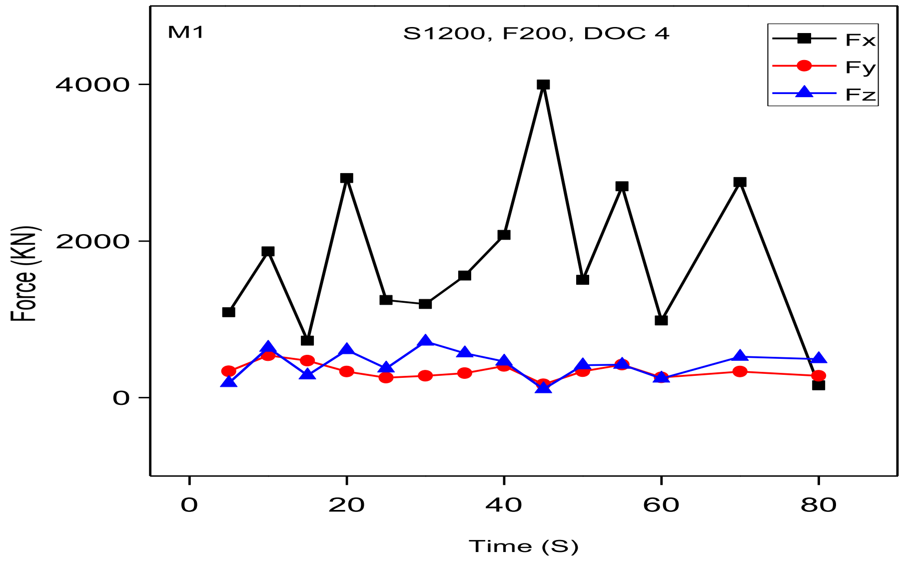


Fig. 6.3.8 Force Vs Time (S1200, F200,DOC4)

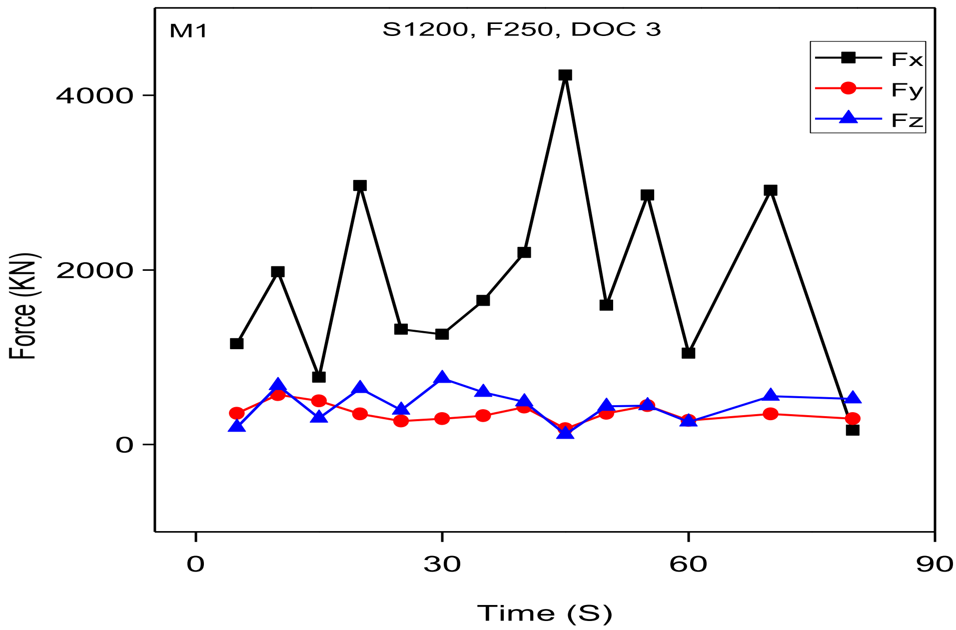


Fig. 6.3.9 Force Vs Time (S1200,F250,DOC3)

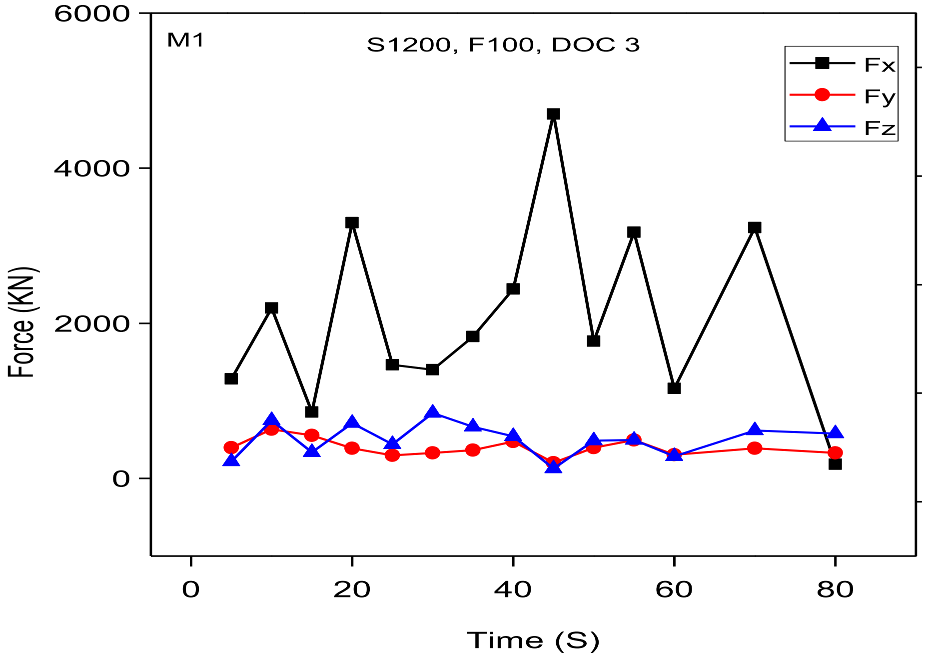


Fig. 6.3.10 Force Vs Time (S1200,F100,DOC3)

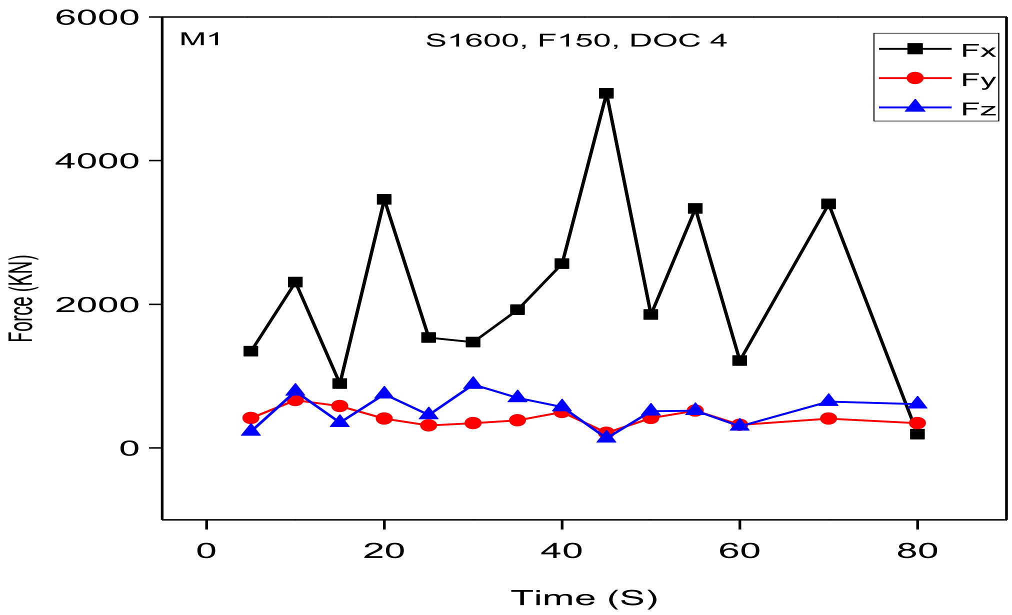


Fig.6.3.11 Force Vs Time (S1600,F150,DOC4)

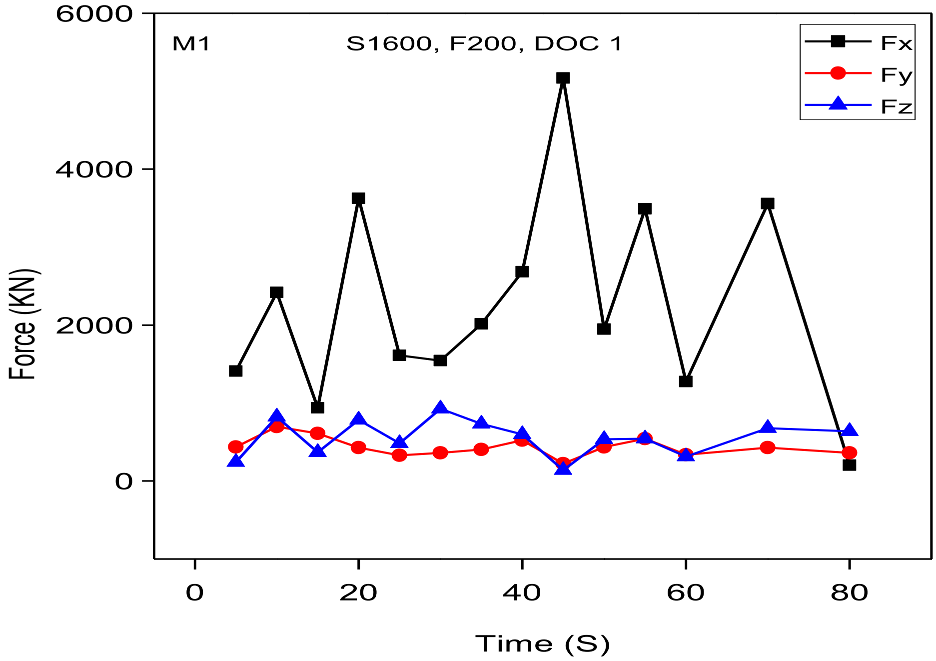


Fig. 6.3.12 Force Vs Time (S1600,F200,DOC1)

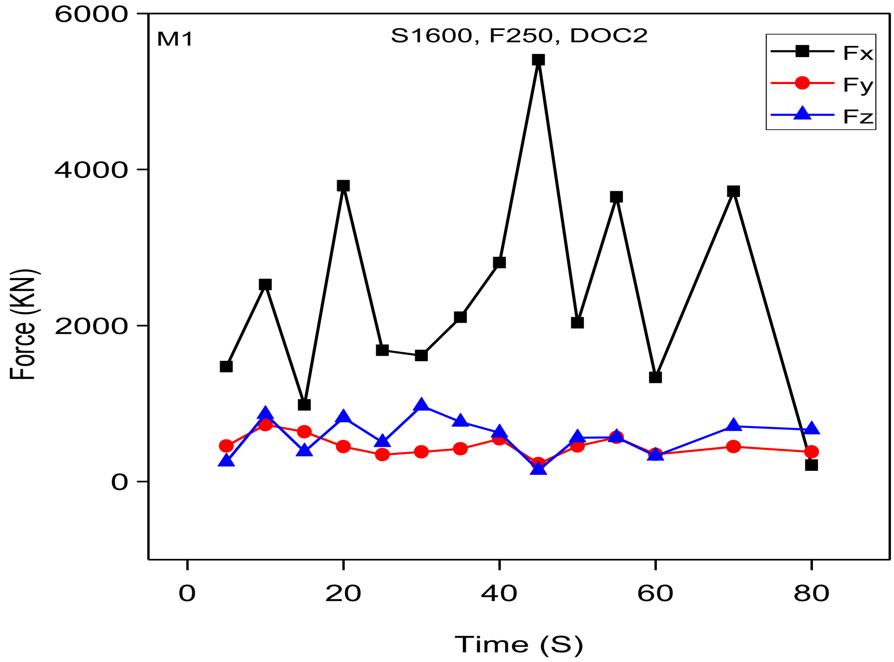


Fig. 6.3.13 Force Vs Time (S1600,F250,SOC2)

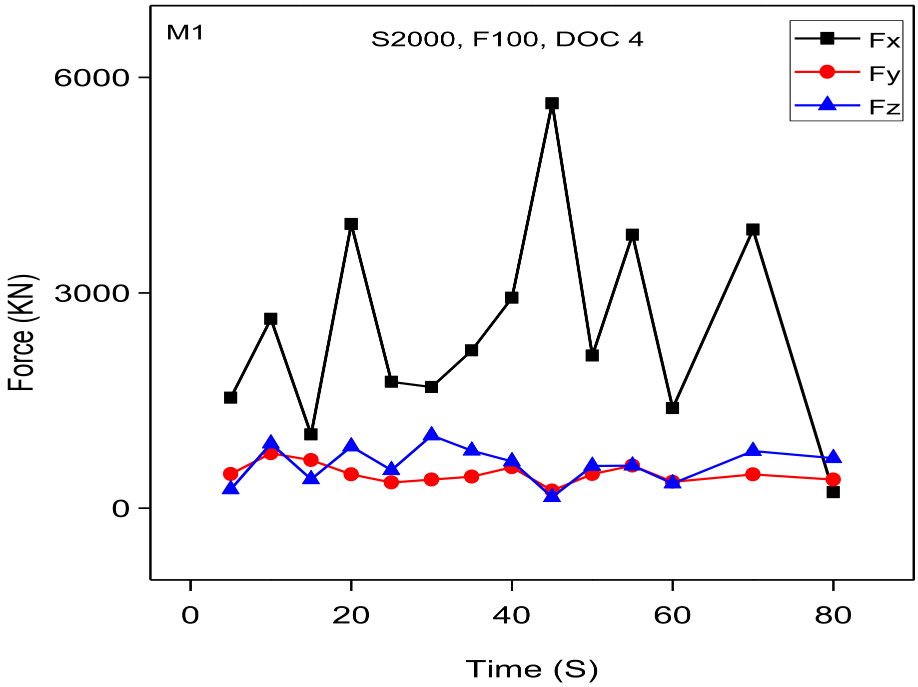


Fig. 6.3.14 Force Vs Time (S2000,F100,DOC4)

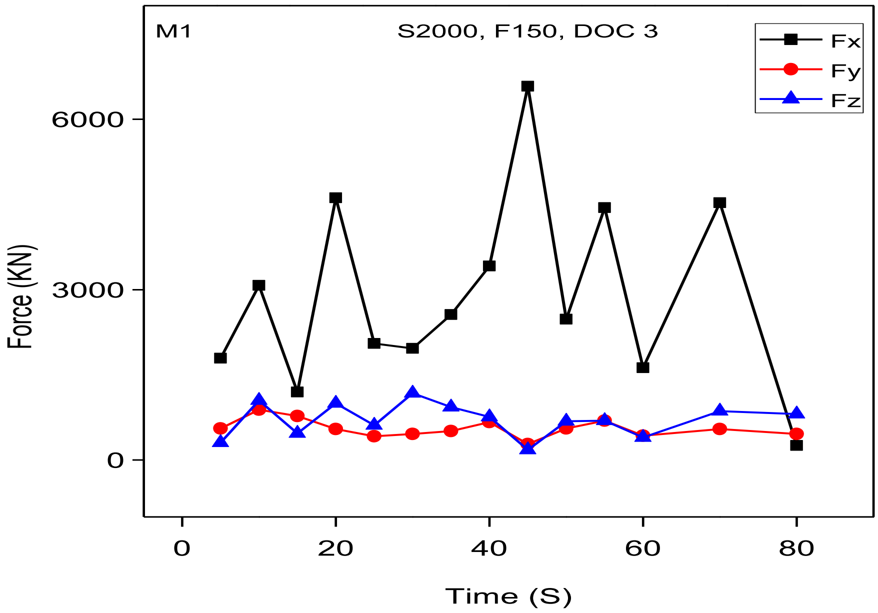


Fig. 6.3.15 Force Vs Time (S2000,F150,DOC3)

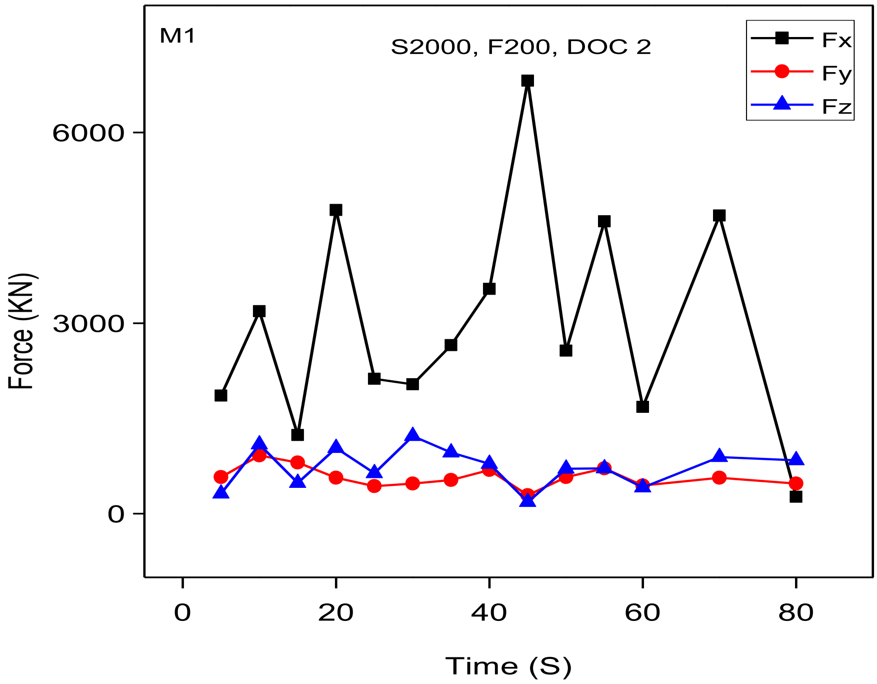


Fig. 6.3.16 Force Vs Time (S2000,F200,DOC2)

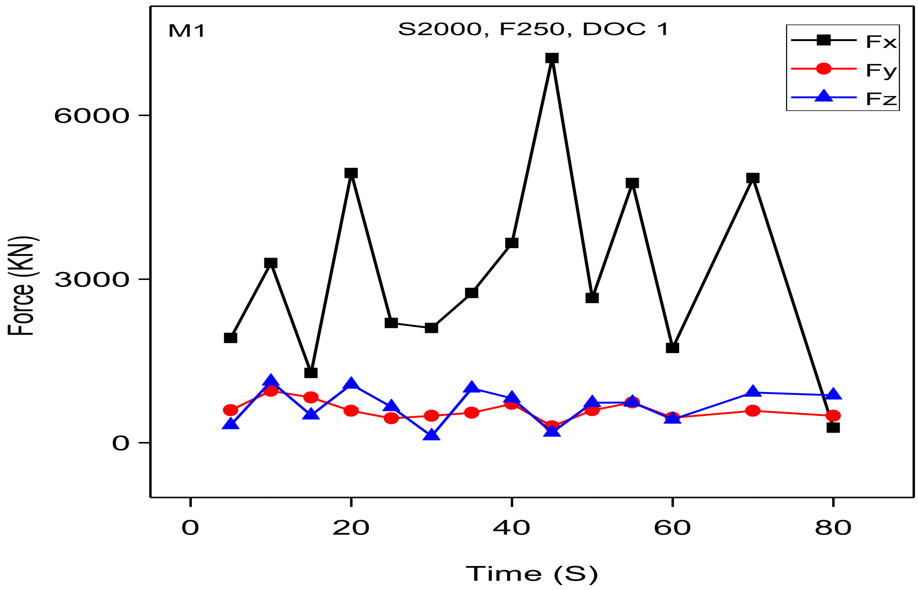


Fig.6.3.17 Force Vs Time (S2000,F250,DOC1)

Chapter 7: Conclusions and suggestions for future work

7.1 Sustainability and life cycle energy assessment

To find out some chances and possibilities for development of this industry, the life cycle analysis of the extraction of marble is done from quarrying to the processing stage, the conclusion drawn is listed below. A case study is conducted in the industry to find out the different tools/inserts used by the SME's to cut the marble, and these inserts were characterized to find out the composition of tool.

Marble extraction process begins from quarry, where rocks are extracted from rock mountains. This extracted rocks are supplied to the construction industries through three stages. At first stage extracted rocks are transported to cutting (factories and workshops) to be sliced and turned into required dimensions to suit construction and building applications. At second stage, these rocks from cutting factories are sent to polishing processing units where required polishing is done. At final stage the remaining small pieces of stones which cannot be used for construction and building are transported to crushers where they are further crushed into aggregates of different sizes, to be directly used as raw material in concrete mixtures. Dried stone powder from polishing and processing's units can be utilized at construction site. The remaining waste from buildings can re-sized and returned back to quarries to fill the excavation site in order to reclaim the land and improve the landscape of the site. After demolishing the built houses for many reasons, stones from it can be re-used by returning back to the cutting and polishing process before being used as re-build again. The lifecycle of marble extraction has been completely designed in the form in order to facilitate a better understanding of the whole process. The stone can be considered as a sustainable material throughout the processes, since it goes through the cycle back and forth as shown in the flow chart. The marble stone industry of Rajasthan has extremely high percentage of waste generation like solid marble waste, powder and slurry which are the major sources for environmental degradation where marble quarries and processing's are located. Later, the life cycle analysis of the processing industry is done to find the energy consumption at each stage of the process, according to ISO 14040. The following conclusions can be drawn.

1. The FESEM and EDM analysis of the collected five tools revealed that they have different composition. Tool A is made of (40.98 % of Fe, 7.03% of Co,

6.82% of Si, 13.82% of Ni, 4.29% of Ca and 8.08 % of C), Tool B is made of (3.19% of Fe, 33.05% of Co, 7.35% of Si, 0.03% of Ni, 49.67% of Ca and 6.71% of C), Tool C is made of (1.34% of Fe, 54.22% of Co, 0.86% of Si, 1.01% of Ca and 8.70% of C), Tool D is made of (25.74% of Fe, 23.12% of Co, 1.13% of Si, 0.70% of Ni, 3.46% of Ca and 8.37% of C) , Tool E is made of (13.41% of Fe, 8.71% of Si, 0.89% of Ca and 18.87% of C).

2. If the hardness of the marble is high tungsten carbide is used with cobalt, iron , nickel and copper. Cobalt can be used as a replacement of iron powder in the metal matrix.
3. FESEM test revealed that most of the industries use natural diamond in their tools. But, instead of natural diamond synthetic diamond can also be used as a replacement to satisfy virtually any specific requirements. By using either cobalt-base alloy or nickel-based alloy with synthetic diamond crystals, varied range of properties can be obtained from tool bits.
4. In addition to the internal structure, the particle shape and size will also affect the crystal breakdown characteristics. Diamonds that have smooth faces and a perfectly cubo-octahedral shape are stronger than irregular crystals.

The sustainability study done for the stone extraction process clearly explains how sustainability can be achieved by considering the Environmental Sustainability Index. This sector has a major contribution to country's economy but requires major improvements in technologies, methods that are being currently used including adapting new technologies. Different cutters that are used currently in Rajasthan explained with neat sketches. Full energy audit is done for the industries to calculate the energy consumption. A detailed layout of marble block processing to final slab production is explained with neat sketches. While processing these blocks to slabs, tons of marble slurry is generated whose disposal is a great problem faced throughout the world.

Finally, the life cycle energy assessment was done to the slab and tile processing unit to find out the energy required for processing a unit slab or tile was calculated, and some of the conclusions are drawn by LCEA

1. Transportation of the block from quarrying to the processing plant required an energy of 166kWh/block
2. The cutting of the block to slab and tile required an energy prerequisite of about 906.41 Kwh/block

3. To perform finishing operation for the whole block it required an energy of 212 Kwh/block.
4. When we look into the whole processing plant in three stages like transportation, cutting and finishing, the energy requirement for cutting is 70.56% , 16.51% for finishing and finally for transportation and energy of 12.92% was required.

Instead of using the electricity as energy source for each process if a total shift of energy is done to solar energy instead of electricity a large amount of pollutants can be reduced releasing to the atmosphere. Hence, increasing the sustainability of the whole processing plant.

7.2 Characterization and grading of marble stones

Natural stones can be classified according to their mineral content and the process of formation. Most of these minerals can be identified by their color, hardness, and crystal structure. However a wide range of crystals are difficult to identify. Good marble stones are characterized by durability, hardness, strength, amenability to dressing, appearance, weight, grain size, compactness, porosity and absorption.

One of the important tests for identifying specimens is the Mohs Hardness Test. This test compares the resistance of a mineral to being scratched by ten different reference minerals known as the Mohs Hardness Scale which is explained in detail in the chapter 4, their grading according to the Mohs Hardness is given as

1. Makarana marble which is white in appearance and has a hardness value of 42 (HRC), the nature of the stone is hard and compact and made of fine grains. Hence, it is classified as Grade C marble with MOH number 2.5, having mild softer texture.
2. Bhainslana marble which is dark gray in appearance has a hardness value of 48 (HRC), the nature of the stone is hard and compact and made of fine grained. Hence, it is classified as Grade A (Altered ultrafamic serpentinite) with MOH value of 3,having moderate texture.
3. Andhi marble which is white in appearance has a hardness value of 42 (HRC), the nature of the stone is hard and compact and made of fine grained. Hence, it is classified as Grade C marble with MOH value of 2.5, having mild softer texture.

4. Sea green which is dark green in appearance has a hardness value of 45 (HRC), the nature of the stone is very hard and compact and made of very fine grains. Hence, it is classified as Grade B Quartzite marble stone with MOH value of 4 having harder texture compare to all other samples.
5. Agaria which is white in appearance has a hardness value of 43 (HRC), the nature of the stone is hard and compact and made of fine grains. Hence, it is classified as Grade C marble with MOH value of 2.5, having mild softer texture.

There are 4 classifications of marbles. Class A, being the most resistant to breakage and having the least amount of natural inclusions, veins, and inconstancies. Class B, Class C, and finally Class D, which is the most likely to break because of the above reasons. Normally, the class A materials are more consistent looking while the Class D marbles are more ornate. Class A marbles would usually be harder and more dense, while Class D marbles would be softer and more porous.

Chemical analysis of the sample revealed various minerals that are present in the samples, M1 has (1.36 % of SiO_2, 51.58% of CaO (Lime), 0.20% of MgO (Priclase), traces of (Al_2O_3, Fe_2O_3), M2 has (9.12% of SiO_2, 47.74% of CaO (Lime), 0.7% of MgO (Priclase), 1.99% of Fe_2O_3 and traces of Al_2O_3. M3 has (3.17% of SiO_2, 43.89% of CaO (Lime), 8.91% of MgO (Priclase), 0.3% Fe_2O_3 and traces of Al_2O_3. M4 has (traces of SiO_2, 47% of CaO (Lime), 16% of MgO (Priclase), traces of Fe_2O_3 and Al_2O_3 and M5 has (0.01% of SiO_2, 43% of CaO (Lime), 1% of MgO (Priclase), traces of Fe_2O_3 and Al_2O_3.

Thin section analysis of Marble stones (petrographic analysis)

The petrographic analysis revealed the following information about the marble stones which were characterized.

1. M1:- It is a white stone having a nature of hard and compact essentially composed of dolomite and calcite. A medium to fine grained termolite marble with strong post crystalline deformation at low temperature conditions than 200 degree celcius. Therefore, the strong interlocking grains show clearly bent twin lamellae. The irregularly distributed brown haze of the grain structure suggests an incipient weathering out (Fe-hydroxide). Amphibole (actinolite-tremolite) occurs as accessory. Dolamite/calcite shows rhombohedral cleavage,

polysynthetic twinning occurs as polygonal grains. The rock is medium to coarse grained and shows granoblastic texture

2. M2:- It is a dark grey having a nature hard and compact essentially composed of calcite. A fine grained calcite marble with strong foliation and accordingly flattered calcite grains. The calcite grains show internal pressure twin lamellae. From this it can be deduced that weak deformation followed after completion of the calcite recrystallization. Tourmaline, opaque and amphibole (termolite-actinolite) is present as accessory. Calcite grains shows a perfect rhomboheral cleavage and polysynthetic twinning at places. Fine dust of opaque minerals is distributed over the carbonates.
3. M3:- It is a white marble having a nature of fine grained termolite-dolamite marble with polygonal dolomite aggregates. The euhedral termolite are porphyroblast a primary component of the rock. Twin lamellae indicate a weak post crystalline deformation. The metamorphic grade corresponds to amphibolite facies conditions. The nature of the stone is hard and compact essentially of calcite. Amphibole (actinolite-tremolite) occurs as accessory. Calcite shows rhombohedral cleavage, polysynthetic twinning and occurs as polygonal grains.
4. M4:- It is a dark green marble having a nature of fine grained mixture of antigorite and carbonate with dendric grain shapes, calcite is a secondary product of the replacement offer antigorite. Calcite in connection with antigorite is not stable under greenschist facies to amphibolite facies conditions. The nature of the stone is hard and compact essentially of antigorite and lizardite. Opaque and amphibole are present as accessory. Secondary calcite veins are common as criss-cross veins, asbestos veins is also observed. The rock is fine grained with plenty of antigorite. The rock shows mesh texture. The sample on evaluation is identified as altered ultramafic (serpentinite)
5. M5:- It is a white marble, having a nature of fine grained calcite-dolamite marble with polygonal to slightly interlocked grain structure. Twin lamellae indicate weak deformation after completion of the crystallization of calcite and dolomite. The nature of the stone is hard and compact essentially composed of dolomite and calcite, amphibole (actinolite-tremolite) occurs as accessory. Dolamite/calcite shows rhombohedral cleavage, polysynthetic twinning occurs

as polygonal grains. The rock is medium to coarse grained and shows granoblastic texture

Thermo-gravimetric analysis

M1:- the peak temperature is 826.84^{0}C and the weight loss regisered is (-4.68) %, M2:- the peak tmeperature is 834.43^{0}C and the weight loss registered is (-4.19) %. M3:- the peak temperature is 824.80^{0}C and the weight loss registered is (-4.30) %. M4:- the peak temperature is 739.13^{0}C and the weight loss registered is (-1.67)%. M5:- the peak temperature is 810.41^{0}C and weight loss is registered is (-4.69)%.

7.2.1 Abrasion resistance and their correlation

Abrasion is an important phenomenon to know the mechanical erosion of rocks which occurs due to the different elements that are in constant contact with the surface of the rock. Abrasion leads to decrease in mechanical and aesthetical properties. Typical abrasion testing was performed on three different marbles (M1, M2 and M3) using varying loads and sliding speeds according to European standard EN 14157.

When the marble stones are used as internal and outdoor flooring applications in bus-stations, railway stations, airports, cinema malls and supermarkets the abrasive wear mechanism resulting from foot traffics is considered to be a three-body wear and tear mechanism. The wide wheel abrasion (WWA) is most widely used standard simulating test to check the suitability of marble stones in such vast applications. In spite of WWA being widely used inspection test no comprehensive report concerning the varying applied load and sliding speed was reported or published. In present study, abrasion wear results of 48-samples were analysed under varying applied loads ranging from 40N to 140N, and sliding speed ranging from 15 RPM to 75 RPM keeping other operational parameters constant. For the test following conclusions can be drawn.

1. Abrasion wear rates of all marbles increased with the applied load. However this increase in abrasion wear rate was not same for all marbles. The increase in abrasion wear rate with the increasing load was sharper in M2, followed by M3 and M1 marbles. The M1 was less sensitive to increasing loads than other two marbles due to its high mechanical strength.
2. Abrasion wear of all marbles increased initially with the sliding speed and then decreased. With the increased speed, abrasive grits failed to entrain (penetrate)

into the wear contact and just flow around the sides. This resulted in less number of abrasive grits in the wear contact which ultimately lead to the decrease in the wear of the marble specimen.

3. High correlations exist between the applied load and abrasion wear as well as between the sliding speed and the abrasion wear
4. The results of the experimental findings also indicated that, in some cases, changes in the applied load and sliding speed could be an influencing factor in the ranking of marbles with respect to abrasion wear rate
5. According to EN standard, the testing on wide wheel abrasion apparatus is done at fixed load and 75RPM. But from the results, it can be concluded that 40 to 45 RPM will provide better abrasion wear results at fixed load for marbles. However the results may be different for other natural stones like granites.

7.2.2 Abrasion wear characterization of marble stones subjected to foot traffic

Abrasion resistance is a property of a marble which gives an indication of the marble wearing quality when it is exposed to foot traffic. This property is tested according to ASTM C241 standards. Abrasion further helps in determining whether a marble is economically desirable and practical for floors, stairs etc. For this 48 samples were selected from different processing units of Rajasthan and were tested.

Regression analysis was carried out to investigate the relation between the abrasion resistance and the mechanical properties of marbles determined according to ASTM standards. Although, it is believed that abrasion resistance of many materials are greatly affected by its hardness and it increases with the increase in the hardness.

Abrasion resistance is one of the key consideration determining the suitability of a marble for applications like internal flooring and external pavements. Marble having abrasion resistance Ha value of 10 or more are recommended to use as internal flooring. A minimum value of Ha 15 is recommended for heavy foot traffic like for railway platforms, airports. Shopping malls and showrooms. Although for decoration purposes whenever two or more marbles are used their Ha difference value would not be more than 5, Table III shows the abrasion resistance value of five famous Rajasthan marble types determined according to ASTM C241 standards.

From the Table 3 and 4 following conclusions can be drawn

1. Due to its high abrasion resistance M4 (78.75), M2 (25.47) and M1 (22.23) marble should be used for heavy traffic manoeuvre’s like for railway platforms, airports, showrooms and shopping centres.

2. All the five marbles can be used for internal flooring purposes due to their high abrasion resistance value (Ha).

3. M4 marble should not be used with any other marble for flooring purposes due to its high abrasion resistance when used together with other marble will lead to un-even wear of flooring

4. M2 marble (having Ha value 25.47) should be used with M1 marble (having Ha 22.23) for only flooring applications because of their Ha values have difference less than 5.

5. However M3, M1 and M5 can be used together for flooring purposes (due to their approximate same difference Ha values 18.84, 22.23, and 19.12 respectively).

6. As the regression values are highly correlated with modulus of rupture, compressive strength, flexural strength and hardness the abrasion values can be predicted, whereas rough estimates could be made with the water absorption and bulk specific gravity due to their low correlation.

7. More abrasion resistant marbles are likely to have high compressive strength, modulus of rupture, flexural strength, hardness and low bulk specific gravity.

The authors would hope this research would help architects, designers, miners, industrialists and government agencies who are dealing with noble natural stone marble could take advantage of these in-depth results.

7.2.3 Rheological investigations of marble powder

Rheological investigations with different coolants were tested to check the behavior of the fluid. The rheological study of marble slurry is a vital characteristic for the calculation of marble characteristics, and for the parameter optimization. To achieve this, four marble sample pastes were made ready by keeping the powder to coolant ratio constant i.e. 0.5

Marble slurry obtained by cutting process has high viscosity. As, this process continues uninterrupted for long hours this slurry dries up and shear thickening occurs. This thickened slurry sticks to the newly emerged diamond particles and deteriorates the surface. The main aim of this paper is to identify a coolant whose viscosity decreases or shear thinning occurs. After the series of experiments performed using different coolants, with the marble powder the following conclusions can be drawn.

a) TGA investigation carried out resulted that the powder contains 44% of calcium carbonate $CaCO_3$ and it is stable till 824^0 C.

b) X-Ray diffraction patterns show the presence of quartz, lime, hematite and alumina.

c) Marble paste mixed with paraffin based oil showed the highest value of yield stress which varies from 10.5 to 15.3 Pa. Lowest yield stress values -2.179 Pa was observed for marble to hydro carbon oil mixture.

d) A uniform plastic viscosity at different time intervals was observed in the paste prepared with water as coolant. In this study a higher value of viscosity 0.444 Pa-sec is observed with cutting fluid paste, and lowest value of viscosity of 0.0027 Pa-sec was observed in the paste prepared with water as coolant.

e) Marble paste prepared exhibits a Non-Newtonian behavior and it was observed the fluid follows Harshal Buckley Model.

7.3 Machinability results

7.3.1 Diamond tool wear and correlation analysis

Five marble samples which were selected are characterized physico-mechanically and chemically for different properties like (water absorption, density, modulus of rupture, compressive strength, abrasion, flexural strength, and hardness, mineral properties) later their thin section analysis was done to find different minerals and their grain sizes. Sawing experiments were performed in down cutting mode to find out the wear of the tool. A diamond segment blade was used in the experimentation has 110 mm dia which is widely used for sawing.

Regression and correlation analysis was done in order to find out the relations between marble properties and SWR. Significance of the relations were checked statistically and validity of the relations were also evaluated by using some statistic tests. The R-squared value which is also termed as the co-efficient of determination, it's the segment of variance of dependent parameter which could be predicted by any independent parameter. Standard error which is denoted by Std is its standard deviation for error, and is the square root of the mean squared residual. Significance of the level observed for the experiment is denoted by probability P-value. The conventional 5 percent significance level is followed in this study. Therefore, any result which has a P-value of less than (0.05) are examined to be statistically significant with a level of confidence 95 percent.

From the results determined experimentally by sawing experiments, related to the marble for applied conditions of operations the following conclusions can be drawn with respect to various marble types found in Rajasthan region:-

1. Except hardness, no significant relation were observed among the mechanical properties with the SWR of blade. Hardness can also be more influential to the wear rate of the blade which is further associated to the various minerals present in the marble. Therefore, for any marble processing industry it may not be appropriate to take the mechanical properties of marble alone for estimation of wear performance. But, it is viable to recommend that the mechanical properties are convenient for selection of marble for specific purpose like claddings, tiles, flooring, and roofing, etc.

2. Maximum grain size of lime and quartz were spotted as the significant affecting factors influencing the specific wear rate. When these both grain sizes are considered together the maximum grain size is more correlated to wear than the mean grain size. This being the important contribution to the research revealing that the larger the grain size harder the mineral which effect the SWR more when compare to the smaller grain sizes.

3. Although in many cases the quartz volume content is considered as a major factor of influence in stone processing industry. The poor relation between the quartz and SWR clearly indicates that quartz alone should not be used as the deciding factor when defining the machinability of the marble.

7.3.2 Specific energy calculation

Specific energy (SE) is an important parameter to be studied while performing milling operations on marble stone. Taguchi L16 orthogonal array was used for the design of experiments, ANOVA was used to test the competence of the models. A CNC milling machine was used with two diamond coated end mill cutters to perform the milling operations on the workpiece, a digital energy meter used to record the power consumption simultaneously. Regression analysis was used to find out the relation between the parameters. The regression equation developed can be successfully used to predict the SE with different parameters. Finally ANN architecture was used to predict the SE of the operation. The results obtained using ANN model was in close agreement with the experimental values. Hence, ANN proved to be more advantageous in predicting the SE_{cut} in relation with process optimization influencing the key factors effecting the machining process

Samples were tested in laboratory to obtain different physico-mechanical properties as well as chemical properties, X-ray diffraction was done to find the components present in the sample. Thermogravimetric analysis assisted in knowing the amount of calcium present in the sample. Two diamond coated end mill cutters of 10 mm and 12 mm were used to find the Specific Energy consumption while milling.

With the use of Taguchi L16 orthogonal array design of trials were carried out. In these trials the influence of the milling conditions speed, feed and depth of cut with four different combinations was measured to see its influence on Specific Energy consumption. Using regression equation a mathematical relation between input and output variables were obtained. The competence of the model was verified with the ANOVA. It's concluded that Depth of cut plays a major role in the SE_{cut}, The results of analysis of variance along with the power consumption with respect to different speed, feed and depth of cut were plotted.

Finally the practice of ANN model for the prediction of experimental outcome was investigated. Numerous network designs and training procedures were inspected to determine the prime settings like number of neurons and epochs for the model. A comparison between experimental and ANN model were plotted. Hence, ANN proved to be more advantageous in predicting the SE_{cut} in terms of process optimization influencing the main factors effecting the machining process.

Recommendations and Suggestions for future

1. Case study done on different marble stone processing industries there is a large scope of fabricating the customized tools according to the hardness of the marble stones to be cut. So, further research can be carried out for fabricating customized inserts.
2. Water recycling method followed by these SME's are not of standards as suggested by the pollution board of Rajasthan. Different waste management strategies can be implemented to save the water and this can be taken as future studies.
3. Rheological studies carried out with different coolants showed that paraffin based coolants are more favorable for marble cutting, further studies in the processing industries can be carried out to check its effect on the tool wear.
4. Since, aesthetics is paramount in selection of the marble stones for specific purposes the reactive nature of the paraffin based coolants study can be carried out, in order to check whether its properties remain intact.
5. Milling experiments were performed to evaluate the specific energy consumption and the results were predicted using ANN technique. Since, current experiments are very few the results predicted by ANN is comparable with the regression analysis. Further, prediction of other parameters like force calculation, wear on tool etc. from large data base can be done in future work and correlated with the physico-mechanical properties.
6. Quarrying is the activity where about 50% of waste is generated while extracting the marble stone from rocky mountains, if a proper energy management strategies are applied to the process most of the energy could be saved.
7. There is a vast scope of manufacturing/fabrication for customized tools for sawing different marble stones of Rajasthan this can be taken as future study.
8. Improving product quality by the use of cutting edge technology in marble stone industries are lacking. Significant investment in equipment, high precision cutting equipment to cut-to-size, thin tiles and customized products to be sold in market.

Recommendations to Industries

1. The systematic characterization done in chapter 2 will be useful for industries as a catalogue to obtain information regarding mineral composition and physico-mechanical properties of different marble stones.
2. Industries can use the data obtained in rheological characterization, and replace the conventional coolant with paraffin based coolant which will increase the life of the tool.
3. Grading chart given in chapter 3 will help industries as a catalogue to follow and use it for selection of marble stones based on different applications.
4. If any marble processing industry has challenges in optimizing their processing parameters for increasing the efficiency of cutting/polishing or energy saving's etc. They can use the data given in chapter 6 for obtaining optimized parameters.
5. To use an alternative/customized tool, for cutting specific marble the table given in chapter 3 will help small scale industries to fabricate their own tool from the data.
6. If a marble processing industry desires to calculate their environmental foot prints they can follow the technique given in chapter 4 (sustainable study by using life cycle assessment of marble processing) to obtain various results and seek alternative energy sources or machines to reduce the environment impacts.

References

[1] I. Ashmole, “Reclamation and environmental management in,” pp. 155–178, 2008.

[2] K. Helming and M. Pérez-soba, *Sustainability Impact Assessment of Land Use Changes*. 2007.

[3] R. W. Kates, T. M. Parris, and A. A. Leiserowitz, “What is sustainable,” *Environ. Sci. Policy Sustain. Dev*, vol. 47, no. 3, pp. 8–21, 2005.

[4] W. J. Rankin, *Minerals, metals and sustainability : meeting future material needs*. Collingwood, Vic.: CSIRO, 2011.

[5] D. Van Zyl, M. Sassoon, C. Digby, A. Fleury, and S. Kyeyune, “Mining for the Future Main Report Contents of the Main Report,” no. 68, 2002.

[6] Montani C, “XXII Report 2011 world marble and stones,” 2011.

[7] US Department of the Interior, “US Geological Survey,” Virginia, 2011.

[8] S. and tile India, “Stone and life in india,” *Mediology Software Pvt Ltd*, 2015. [Online]. Available: http://stonetileindia.com/?p=1569. [Accessed: 12-May-2015].

[9] S. & M. E. Ministry of Micro, “Status report on,” 2009.

[10] P.- Ii, “Indian Minerals Yearbook 2011,” *Indian Miner.*, vol. 2011, no. October, 2012.

[11] V. Corinaldesi, G. Moriconi, and T. R. Naik, “Characterization of marble powder for its use in mortar and concrete,” *Constr. Build. Mater.*, vol. 24, no. 1, pp. 113–117, 2010.

[12] R. Rehan and M. Nehdi, “Carbon dioxide emissions and climate change : policy implications for the cement industry,” vol. 8, no. 2005, pp. 105–114, 2012.

[13] F. A. R. I. Joekes, “Cement industry: sustainability, challenges and perspectives,” pp. 151–166, 2011.

[14] M. António and S. Frazão, “Cutting Process Analysis by the Multiblade Gangsaw,” no. 2002, pp. 1–10, 2015.

[15] E. Rodrigues, “Sawing of blocks of siliceous dimension stone : influence of texture and mineralogy,” pp. 101–107, 2007.

[16] A. S. Robleda and J. T. Castro, “The rock processing sector : part i : cutting technology tools , a new diamond segment band saw part ii : study of cutting forces el sector transformador de roca : parte i : tecnologías de corte , una nueva sierra de cinta con segmentos de diamante parte ii : estudio,” pp. 77–87, 2009.

[17] N. Careddu and G. Marras, “Marble Processing for Future Uses of $CaCO_3$ - Microfine Dust: A Study on Wearing out of Tools and Consumable Materials in Stoneworking Factories,” *Miner. Process. Extr. Metall. Rev.*, vol. 36, no. 3, pp. 183–191, 2015.

[18] J. M. F. Mendoza, C. Capitano, G. Peri, A. Josa, J. Rieradevall, and X. Gabarrell, “Environmental management of granite slab production from??an??industrial ecology standpoint,” *J. Clean. Prod.*, vol. 84, pp. 619–628, 2014.

[19] H. Vettorazzi, R. E. Coppedê, H. Vettorazzi, N. F. Castro, and R. Elisa, “ROCK PROPERTIES AND STEEL BLADES AND GRIT CONSUMPTION Rock properties and steel blades and grit consumption in granite multi blade sawing process,” 2012.

[20] C. Sung, “Brazed diamond grid : a revolutionary design for diamond saws,” vol. 8, pp. 1540–1543, 1999.

[21] C. Y. Hsu, C. S. Chen, and C. C. Tsao, “Free abrasive wire saw machining of ceramics,” pp. 503–511, 2009.

[22] H. K. Tönshoff and H. Hillmann-Apmann, “Diamond tools for wire sawing metal components,” *Diam. Relat. Mater.*, vol. 11, no. 3–6, pp. 742–748, 2002.

[23] R. M. Ghaysari, Mohammad Ataei and F. SereshkiNarges, “Predicting the production rate of diamond wire saw using statistical analysis,” *Arab. J. Geosci.*, vol. 5, no. 6, pp. 1289–1295, 2012.

[24] G. Q. Huang and X. P. Xu, “Analysis of the Breakage of Diamond Wire Saws in Sawing of Stone,” vol. 305, pp. 123–126, 2006.

[25] Y. Ozcelik and E. Yilmazkaya, “The effect of the rock anisotropy on the efficiency of diamond wire cutting machines,” *Int. J. Rock Mech. Min. Sci.*, vol.

48, no. 4, pp. 626–636, 2011.

[26] H. C. Ã, “Linear stone cutting tests with chisel tools for identification of cutting principles and predicting performance of chain saw machines,” *Int. J. Rock Mech. Min. Sci.*, vol. 47, no. 1, pp. 104–120, 2010.

[27] S. C. J. S. S. Rathore, “Prediction of Cutting Performance of Diamond Wire Saw Machine in Quarrying of Marble : A Neural Network Approach,” pp. 367–371, 2011.

[28] B. C. Liu, Z. P. Zhang, and Y. H. Sun, “Sawing Trajectory and Mechanism of Diamond Wire Saw,” vol. 260, pp. 395–400, 2004.

[29] A. Ersoy, S. Buyuksagic, and U. Atici, “Wear characteristics of circular diamond saws in the cutting of different hard abrasive rocks,” vol. 258, pp. 1422–1436, 2005.

[30] S. Kulaks, “Assessment of the wear of diamond beads in the cutting of different rock types by the ridge regression,” vol. 127, 2002.

[31] M. A. Azmir and A. K. Ahsan, “Investigation on glass / epoxy composite surfaces machined by abrasive water jet machining,” vol. 8, pp. 122–128, 2007.

[32] D. Arola and M. Ramulu, “Material removal in abrasive waterjet machining of metals Surface integrity and texture,” *Wear*, vol. 210, no. 1–2, pp. 50–58, 1997.

[33] I. Karakurt, G. Aydin, and K. Aydiner, “A machinability study of granite using abrasive waterjet cutting technology,” *Gazi Univ. J. Sci.*, vol. 24, no. 1, pp. 143–151, 2011.

[34] I. C. Engin, A. Kocatepe, I. C. Engin, and A. Kocatepe, “A correlation for predicting the abrasive water jet cutting depth for natural stones,” vol. 108, pp. 1–11, 2012.

[35] M. Junkar, B. Jurisevic, M. Fajdiga, and M. Grah, “Finite element analysis of single-particle impact in abrasive water jet machining,” vol. 32, pp. 1095–1112, 2006.

[36] F. L. Chen and E. Siores, “The effect of cutting jet variation on striation formation in abrasive water jet cutting,” vol. 41, pp. 1479–1486, 2001.

[37] A. M. Hoogstrate, C. A. Van Luttervelt, P. Gosger, A. W. Momber, H. K. Tönshoff, F. K. H. Louis, and D. Riviere, “Opportunities in abrasive water-jet machining,” *Mech. Mater. Eng.*, vol. 46, no. 2, pp. 697–714, 1997.

[38] L. M. Hlaváč, I. M. Hlaváčová, L. Gembalová, J. Kaličinský, S. Fabian, J. Měšťánek, J. Kmec, and V. Mádr, “Experimental method for the investigation of the abrasive water jet cutting quality,” *J. Mater. Process. Technol.*, vol. 209, no. 20, pp. 6190–6195, 2009.

[39] C. Ma and R. T. Deam, “A correlation for predicting the kerf profile from abrasive water jet cutting,” *Exp. Therm. Fluid Sci.*, vol. 30, no. 4, pp. 337–343, 2006.

[40] a. Ersoy, S. Buyuksagic, and U. Atici, “Wear characteristics of circular diamond saws in the cutting of different hard abrasive rocks,” *Wear*, vol. 258, no. 9, pp. 1422–1436, 2005.

[41] O. Akkoyun and H. Ankara, “Cost of quality management : An empirical study from Turkish marble industry,” *Sci. Res. abd Essay - Acad. Journals*, vol. 4, no. 11, pp. 1275–1285, 2009.

[42] I. G. Gyurika, “Optimal opportunities at stone machining processes done by diamond tool,” vol. 2, pp. 85–89, 2011.

[43] G. Aydin, I. Karakurt, and K. Aydiner, “Development of Predictive Models for the Specific Energy of Circular Diamond Sawblades in the Sawing of Granitic Rocks,” pp. 767–783, 2013.

[44] H. K. Tönshoff, H. Hillmann-Apmann, and J. Asche, “Diamond tools in stone and civil engineering industry: Cutting principles, wear and applications,” *Diam. Relat. Mater.*, vol. 11, no. 3–6, pp. 736–741, 2002.

[45] A. Di Ilio and A. Togna, “A theoretical wear model for diamond tools in stone cutting,” *Int. J. Mach. Tools Manuf.*, vol. 43, no. 11, pp. 1171–1177, 2003.

[46] K. Aslantas, O. Özbek, İ. Ucun, and İ. S. Büyüksağ[idot]ş, “Investigation of the Effect of Axial Cutting Force on Circular Diamond Sawblade Used in Marble Cutting Process,” *Mater. Manuf. Process.*, vol. 24, no. 12, pp. 1423–1430, 2009.

[47] U. Atici and a. Ersoy, “Correlation of specific energy of cutting saws and drilling

bits with rock brittleness and destruction energy," *J. Mater. Process. Technol.*, vol. 209, no. 5, pp. 2602–2612, 2009.

[48] B.Unver, "A statistical method for practical assessment of sawability of rocks," in *International Society for Rock Mechanics*, 1999.

[49] S. M, "Modeling of small-diameter rotary drilling tests on marbles," *Int. J. Rock Mech. Min. Sci.*, vol. 43, no. 7, pp. 1034–1051, 2006.

[50] E. Detournay and P. Defourny, "A phenomenological model for the drilling action of drag bits," *Int. J. Rock Mech. Min. Sci. Geomech.*, vol. 29, no. 1, pp. 13–23, 1992.

[51] G. Exadaktylos, P. Tiano, and C. Filareto, "Validation of a model of rotary drilling of rocks with the drilling force measurement system," *Restor. Build. Monum.*, vol. 6, no. 3, 2014.

[52] S. Malkin, "Grinding Mechanisms and Strength Degradation for Ceramics," vol. 111, 2017.

[53] B. Brook, "Principles of diamond tool technology for sawing rock," *Int. J. Rock Mech. Min. Sci.*, vol. 39, no. 1, pp. 41–58, 2002.

[54] S. Liu and J. Xu, "Study on dynamic characteristics of marble under impact loading and high temperature," *Int. J. Rock Mech. Min. Sci.*, vol. 62, pp. 51–58, 2013.

[55] I. S. Buyuksagis, "Effect of cutting mode on the sawability of granites using segmented circular diamond sawblade," *J. Mater. Process. Technol.*, vol. 183, no. 2–3, pp. 399–406, 2007.

[56] D. M. AG Evans, "Wear mechanisms in ceramics," *Fundam. Frict. wear Mater.*, pp. 439–452, 1980.

[57] C. Zografidis and K. Adam, "Evaluation of the environmental performance of the natural stone industry based on sustainable indicators," no. June, pp. 1–8, 2007.

[58] R. M. Clugston and W. Calder, "Critical Dimensions of Sustainability in Higher Education 1," 1999.

[59] H. A. Rathod and P. J. Pitroda, "From Bricks To Blocks : A Masonary Unit From Western Gujarat Region Of India From Bricks To Blocks : A Masonary Unit From Western Gujarat Region Of India," no. JUNE 2013, 2015.

[60] a. Gazi, G. Skevis, and M. a. Founti, "Energy efficiency and environmental assessment of a typical marble quarry and processing plant," *J. Clean. Prod.*, vol. 32, pp. 10–21, 2012.

[61] G. of India, "Commercial utilization of marble slurry in Rajasthan," 2013.

[62] A. Pathak, S. Kumar, and V. K. Jha, "Development of Building Material from Geopolymerization of Construction and Demolition Waste (CDW)," *Trans. Indian Ceram. Soc.*, vol. 73, no. 2, pp. 133–137, 2014.

[63] S. M. El-Bashir and a. Hendi, "A Decorative Construction Material Prepared by Making Use of Marble Waste Granules and PMMA/SiO_2 Nanocomposites," *Polym. Plast. Technol. Eng.*, vol. 49, no. 1, pp. 78–82, 2009.

[64] S. M. El-Bashir and A. Hendi, "A Decorative Construction Material Prepared by Making Use of Marble Waste Granules and PMMA/SiO_2 Nanocomposites," *Polym. Plast. Technol. Eng.*, vol. 49, no. 1, pp. 78–82, 2009.

[65] S. E. Ghazy, S. E. Samra, and A. M. Mahdy, "Removal of copper (ii) from some environmental samples by sorptive-flotation using powderd marble wastes as sorbents and oleic acid as surfactant," vol. 25, no. Ii, pp. 1221–1231, 2004.

[66] N. Haddadou, R. Chaid, and Y. Ghernouti, "Experimental study on steel fibre reinforced self-compacting concrete incorporating high volume of marble powder," *Eur. J. Environ. Civ. Eng.*, no. November 2014, pp. 1–17, 2014.

[67] K. K. Alzboon and K. N. Mahasneh, "Effect of Using Stone Cutting Waste on the Compression Strength and Slump Characteristics of Concrete," pp. 491–496, 2009.

[68] M. S. Hameed, a. S. S. Sekar, L. Balamurugan, and V. Saraswathy, "Self-compacting concrete using Marble Sludge Powder and Crushed Rock Dust," *KSCE J. Civ. Eng.*, vol. 16, no. 6, pp. 980–988, 2012.

[69] O. Ortiz, F. Castells, and G. Sonnemann, "Sustainability in the construction industry: A review of recent developments based on LCA," *Constr. Build.*

Mater., vol. 23, no. 1, pp. 28–39, 2009.

[70] U. States, "Sustainable building and construction : facts and figures," no. September, 2003.

[71] M. Ã. Asif, T. Muneer, and R. Kelley, "Life cycle assessment : A case study of a dwelling home in Scotland," vol. 42, pp. 1391–1394, 2007.

[72] G. M. Nicoletti, B. Notarnicola, and G. Tassielli, "Comparative Life Cycle Assessment of flooring materials : ceramic versus marble tiles ଝ," vol. 10, pp. 283–296, 2002.

[73] F. ISI, "Electricity Costs of Energy Intensive Industries An International Comparison Electricity Costs of Energy Intensive Industries An International Comparison," Germany, 2015.

[74] F. A. Ximenes and T. Grant, "Quantifying the greenhouse benefits of the use of wood products in two popular house designs in Sydney, Australia," vol. 18, no. 4, pp. 891–908, 2013.

[75] C. K. Ã and A. Dompros, "Environmental assessment of brick production in Greece," vol. 42, pp. 2114–2123, 2007.

[76] X. Wu, Z. Zhang, and Y. Chen, "Study of the environmental impacts based on the '" green tax "'— applied to several types of building materials," vol. 40, pp. 227–237, 2005.

[77] T. E. Ã, "A study regarding the environmental impact analysis of the building materials production process (in Turkey)," vol. 42, pp. 3860–3871, 2007.

[78] A. De Gracia, L. Rincón, A. Castell, M. Jiménez, D. Boer, M. Medrano, and L. F. Cabeza, "Life Cycle Assessment of the inclusion of phase change materials (PCM) in experimental buildings," vol. 42, pp. 1517–1523, 2010.

[79] V. Liguori, G. Rizzo, and M. Traverso, "Marble quarrying : an energy and waste intensive activity in the production of building materials," vol. 108, pp. 197–207.

[80] J. E. Lindqvist, U. Åkesson, and K. Malaga, "Microstructure and functional properties of rock materials," vol. 58, no. April, pp. 1183–1188, 2007.

[81] P. N. Manoudis, A. Tsakalof, I. Karapanagiotis, I. Zuburtikudis, and C.

Panayiotou, “Fabrication of super-hydrophobic surfaces for enhanced stone protection,” *Surf. Coatings Technol.*, vol. 203, no. 10–11, pp. 1322–1328, 2009.

[82] P. Maravelaki-Kalaitzak and G. Biscontin, “Origin, characteristics and morphology of weathering crusts on Istria stone in Venice,” *Atmos. Environ.*, vol. 33, no. 11, pp. 1699–1709, 1999.

[83] J. F. Asmus, Seracini, Maurizio, and M. . Zetler, “Surface morphology of laser-cleaned stone,” *Conserv. Inf. Netw.*, vol. 1976, no. 1, pp. 23–46, 1976.

[84] V. Fassina, “New findings on past treatments carried out on stone and marble monuments’ surfaces,” *Sci. Total Environ.*, vol. 167, pp. 185–203, 1995.

[85] N. Gunes Yilmaz, R. M. Goktan, and Y. Kibici, “An investigation of the petrographic and physico-mechanical properties of true granites influencing diamond tool wear performance, and development of a new wear index,” *Wear*, vol. 271, no. 5–6, pp. 960–969, 2011.

[86] Y. Ozcelik, E. Polat, F. Bayram, and A. M. Ay, “Investigation of the effects of textural properties on marble cutting with diamond wire,” *Int. J. Rock Mech. Min. Sci.*, vol. 41, no. 1, pp. 228–234, 2004.

[87] O. Gencel, C. Ozel, F. Koksal, E. Erdogmus, G. Martínez-Barrera, and W. Brostow, “Properties of concrete paving blocks made with waste marble,” *J. Clean. Prod.*, vol. 21, no. 1, pp. 62–70, 2012.

[88] Y. Lin, J. Lu, L. Wang, T. Xu, and Qunji Xue, “Surface nanocrystallization by surface mechanical attrition treatment and its effect on structure and properties of plasma nitrided AISI 321 stainless steel,” *Acta Mater.*, vol. 54, no. 20, pp. 5599–5605, 2006.

[89] J. E. Lindqvist, U. Åkesson, and K. Malaga, “Microstructure and functional properties of rock materials,” *Mater. Charact.*, vol. 58, no. 11–12, pp. 1183–1188, 2007.

[90] A. Tosun and H. Y. Erbil, “Evaporation rate of PTFE liquid marbles,” *Appl. Surf. Sci.*, vol. 256, no. 5, pp. 1278–1283, 2009.

[91] V. Brotóns, R. Tomás, S. Ivorra, and J. C. Alarcón, “Temperature in fl uence on the physical and mechanical properties of a porous rock : San Julian ’ s

calcarenite," *Eng. Geol.*, vol. 167, pp. 117–127, 2013.

[92] E. Güneyisi, M. Gesoğlu, and E. Özbay, "Effects of marble powder and slag on the properties of self compacting mortars," *Mater. Struct.*, vol. 42, no. 6, pp. 813–826, 2009.

[93] A. Ersoy and U. Atıcı, "Performance characteristics of circular diamond saws in cutting different types of rocks," vol. 13, pp. 22–37, 2004.

[94] D. F. Howarth and J. C. Rowlands, "Quantitative assessment of rock texture and correlation with drillability and strength properties," *Rock Mech. Rock Eng.*, vol. 20, no. 1, pp. 57–85, 1987.

[95] J. Xie and J. Tamaki, "Parameterization of micro-hardness distribution in granite related to abrasive machining performance," *J. Mater. Process. Technol.*, vol. 186, no. 1–3, pp. 253–258, 2007.

[96] I. S. Buyuksagis and R. M. Goktan, "Investigation of marble machining performance using an instrumented block-cutter," *J. Mater. Process. Technol.*, vol. 169, no. 2, pp. 258–262, 2005.

[97] C. . Wang and R. Clausen, "Marble cutting with single point cutting tool and diamond segments," *Int. J. Mach. Tools Manuf.*, vol. 42, no. 9, pp. 1045–1054, 2002.

[98] J. Xie and J. Tamaki, "Parameterization of micro-hardness distribution in granite related to abrasive machining performance," *J. Mater. Process. Technol.*, vol. 186, no. 1–3, pp. 253–258, 2007.

[99] R. M. Miranda and L. Quintino, "Microstructural study of material removal mechanisms observed in abrasive waterjet cutting of calcareous stones," *Mater. Charact.*, vol. 54, no. 4–5, pp. 370–377, 2005.

[100] W. Polini and S. Turchetta, "Force and specific energy in stone cutting by diamond mill," *Int. J. Mach. Tools Manuf.*, vol. 44, no. 11, pp. 1189–1196, 2004.

[101] X. Xu, "Friction studies on the process in circular sawing of granites," *Tribol. Lett.*, vol. 7, no. 4, pp. 221–227, 1999.

[102] C. Diamond and S. Blade, "Kinematics Analysis of the Chipping Process Using

the Circular Diamond Saw Blade One," vol. 121, no. May 1999, pp. 257–264, 2017.

[103] S. Turchetta, "Cutting force on a diamond grit in stone machining," *Int. J. Adv. Manuf. Technol.*, vol. 44, no. 9–10, pp. 854–861, 2009.

[104] L. Hu, C. Peng, S. Evans, T. Peng, Y. Liu, and R. Tang, "Minimising the machining energy consumption of a machine tool by sequencing the features of a part," *Energy*, vol. 121, pp. 292–305, 2017.

[105] G. Totis, G. Wirtz, M. Sortino, D. Veselovac, E. Kuljanic, and F. Klocke, "Development of a dynamometer for measuring individual cutting edge forces in face milling," *Mech. Syst. Signal Process.*, vol. 24, no. 6, pp. 1844–1857, 2010.

[106] G. Totis, P. Albertelli, M. Sortino, and M. Monno, "Efficient evaluation of process stability in milling with Spindle Speed Variation by using the Chebyshev Collocation Method," *J. Sound Vib.*, vol. 333, no. 3, pp. 646–668, 2014.

[107] B. H. A, J. F. Hutton, and F. R. S. Walters, "An introduction to Rheology." 1970.

[108] R. Hischier, B. W. Editors, H. Althaus, C. Bauer, G. Doka, R. Dones, R. Frischknecht, S. Hellweg, S. Humbert, N. Jungbluth, T. Köllner, Y. Loerincik, M. Margni, and T. Nemecek, "Implementation of Life Cycle Impact Assessment Methods," 2010.

[109] A. W. Saak, H. M. Jennings, and S. P. Shah, "New methodology for designing self-compacting concrete," *ACI Mater. J.*, vol. 98, no. 6, pp. 429–439, 2001.

[110] I. Karakurt, G. Aydin, and K. Aydiner, "Experimental and statistical analysis of cutting force acting on diamond sawblade in sawing of granitic rocks," *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 227, no. 2, pp. 286–300, 2012.

[111] P. M. Amaral, J. C. Fernandes, and L. G. Rosa, "Wear mechanisms in materials with granitic textures-Applicability of a lateral crack system model," *Wear*, vol. 266, no. 7–8, pp. 753–764, 2009.

[112] Yakup Turgut, "High capacity three-component dynamometer design, construction and its calibration," *Sci. Res. Essays*, vol. 7, no. 30, pp. 2699–2707, 2012.

[113] S. Yaldiz, F. Unsacar, H. Saglam, and H. Isik, “Design, development and testing of a four-component milling dynamometer for the measurement of cutting force and torque,” *Mech. Syst. Signal Process.*, vol. 21, no. 3, pp. 1499–1511, 2007.

[114] S. Yaldiz and F. Ünsaçar, “A dynamometer design for measurement the cutting forces on turning,” *Meas. J. Int. Meas. Confed.*, vol. 39, no. 1, pp. 80–89, 2006.

[115] S. Karabay, “Analysis of drill dynamometer with octagonal ring type transducers for monitoring of cutting forces in drilling and allied process,” *Mater. Des.*, vol. 28, no. 2, pp. 673–685, 2007.

[116] B. B. Singh, N. Saini, S. Dhar, and V. Garg, “Design and development of a Strain Gauge based Dynamometer for measurement of cutting force on a Lathe,” vol. 2006, no. Ame, 2006.

7.4 Research publications

Patent:-

1. H.S Mali, B Pathri, Sandeep, Manish, Ankit, Rohit. 2016, Smart stone cutter based on direct use of electromagnetic forces and intelligent electronics circuitry, INDIAN. Patent- 201611027416 A, Filed August 11, 2016, and issued August 26, 2016

International Journals:-

1. B. Prajwal, Arpit, DR Unune, H.S Mali, S.S Dhami, Ravindra Nagar. (2016), "Design and fabrication of a strain gauge type 3-axis milling tool dynamometer: Fabrication and Testing", International Journal of Materials Forming and Machining Processes (IJMFMP), ISSN: 2334-4563, Vol 3, Issue 2, 1-15, (Scopus)
2. B. Prajwal, H.S Mali, R. Nagar. (2016), "Prediction and calculation of specific cutting energy while performing milling operation on natural stone", Wulfenia Journal, Vol 23, Issue 12, (SCI)
3. B. Prajwal, H.S. Mali, R. Nagar, "Influence of the physico-mechanical and mineral properties of various marble on the diamond tool wear", International Journal of Materials Engineering Innovation. (Scopus), Accepted
4. B. Prajwal, R. Chaudhary, H.S Mali, R. Nagar. (2017), "Abrasion wear characterization of natural stones subjected to foot traffic and correlation between abrasion and mechanical properties", Journal of material science, Vol.4, Issue.4, 10-17. (NON-SCI)
5. B. Prajwal, R. Chaudhary, H.S Mali, R. Nagar, "Abrasion resistance of some Rajasthan marble stones subjected to varying loads and sliding speeds according to EN: 14157 Standards", Journal of materials and Environmental Science. (Scopus) In-review.
6. B prajwal, H S Mali, R. Nagar, "An overview of Stone and marble industry of Rajasthan with Life Cycle Analysis as a case study" International journal of sustainable manufacturing, (Scopus), In-review

International Conferences:-

1. Bhargav Prajwal, Harlal singh mali, Rohit, Ankit, Sandeep, Manish, "Study & analysis of various marble cutters used in stone and marble Industry of Rajasthan", International Conference on Precision, Meso, Micro and Nano Engineering **(COPEN-9) at IIT Bombay**, India, 10-12 Dec. 2015.
2. B. Prajwal, P. Chauhan, H.S. Mali, and R. Nagar, "Sustainability Study and Energy Audit of Marble Industry of Rajasthan", 6th International & 27th All India Manufacturing Technology, Design and Research Conference, **at COEP Pune**, India, 16-18 Dec 2016.
3. Bhargav Prajwal, Jaikishan Sanbharia, Harlal Singh Mali, Ravindra Nagar, "Mechanical, Thermal and Rheological Characterization of marble waste with Different Coolants", Materials today: Proceedings, Elsevier, May (2016).

Annexure I Design and development of strain gauge dynamometer

6.7.1 Design of octagonal rings

High rigidity, sensitivity and natural frequency are basic requirements in dynamometer design [112]. Among the various types of elastic members, octagonal ring gives greater rigidity and natural frequency. Four octagonal rings (AISI 1020 steel) each having radius=20 mm and thickness= 5mm. Strain gauges having a gauge factor = 2.0 ± 1 % and resistance of 350 Ω are bonded on to the octagonal rings. Total 16 strain gauges are bonded on 4 octagonal rings. Two strain gauges one inside and the other outside are bonded vertically on each of the ring. Similarly two more strain gauges are bonded horizontally on to the outside surfaces of each ring at 45 ° angle. Figure 11 shows location of strain gauges and orientation of octagonal rings.

6.7.2 Orientation of strain gauges on the octagonal rings

The radial force F_t is supported by A–D rings of the dynamometer as shown in figure.12. The strain gauges 3, 4, 7, 8, 11, 12, 15 and 16 are affected by the radial force F_t. Among these strain gauges, 3, 7, 11 and 15 are subjected to tensile stress while 4, 8, 12 and 16 are subjected to compressive stress. The feed force F_f is supported by A and C rings of the dynamometer. The strain gauges to measure the feed force F_f should be mounted on the outer surfaces of A and C rings with 45° inclination angle. The strain gauges 1, 2, 5 and 6 are affected by the feed force F_f. Among these strain gauges, 1 and 5 are subjected to tensile stress while 2 and 6 are subjected to compressive stress. The tangential cutting force F_c is supported by B and D rings. The strain gauges for measuring the tangential cutting force F_c are mounted on rings B and D with 45° inclination angle with respect to the vertical plane. The strain gauges 9, 10, 13 and 14 are affected by the main cutting force F_c. Among these strain gauges, 9 and 13 are subjected to tensile stress while 10 and 14 are subjected to compressive stress [113]. AISI 1020 steel is selected for the construction of most parts of dynamometer as it is the most versatile material and can be easily and economically worked on by means of commonly available machines like lathe, drilling, milling, grinding etc. AISI 1020 steel has a high machinability rating of 72 % taking AISI 1212 as a reference of 100 %. It is also cheap to buy as compared to other plain carbon steels. Circular rings are not considered as they have a tendency of rolling under the action of cutting forces. Octagonal rings are used to avoid rolling tendencies. The outer circle of octagonal ring is divided into eight equal parts. Each of the eight equal parts is acting like a sector with an angle of 45°. The length of each edge of octagonal ring is assumed as 20.71 mm. This much length is suitable for the attachment of the octagonal ring to the top and the bottom plates and for bonding the strain gauges on the ring.

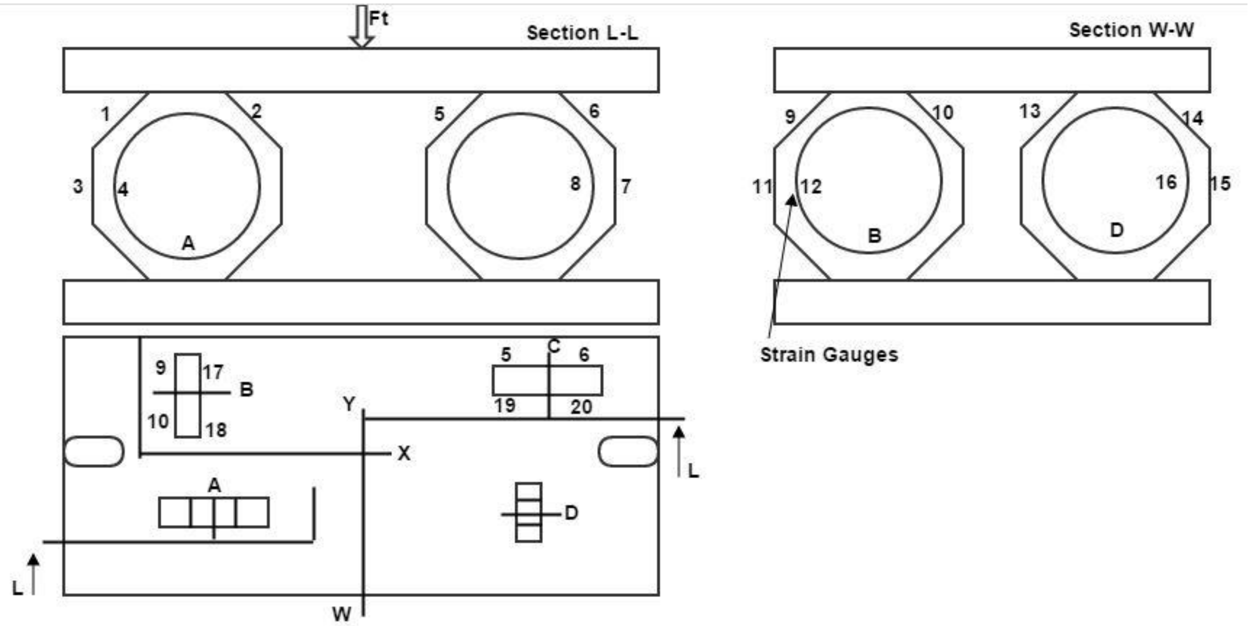


Figure.12 Schematic diagram showing location of strain gauges and orientation of octagonal rings

The octagonal ring is designed based on the bending failure. For design calculations section having the lesser strength or flexural rigidity (EI) is considered. Flexural rigidity (EI) depends on the moment of inertia of the section under consideration. For octagonal ring the flexural rigidity is minimum about the u-v axis as shown in figure.13.

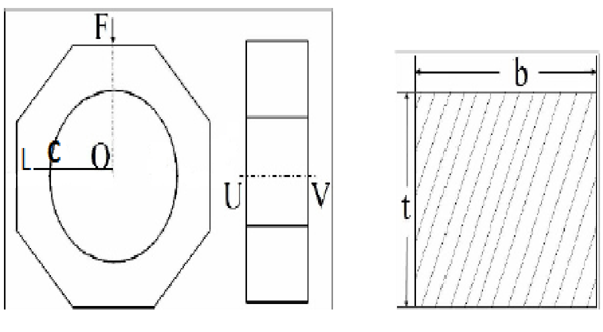


Figure.13 (a) Octagonal ring (b) U-V axis of least flexural rigidity (c) section of flexural rigidity

The length of moment arm from centre of loading is given as:

$$OL = OC + \frac{t}{2}$$

$$= 20 + 2.5$$

$$= 22.5 \text{ mm.}$$

The maximum force acting on each octagonal ring is assumed as 3000 N. Therefore the bending moment occurring on each octagonal ring is:

$$M = 3000 \times 22.5$$

$$= 67500 \text{ N- mm}$$

$$= 67.5 \text{ N-m.}$$

The octagonal ring has two arms and both the arms share the bending moment equally. Therefore the bending moment acting on each arm is 33.75 N-m.

Moment of inertia (I) of the octagonal section shown in Fig   is given by:

$$I = \frac{1}{12} bt^3$$

$$= \frac{1}{12} b(0.005)^3$$

Where

'b' is the width of the octagonal ring

AISI 1020 steel is selected as the ring material. The yield strength of AISI 1020 steel in cold rolled condition is 350 MPa.

Taking a factor of safety of 1.5, bending stress (σ_b) = $\frac{350}{1.5} = 233.3$ MPa

Width (b) of the octagonal ring is calculated as follows:

$$\sigma_b = \frac{M}{I} Y$$

$$\text{Where } Y = \frac{t}{2}$$

Substituting the values of bending stress (σ_b), bending moment (M), moment of inertia (I)

We get width (b) of the octagonal ring = 34.714 mm. The ring width is taken as 35 mm in order to have a higher safety factor in the final design. The final dimension of the octagonal ring is shown in figure.14. The thickness (t), radius (r) and width (b) were taken as 5mm, 20mm, 35mm.

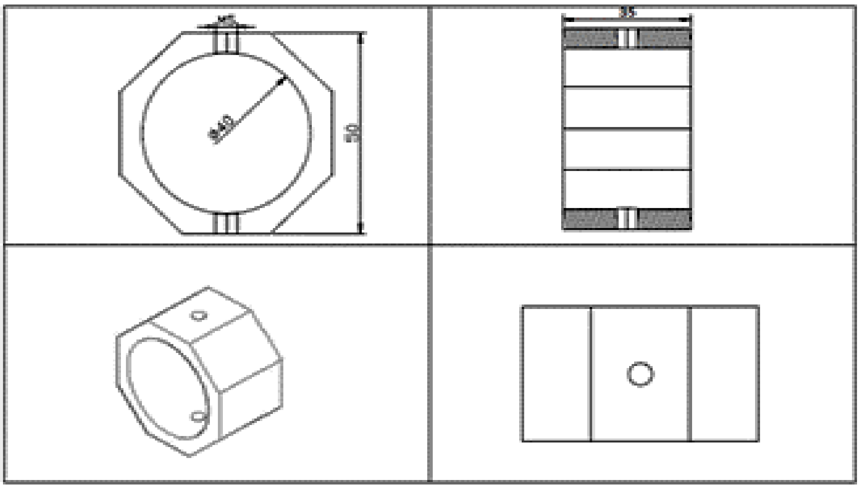


Figure.14 Fabricated octagonal rings

The strain produced on the octagonal ring is different at different locations of the ring. The strain gauges should be placed where the stress concentration has a maximum value [114]. The appropriate location for mounting strain gauges for maximum deflection is shown in figure 12 for a circular ring, maximum deflection occurs at section A-A at 90° from the vertical axis due to vertical force and at section B-B at 39.61° from the vertical axis due to horizontal force. In case of octagonal ring it was experimentally found that the maximum deflection occurs at 45° from the vertical axis instead of 39.61° for circular ring [115].

6.7.3 Verifying the Dimensions of Octagonal Ring

$$\text{Radial Strain } (e_r) = \pm \frac{1.09 F_r r}{E b t^2} \qquad (6)$$

$$\text{Stiffness } K_r = \frac{F_r}{\delta r}$$

$$= \frac{Ebt^3}{1.8r^3} \qquad (7)$$

Divide Equation (6) by F_r

$$\frac{e_r}{F_r} = \pm \frac{1.09r}{Ebt^2} \qquad (8)$$

Multiply Equation (8) and (7)

$$\frac{e_r}{F_r} \text{ x } \frac{F_r}{\delta r} = \frac{1.09r}{Ebt^2} \text{ X } \frac{Ebt^3}{1.8r^3}$$

We get: $\frac{e_r}{\delta r} = \frac{0.61t}{r^2}$

$$\frac{\boldsymbol{e_r}}{\frac{\boldsymbol{\delta r}}{\boldsymbol{r}}} = \frac{0.61t}{r} \qquad (9)$$

Where, $\frac{e_r}{\frac{\delta r}{r}}$ = strain per unit deflection

t = thickness of the ring

r = r_1 = inner radius of the ring

There is no effect of ring width 'b' and modulus of elasticity 'E' on strain per unit deflection as given by Equation (8). The strain per unit deflection should be as large as possible in order to have maximum sensitivity and rigidity [113]. So, inner radius of the ring (r) should be small and thickness (t) should be as large as possible. But small values of inner radius of the ring bring difficulties in mounting the internal strain gauges accurately. So, for a given size of ring radius (r) and ring width (b), thickness (t) should be large enough to be consistent with the desired sensitivity. For sufficient stiffness the ratio of $\frac{t}{r}$ should be equal to 0.25 or greater**.** In order to be consistent with this expression, the ring thickness and ring radius were taken as 5 mm and 20 mm, respectively[116]. Thus, the rate of t/r (5/20=0.25) provided necessary conditions for the construction of octagonal ring. The maximum expected force which the rings may face in each direction is assumed to be 3000 N taking into account the dimensions as seen in Fig. (b=35mm, t=5 mm, r =20 mm), elastic strains εv and εH due to radial force (Fr) and tangential cutting force (Fc) are calculated according to modified ring theory[113].

For Octagonal rings let:

ε_v =Strain due to radial force (F_r)

ε_H =Strain due to tangential cutting force (F_C)

$$\varepsilon_V = \frac{0.7 F_r r}{E b t^2} \qquad (10)$$

$$= \frac{0.7 \; X \; 3000 \; X \; 20}{200000 \; X \; 35 \; X \; 5 \; X \; 5}$$

$$= 2.4 \text{ x } 10^{-4}$$

$$\varepsilon_H = \frac{1.4 F_C r}{E b t^2} \qquad (11)$$

$$= \frac{1.4 \; X \; 3000 \; X \; 20}{200000 \; X \; 35 \; X \; 5 \; X \; 5}$$

$$= 4.8 \text{ x } 10^{-4}$$

The maximum stresses induced in the rings due to radial force (F_r) and tangential cutting force (F_C) is given by Equation 12 and 13

$$\text{Stress } \sigma_V = E \text{ x } \varepsilon_v \qquad (12)$$

$$=200000 \text{ x } 2.4 \text{ x } 10^{-4}$$

$$= 48 \text{ MPa}$$

$$\text{Stress } \sigma_H = E \text{ x } \varepsilon_H \qquad (13)$$

$$=200000 \text{ x } 4.8 \text{ x } 10^{-4}$$

$$= 96 \text{ MPa}$$

As the allowable yield strength of AISI 1020 steel is 233.3 MPa the calculated stress values occurring on the rings are within the safety limits of this material. Hence, the design of octagonal rings is safe.

6.7.4 Determination of natural frequency of the developed dynamometer

The dynamometer should have a natural frequency of at least four times the vibration frequency of the machine tool. Vibration frequency of the machine tool is related to the spindle speed of the machine. The dynamometer is assumed to be a small mass which is supported by octagonal ring element for analytical purpose as shown in figure.15.

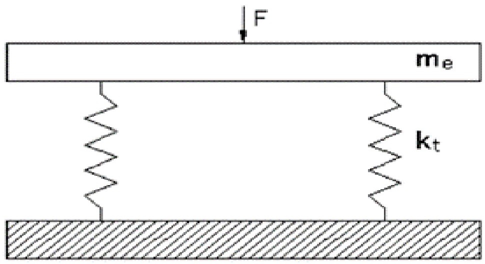


Figure.15 Free body diagram of the developed dynamometer

Dynamometer ring constant in radial direction (K_t) $=\frac{F_r}{\delta r}$

$$= \frac{Ebt^3}{1.8r^3} \qquad (14)$$

$$= \frac{200000 \, X \, 35 \, X \, 5^3}{1.8 \, X \, 20^3}$$

$$= 60763.88 \text{ N/mm}$$

Mass of dynamometer (m_e) = 40 kg

Natural Frequency of dynamometer

$$(f_d) = \frac{1}{2\pi}\sqrt{\frac{K_t}{m}} \qquad (15)$$

$$= \frac{1}{2\,\pi}\sqrt{\frac{60763.88 \, X \, 1000}{40}}$$

$$=196.26 \text{ rev/ sec}$$

The dynamometer should have a natural frequency of at least four times the vibration of the machine tool.

$$\text{So} \quad f_d \geq 4 \text{ x } f_{\text{machine tool}}$$

$$196.26 = 4 \text{ x } f_{\text{machine tool}}$$

$$f_{\text{machine tool}} = 49.06 \text{ rev/sec}$$

$$= 49.06 \times 60$$

$$= 2943.90 \text{ rpm}$$

So the maximum permissible rpm on spindle is 2943.90 nearly equal to 2944 rpm.

Also the maximum deflection of strain gauges is given as:

$$\delta_r = \frac{F_r}{K_t} \qquad (16)$$

$$= \frac{3000}{60763.88}$$

$$= 0.0493 \text{ mm}$$

The strain gauges used have 2.5 % elongation limit on 5 mm length. Maximum elongation = $\frac{2.5 \, X \, 5}{100}$ =0.125 mm. So maximum deflection of strain gauges on applying maximum force of 3000 N is 0.0493 mm which is less than maximum elongation (0.125 mm) produced in the gauge material. So the strain gauges used are within the safety limits.

6.7.5 Strain gauges

Strain gauges are popularly used for the measurement of force, torque, pressure, acceleration and many other parameters. These can be either metallic foil type or semiconductor type.

The strain (ε) induced by the cutting force (Pz) causes a change in resistance of the strain gauges. This change in resistance is related to the developed strain by the following relation:

$$\frac{\Delta R}{R} = G\epsilon$$

where G is the gauge factor which is used to characterize the performance of a strain gauge. It is given as

$$G = \frac{\Delta R/_R}{\Delta l/_l} = 1 + 2\vartheta + \frac{\Delta \rho/_\rho}{\Delta l/_l} \qquad (17)$$

Where ϑ=Poisson's Ratio (0. 3 - 0. 6 for metals)

$$\frac{\Delta\rho/\rho}{\Delta l/l} = \text{Piezo-Resistance coefficient} \quad (0.\ 2\text{- } 0.\ 6)$$

ρ= Resistivity of the material.

The gauge factor for metallic strain gauges varies from 1.8 to 2.6 whereas the gauge factor for semiconductor strain gauges varies in the range of 100 to 150. The commercially available strain gauges found in the market have fixed resistance values such as 120 **Ω**, 350Ω, 1000Ω etc. The manufacturer specifies the gauge factor and the maximum gauge current to avoid self-heating of the gauges (normally in the range of 15 mA to 100 mA). The material for metallic strain gauges should have low temperature coefficient of resistance and should have low coefficient for thermal expansion. Some of the commercially available strain gauge materials found in market are:

a) Constantan/Advance (55 % Cu, 45 % Ni) having a gauge factor between 2.0 to 2.2.
b) Nichrome (80% Ni, 20% Cr) having a gauge factor between 2.2 to 2.5.

Semiconductors type strain gauges have a large value of gauge factor and have a very high sensitivity and non-linear characteristics.

(i) Metallic strain gauges

These are of two types – unbonded and bonded.

Unbonded metallic strain gauges are used for measuring strain between a fixed and a moving structure by fixing four metallic wires so that two of them are in tension and two in compression.

In **bonded metallic** strain gauges the strain gauge metallic foil is fixed on a **base material** such as **phenol acetyl resin**. Besides this impregnated paper, fiber glass is also used as base materials. This base is bonded to a structure whose strain has to be measured with the help of a suitable adhesive. The adhesive normally used is **B 610** solution which is a cyanoacrylate solution **.Epoxy and cellulose solutions** are also used as adhesives.

The gauge connections can be:

a) All four gauges alive resulting in a full bridge circuit giving full sensitivity.
b) Only two gauges alive resulting in half bridge circuit giving half sensitivity.
c) Only one gauge alive resulting in quarter bridge circuit giving ¼ sensitivity.

6.7.6 Fabrication of upper plates and octagonal rings

Different components used for the milling dynamometer is fabricated as follows step by step.

Upper and Lower Plates

Step 1-Two plates of AISI 1020 material having dimensions of 310 x 310 x 20 mm have been procured from market. The plates are machined from all four sides by shaper machine in order to bring them to exact dimensions of 300 x 300 x 20mm.

A slot of 3mm width and 5 mm height has been made on the sides of upper and lower plates for plexiglass protective casing.

Step 2-Four holes of 5 mm diameter are drilled on both upper and lower plates for fastening the octagonal rings to the plates. Two additional holes of 5 mm diameter are drilled on upper plate for fixing the bench vice.

Step 3- In lower plate two grooves of 40 mm length and 16mm width are cut on opposite sides of plate in order to fix the dynamometer into T-slots of bed of CNC Milling machine by means of nut-bolts and washers.

Octagonal Rings:

Step 1-A round bar of AISI 1020 steel having 60 mm diameter and 150 mm length has been procured from the market. Four circular rings each of 30 mm width are cut by hack-saw machine.

Step 2-These circular rings are then turned on lathe machine to bring them to exact dimensions of 50 mm diameter having thickness of 5 mm. Machining operation is performed to remove the material from the centre of the ring to make them hollow.

Figure.18 Turning of circular rings on lathe

Step 3-A mandrel is fabricated for fixing the circular rings on the milling machine.

Figure.19 Mandrel for fixing the circular rings on the milling machine

These rings are then mounted on milling machine to form octagonal faces on the outer periphery.

Figure.20 Fabrication of octagonal faces on the outer periphery of rings.

Step 4-Surface grinding is done for imparting surface finish to the eight faces of the octagonal ring.

Step 5-Two holes of 5mm diameter are drilled on opposite faces of octagonal rings to fasten them with upper and lower plates.

6.7.7 Bonding Procedure for Strain gauges

Selection of strain gauge - The two main criteria for selecting the right type of strain gauge is sensitivity and precision.

Specifications of Strain Gauges used are:

Strain Gauge = NICTECH-CF- 350-5 AA (II)-C20

Gauge Features= Encapsulated gauges with temperature compensation, good flexibility for installation.

Metal foil =Constantan Alloy

Backing material= Phenol Acetyl Resin

Measuring Grid length = 5 mm

Measuring Grid Carrier length = 9 mm

Nominal Resistance (Ω) =350 Ω

Tolerance of Resistance < ± 0.1 %

Gauge factor = 2.0 ± 1 %

Gauge factor Dispersion = < ± 1 %

Strain limit = 2.5 %

Fatigue life = > 10^{7}

Working Temperature Range= - 50 ~+ 80°C

Bonding Adhesive = B 610

The strain gauges used in the present work are shown in figure 16 below.

Figure.21 Strain gauges used for dynamometer

Surface Preparation - Clean the bonding site with degreasing solvent such as methyl-ethyl-ketone (MEK), acetone or iso propyl alcohol (IPA).After proper cleaning do not touch the application area by hands. Use a sand paper of grit size 320-400 for surface polishing of the application area. Figure.17 shows a diagram of surface preparation of the bonding site.

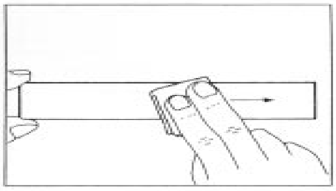


Figure.22 Surface penetration of bonding site

The position of the strain gauges to be bonded on the octagonal ring should be marked with the help of brass needle or 4H pencil. Strain gauges should be handled with rounded tweezers and should never be touched with fingers. Care must be taken while holding the gauges. Hold the strain gauges at the backing support and not at the grid sensing area. Apply a drop of adhesive B -610 to the back of the strain gauge

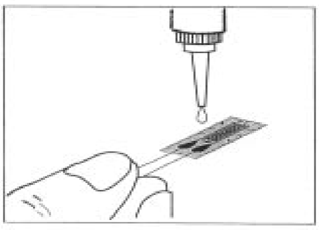


Figure.23 Applying adhesive behind the strain gauge

The strain gauge should be placed in the correct position. It should be covered with a piece of Teflon film

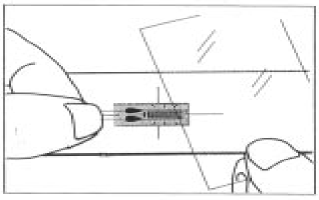


Figure.24 Applying a Teflon film on strain gauge

Now slight pressure is applied with the help of thumb to squeeze out the excess amount of adhesive and to prevent formation of possible air bubbles underneath the gauge. Complete the bonding work by removing the Teflon film as shown in figure 21.

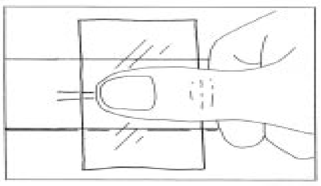


Figure.25 Applying pressure on the strain gauge

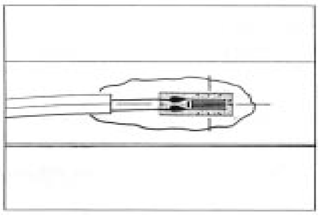


Figure.26 Bonded strain gauge

All the sequential steps completes the bonding procedure on to the strain gauges.

Figure.27 Bonding of strain gauge on the octagonal ring

Silicon resin, Adhesive B610 and IPA solution used in the bonding work is shown in the Figure 23.

Soldering on strain gauges:

(a) Soldering on strain gauges must be performed for completing the circuit and formation of Wheatstone bridge. It is done with the help of temperature controlled soldering iron. The temperature of the soldering iron should be set to approximately 380 °C to 400 °C.

(b) Solder wire used contains 60 % tin and 40 % lead having melting point of 183 °C. Liquid rosin is used as a suitable flux material.

Protection of strain gauges

The strain gauge and the area around it should be protected with a suitable coating against moisture, oil, dust and other chemical influences. The selection of a suitable coating depends on the environmental conditions and the expected temperatures. Silicon

Resin is applied on to the gauges for their protection against moisture, oil, dust and other chemical influences.

6.7.7 Assembly of dynamometer

(a) All the four octagonal rings are fastened to the lower plate with the help of M5 screws. Two of these rings are aligned in the X axis direction and the remaining two rings are aligned in the Y axis direction.

(b) Plexiglass casing is then inserted into the slots of lower plate in order to protect the octagonal rings from hot chips during machining operation.

(c)A small opening is left in the casing from one of the sides so that external excitation voltage supply can be given to the input terminals of Wheatstone bridge circuit and also the output voltage can be suitably interfaced with the amplifier circuit.

(d) Upper plate is then put on to the rings from the top side. It must be made sure that the casing should be properly fitted into the slots of upper and lower plates. The rings are secured and held tightly with the upper plate by M5 screws.

(e) Bench Vice is fitted on to the upper plate with the help of M5 screws.

(f) A Rectangular work piece of AISI 1020 mild steel material having dimensions of 60 x 30 x 20 mm is fitted in the vice for the purpose of experimentation.

Now the Dynamometer is ready for testing work and it can be clamped into the T slots of CNC milling machine bed with the help of nut-bolts and washers.

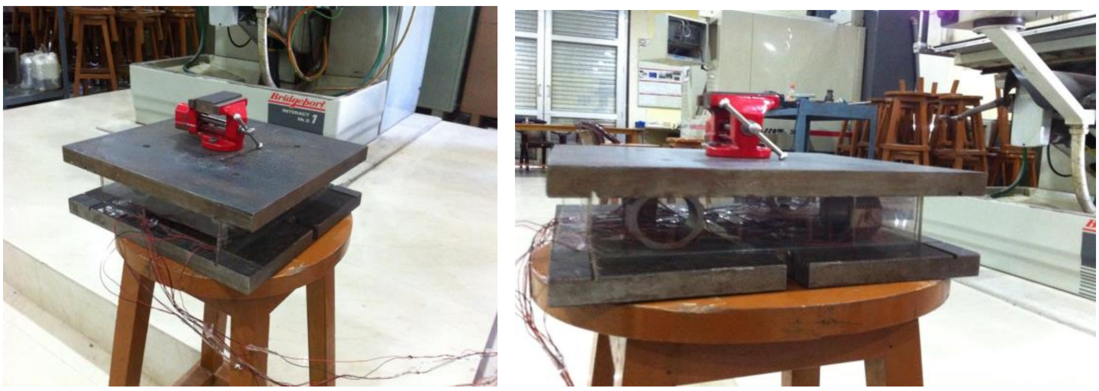
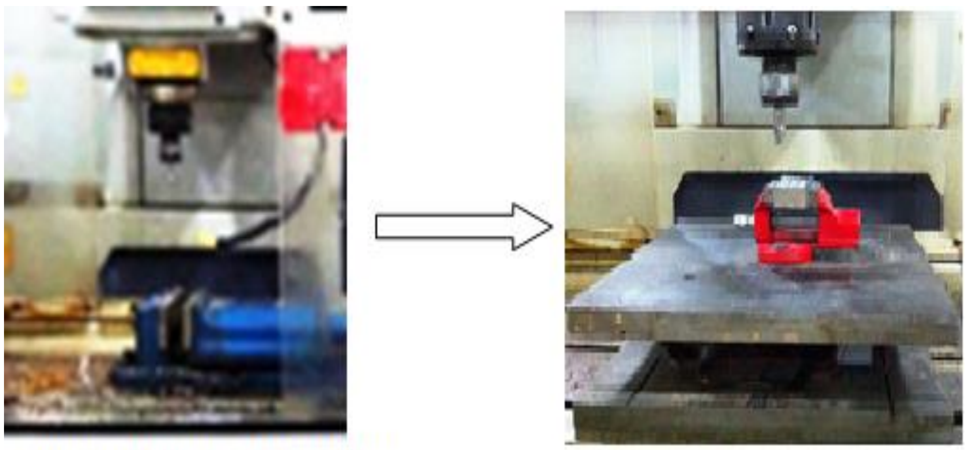


Figure.31 Assembled dynamometer

Table 1: List of components used for dynamometer **assembly**

S.No	Name of the Component	Dimensions(mm)	Quantity
1	Steel plates : AISI 1020	300 x 300 x 20	2
2	Octagonal rings : AISI 1020	Dia. 40, length 50	4
3	Strain gauges: NICTECH-CF- 350-5 AA (II)-C20	-	16
4	Resin : Silicon	-	1
5	Adhesive : B 610	-	1
6	Cleaner : IPA solution	-	1
7	Screws : M5	Dia. 5	4
8	Data logger : Compatible	-	1

The dynamometer designed was a three force component set up capable of measuring cutting forces during milling operations. A computer interface was made for data acquisition. Figure. 32 (a) shows a bench vice fixed on the bed of CNC machine which was removed to install the dynamometer on the machine. figure. 32 (b) shows the complete set up installed on the CNC machine.



(a)Bench vice fixed on CNC machine

Installed Dynamometer

Figure 32 Dynamometer installation on bench vice

6.8 Data acquisition system

DAQ (Data Acquisition) is defined as the process of taking a real world signal as input such as voltage or current into the computer for processing, analysis, storage and other data manipulation purposes. The data have to be analyzed and processed to generate further signals for controlling external equipment. The acquired data may have to be stored, printed and displayed. To read and store the cutting force data automatically on a computer during milling operation, a data logger system with the necessary hardware was devised and connected to the developed dynamometer. The stored cutting force data is in the form of excel sheets which can be retrieved and used for analysis purpose as and when required.

Strain gauges require an excitation voltage to generate a voltage representing strain. This voltage source should be constant and at a level recommended by the strain gauge manufacturer. While no standard voltage level is recognized industry wide, excitation voltage levels of around between 3 and 10 V are common. A higher excitation voltage generates a proportionately higher output voltage. However, such a high voltage can also cause larger errors because of self-heating of strain gauges. Keeping these factors in mind excitation voltage of 5V DC was given to the bridge. Once the voltage readings from the strain gauge were obtained, they are still in analog form as voltage. These analog signals need to be converted to digital signals. This can be done using an Analog to digital converter. ADC 0808 is used for the conversion process. ATMEL AT 89 C52 microcontroller has been used for the processing purpose. The display unit is a standard LCD JHD 629-204A which can display 4 lines of 20 characters each. Thus, the instantaneous force readings are displayed on the LCD screen. Figure.33 shows the complete circuit diagram of the data logger. Figure. 34 gives the flow diagram of the data acquisition process.

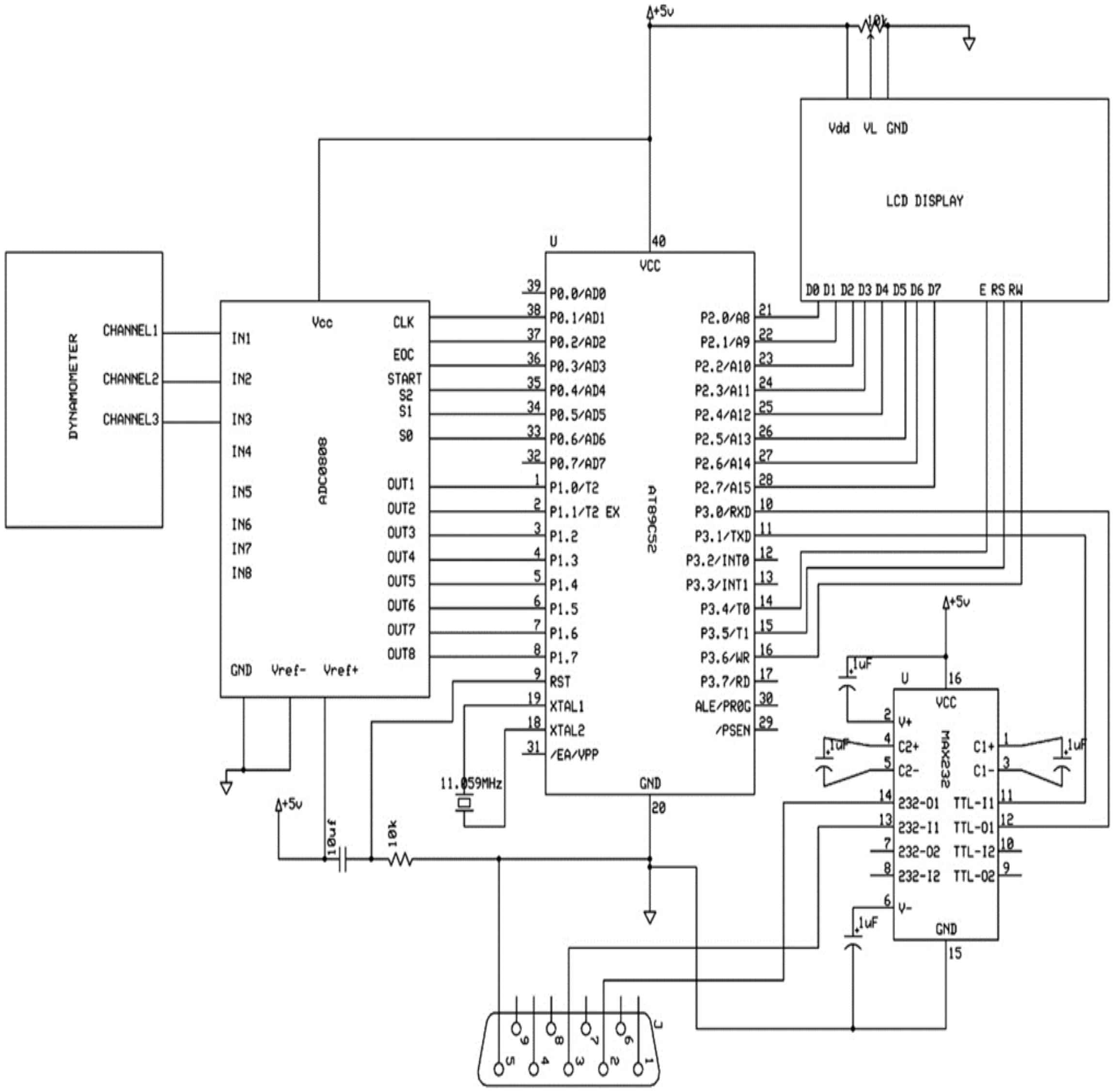


Figure.33 Circuit diagram for data logger

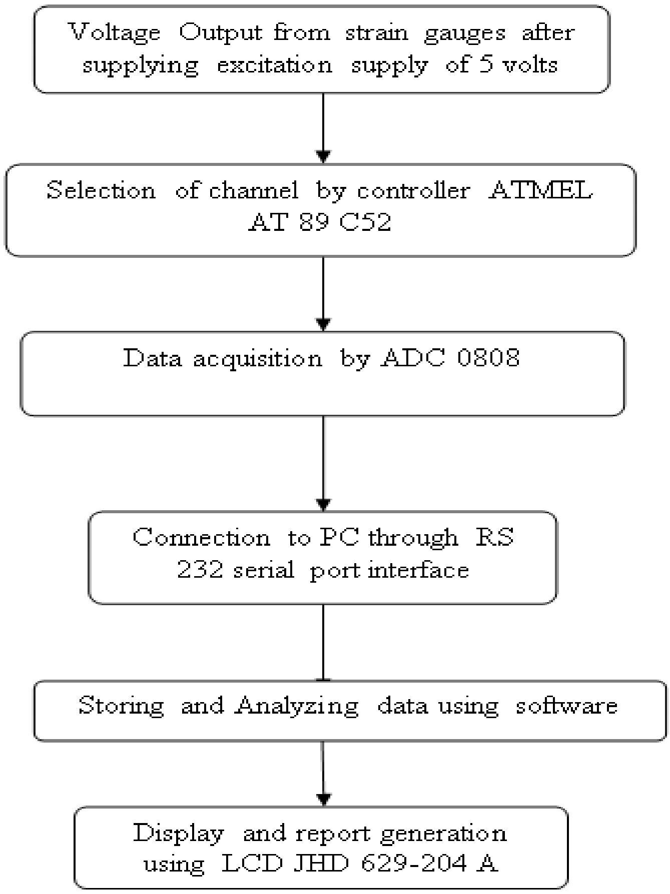


Figure.34 Flow diagram of data acquisition

Data logger

On-line and real-time information of the cutting force data is automatically read and stored by the data logger system during metal cutting. A data-logger contains an electrical circuit, which acts as an interface between the sensors and the computer. PC-based data loggers were first connected to a computer so that they can receive a program of instructions for collecting and storing data from the sensors. Having received its instructions, it can be connected to the experimental data through the sensors it is going to monitor. While performing the experiment, the data-logger was concurrently connected to the computer so that the computer can retrieve the data and display it in the form of excel sheets. The complete fabricated circuit of the data logger is shown in figure.35

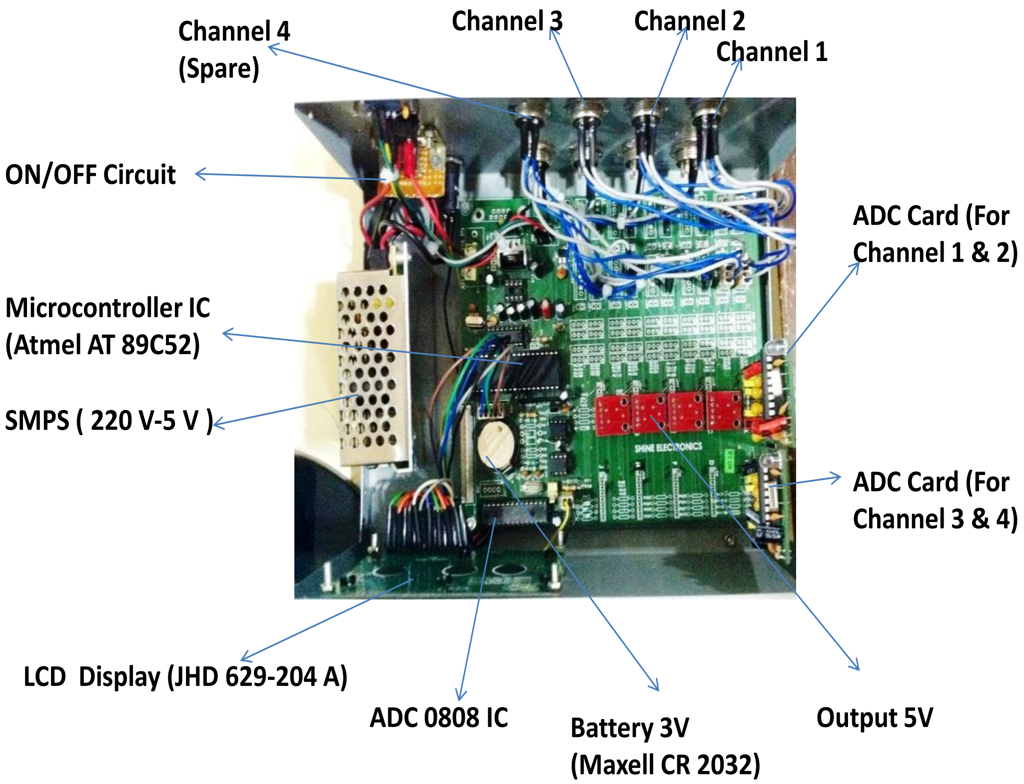


Figure.35 Fabricated data logger circuit diagram

Calibration of the developed dynamometer

For determining the elastic deflection of the octagonal rings and consequently the output voltage under load, the developed force measurement system was calibrated [115] [112] [106]. The calibration was done for the vertical direction. A load of up to 5 KN was applied in an interval of 500 N and the output voltage values were recorded for each load intervals. Hence, calibration curve was obtained to convert the output readings into forces. The effect of cross sensitivity was also examined, and minor fluctuations were observed. These minor fluctuations were small enough to be ignored. A vertical known force is applied on the developed dynamometer with the help of universal testing machine. Each time a known force is applied and the corresponding output voltage was recorded. The calibration curve for vertical force vs. output voltage is shown in Fig. 10. The effect of vertical loading in the horizontal direction was also studied (i.e., cross-sensitivity). It is observed that the sensitivity of horizontal component due to vertical loading is negligible as shown in figure 36. A linear relationship with correlation coefficients (R2) of 0.987 was obtained between the applied force and output voltage. Using this relationship any real time vertical force can be measured.

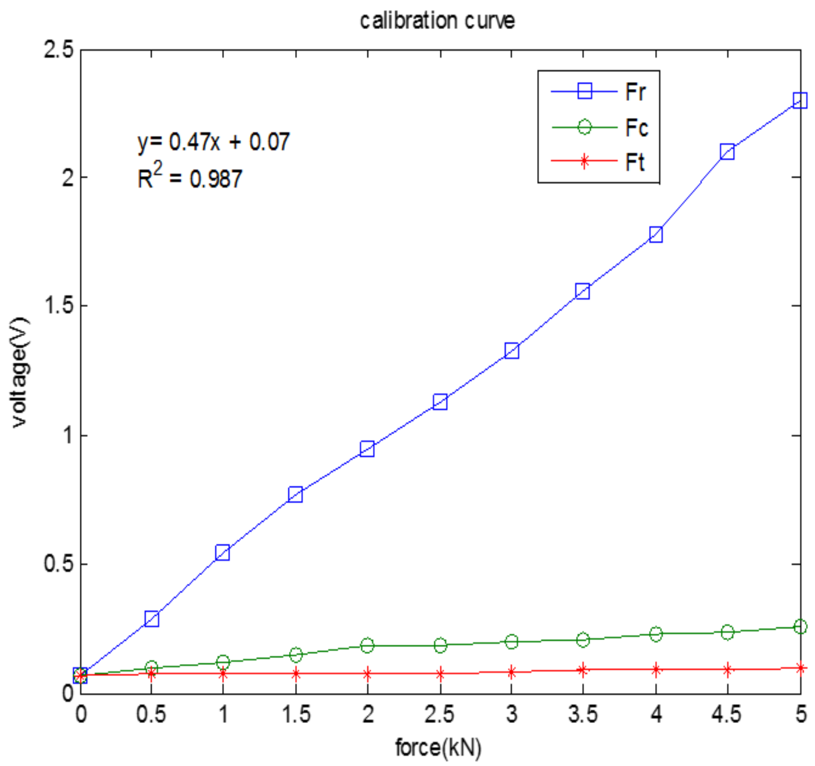


Figure.36 Calibration for vertical loading

The calibration has been performed through the following steps (see, figure. 37). To perform the experiments, workpieces of AISI 1020 steel having dimensions of 60 mm x 30 mm x 20 mm were cut with the help of power saw. After cutting the work pieces of required dimensions, the cleaning of CNC milling machine on which the experiments were to be conducted was carried out and it was prepared for end milling operation. All the necessary related tools and measuring equipment were arranged near the experimental CNC machine.

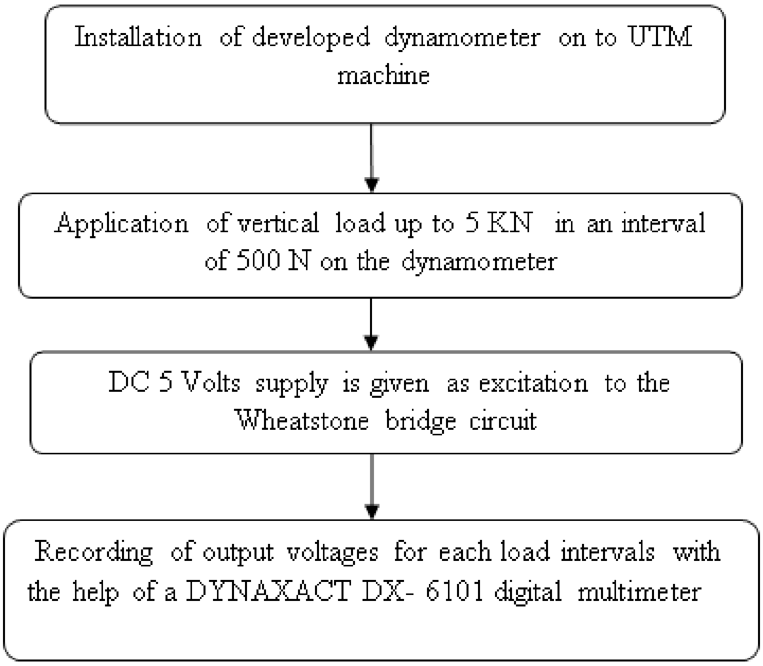


Figure.37 Sequential steps for calibration

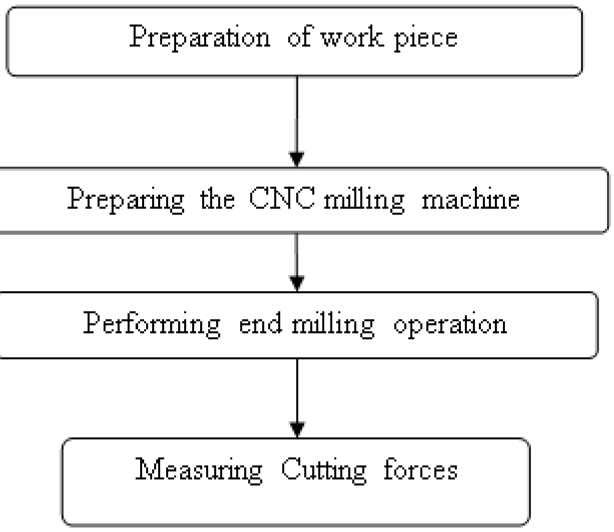


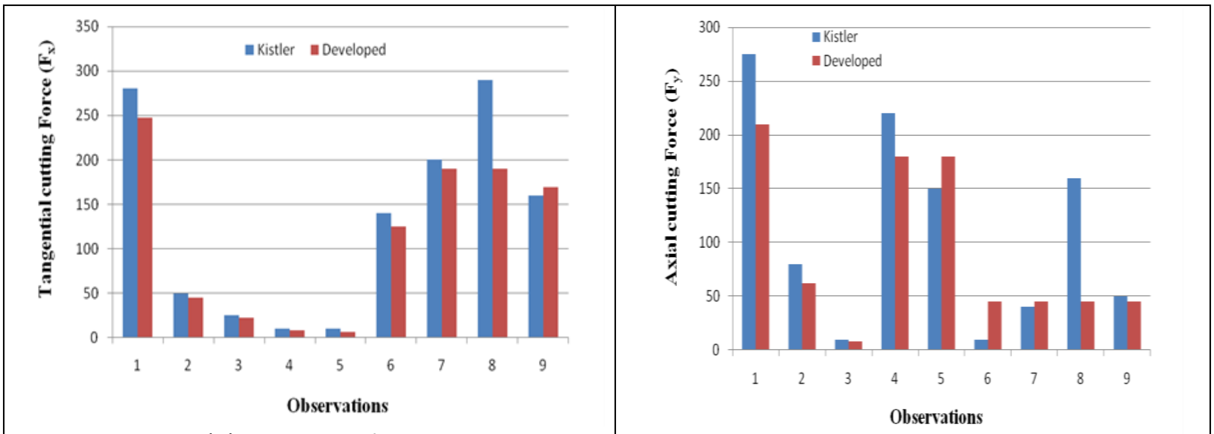
Figure.38 Plan for experimentation

The end milling operation was carried out on marble workpieces using the different combination of cutting parameters designed by Design of experiment on CNC milling machine. The Taguchi design of experiments provides an experimentation design which can analyze effects of all control factors over their entire range with a minimum number of experiments. In this experimental process 9 different combinations of milled lines with 8 mm width were made by performing an end milling operation on different marble samples of 60 mm x 30mm x 20 mm size. Meanwhile, the cutting tool used is diamond coated end milling tool with four flutes (diameter 8 mm). The L9 orthogonal array design was used to get the output data uniformly distributed all over the ranges of input parameters. In this way, 9 experiments were carried out with different combinations of the levels of the input parameters. Thus the three levels of control factors i.e. cutting speed, feed and depth of cut selected for experimentation are given in Table 2.

Table 2: Levels of control factors

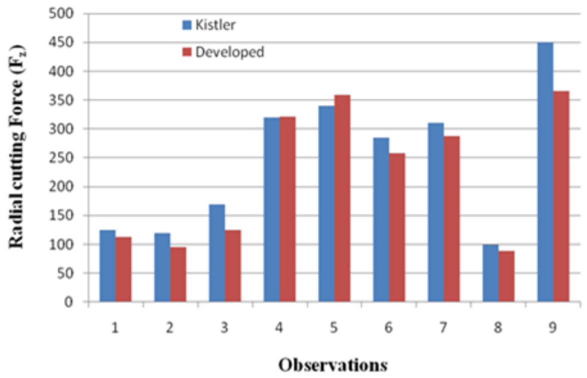
Level	Cutting Speed (rpm)	Feed (mm/min)	Depth of cut (mm)
-1 (low)	204	100	0.25
0 (medium)	450	175	0.50
+1 (high)	680	315	0.75

Cutting forces during the end milling operation were measured and recorded in the excel sheet using the interfaced data logger. Average values of the cutting force peaks were selected. The results of force variations in x, y and z directions at a different combination of input machining parameter viz. Cutting speed, feed, and depth of cut are recorded. The Taguchi L9 orthogonal array is selected to perform the experiments. The measured cutting forces were compared with the cutting forces measured by Kistler – 5070 A dynamometer at same cutting conditions (see, Figure.39). The mean force variation measured using Kistler and Developed dynamometer is shown in figure.40



(a) Tangential Forces

(b) Axial Forces



(c) Radial Forces

Figure.39 Comparison of Cutting forces measured by Kistler and Developed Dynamometer.

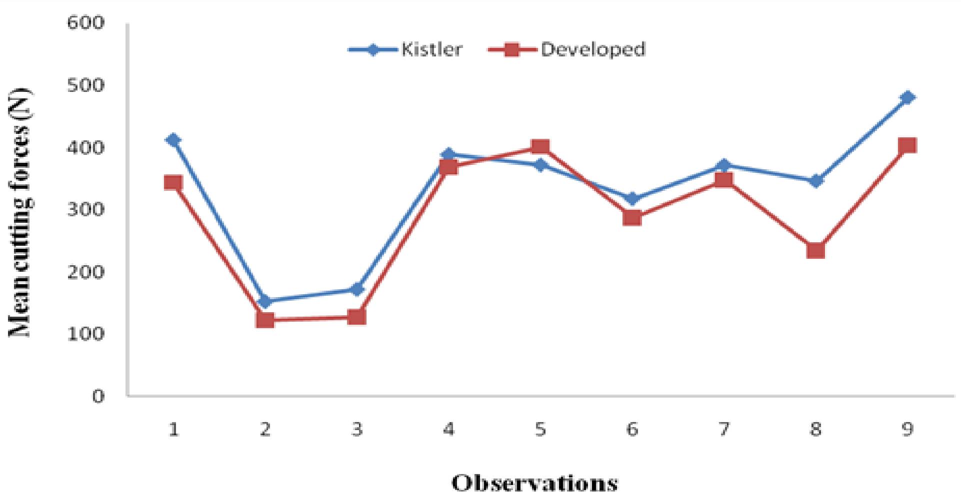


Figure.40 Mean Cutting Force Variation Measured using Kistler and Developed Dynamometer

Annexure II Smart stone cutter based on direct use of electromagnetic forces and intelligent electronics circuitry patent details

The Problem:

The conventional mechanism of stone cutting is done using Electrical motor driven diamond segmented saw blades as shown in Fig. 1. This machining process results in major cost and waste generation while processing of marbles and other natural stones like sandstone and granites etc. The principal factors that require consideration in predicting sawing rates are types of diamond saw, saw operating parameters and properties the sawn rock. Therefore, conventional cutting processes were analyzed with industrial survey in various stone industries located in and around Jaipur. Based on the preliminary inputs for the performance parameters a set of questions were prepared for industrial survey including material of blade and diamond bit, RPM, dimension and slug formation.

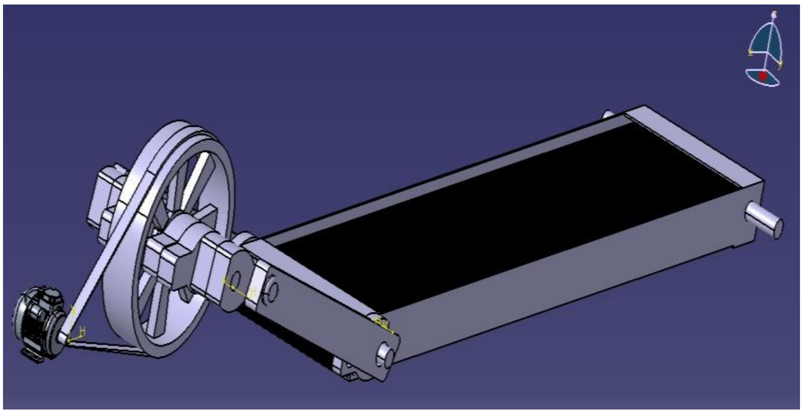


Fig. 1 Conventional gang saw stone cutter arrangement

The industrial survey conducted revealed that there are many reasons for the waste that is being generated during the sawing operations. Some of them can be outlined as below:-

- The use of the conventional machine which are very robust and huge while sawing produces lots of noise pollution as well as vibration which increases the waste generated.

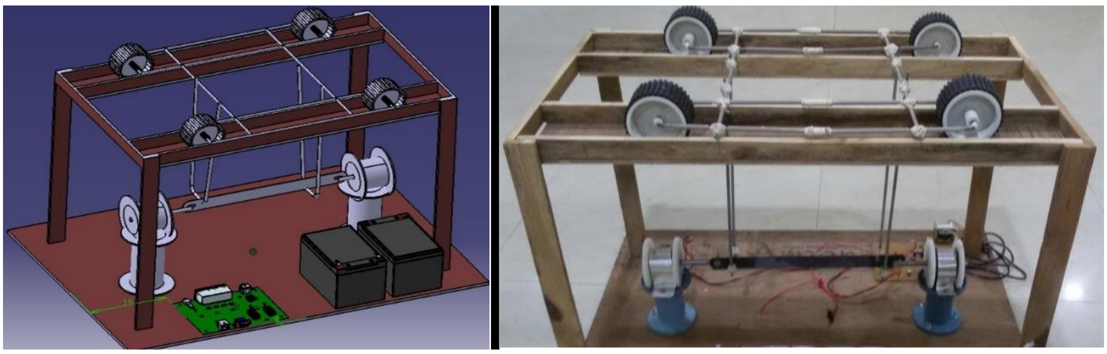
- A series of Sawing blades that are being attached to the machine vibrates and wobbles which leads to inaccurate sawing of the block which causes the increase in the waste.
- Due to the heavy and robust machine the energy consumption of the equipment increases, which is one of the parameters to be considered in the production process.
- The vibration of the sawing blades leads to improper cutting which is directly linked to the improper contact angles of the tool bits to the surface of the marble being cut and hence the tool wears faster than the expected life.
- Thus, worn out tool further increases the waste generated while sawing.

So, due to the above listed reasons a disruptive solution is required looking into an alternate energy source for cutting the stones such as marble. The inventors concluded to work on an idea of different mechanism for stone cutting which is

- Innovative to remove frictional losses caused by flywheel and transmission line.
- Useful even if variation in slab thickness is required.
- Having reduced power consumption and increased safety.
- Compact in structure.

The Proposed Solution:

To meet these requirements design and development of magnetic field assisted stone cutting machine has been done. As shown in Fig. 2, this arrangement includes single blade, solenoid, relay and timer circuit, overhead wheel mechanism, D.C. power batteries and tubes.



(a) **(b)**

Fig. 2 Magnetic Field Assisted Stone Cutting System (a) CAD model (b) Working

Model

- Magnetic field assisted technique is used to reduce mechanical loses and remove transmission line starting from motor to blades in conventional to make it compact.
- Overhead mechanism is provided for betterment i.e. to increase safety by providing cover, to withstand load of cutter.
- Overhead wheels produce extra mechanical energy by rolling which can be further utilized.
- Tubes having small holes to spray water connects 4 wheels as well as remove separate 'static connection required for wet mechanism'.
- Although a single blade is used but multiple parallel gang of blades or diamond beaded wires may be used to overcome problem of variation in slab thickness due to vibrations.
- Relay and timer is used to reverse the polarity of the electric field and ensures the to and fro motion of the blades and wire cutters.
- Proposed arrangement column is used to mount all the parts of the equipment and the work piece to carry out the machining operation.
- The electrical circuitry with controllers, motors and gears enables to control the different parameters of the system like speed, feed, depth of cut, coolant flow and Power requirements according to the required hardness of the marble to be cut.

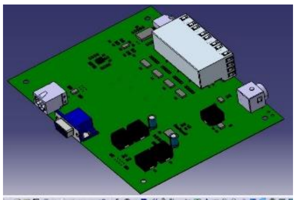


Fig. 3 Relay and Timer circuit

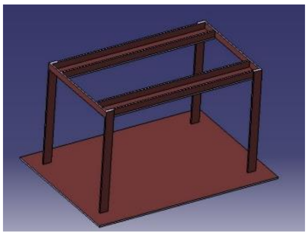


Fig. 4 Proposed Arrangement

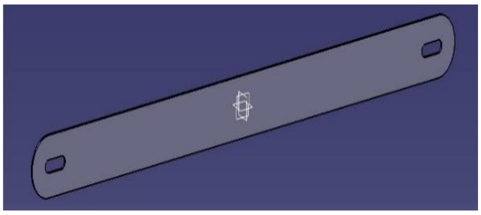


Fig. 5 Blade cutter

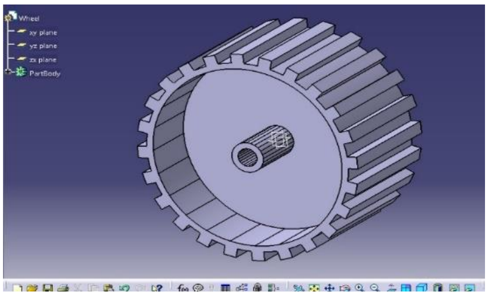


Fig. 6 Robot wheels

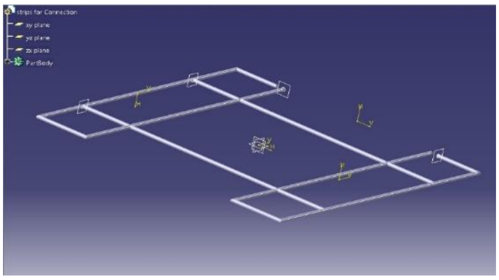


Fig. 7 Cylindrical tubes

The Working Process:

As the current passes in the copper coils (one at each end) by means of D.C. Batteries, a magnetic field generates. This is further controlled with the help of relay and timer circuit, which changes polarity of both solenoids. At a time one solenoid is on, other one is at off condition and vice versa. So reciprocating motion gets generated in cutter being attached with iron core of the solenoid. Overhead wheel arrangement is connected with cutter by means of tubes. These tubes are further connected with wheels to create rolling motion over the bed.

Here is calculation of using coil turns to create force of 4 N and Diameter 2cm.

Magnetic field inside solenoid at center B= μ_0nI

Here $\mu_0 = 4\pi\times10^{-7}$, I =2.1 amp.

Force generated by coil to move cutter is

F= $\pi R^2 B^2(\mu_m/\mu_0 - 1)/2\mu_0$

n= 6991.68 turns/meter

Analyzing available methods in industry and problem faced by them, a novel technique has been designed, analyzed and fabricated. This model has certain advantages over conventional stone cutters to resolve these problems.

- This technique is based on direct use of electromagnetic field for getting reciprocating motion of stone cutting blade to reduce frictional losses. In place of use of rotary devices like electric motors, the direct use of electric field reciprocates cutter blade which is further controlled using rustic timing circuit.
- Overhead mechanism is used to grip the blade, for safety purpose and to generate mechanical power which can be further used for allied application.
- No separate arrangement is required to makes it wet type as water can be supplied through overhead tubes.
- In the prototype, electric power is received by 24 Volt, 7Ah battery, which translates stone cutting blade, the model can be scaled up..
- Timer circuit is provided which is best replacement of ECU used in conventional models.

Brief Bio-data

Bhargav Prajwal currently working as an Assistant professor in Shreyash college of Engineering and Technology, Aurangabad, India. He currently submitted his Ph.D. in Mechanical Engineering from Malaviya National Institute of Technology, Jaipur. He received his bachelor's degree in Mechanical Engineering from JNTU Hyderabad in 2008 and Masters in Automotive Engineering from Coventry University (United Kingdom) in 2010. Worked as Assistant professor in Dehradun Institute of Technology, Dehradun from 2011- 2013. His research interests are Ceramic machining, Advance manufacturing processes, Sustainable manufacturing, Rapid prototyping and CAD/CAM.