A Dissertation Report On

"An Experimental Investigation to Evaluate Abrasion Wear Characteristics and Study the Effect of Micro Cracks on The Mechanical Properties of Various Marbles Types of Rajasthan Region."

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CERTIFICATE

This is to certify that the dissertation report entitled **"An Experimental Investigation to Evaluate Abrasion Wear Characteristics and Study the Effect of Micro Cracks on the Mechanical Properties of Various Marbles Types of Rajasthan Region"** is being submitted by **Mr. Rohit Choudhary**, M.tech-4th semester **(2013PPE5022)** in partial fulfillment of award of the degree of Master of Technology, Production Engineering, Mechanical Engineering Department, Malaviya National Institute of Technology, Jaipur is found to be satisfactory and is hereby approved for submission.

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ABSTRACT

Marble plays an important role in construction and decorative industry. It has high performance due to its durability and attractive aesthetic properties. Due to this demand for marble is growing worldwide. These stones are used in various applications like internal floorings, claddings and external pavement applications. Floor coverings by natural stones are usually tested by third body abrasive wear test. The abrasive particles are loose, free to rotate and move in third- body abrasive wear. The abrasive particles used for the test was white fused alumina with a grit size of 80 in accordance with standard FEPA 42F.

Abrasive wear tests were performed on different types of marbles found in Rajasthan according to ASTM C241 standard. Regression analysis was carried out to investigate the relationship 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 hardness. To ascertain this statement Vicker's hardness test was carried out to determine hardness of various marble types found in Rajasthan state. The same was correlated with various other properties of the specimen. As a result, abrasion resistance was found to be highly related with properties like modulus of rupture ($R^2 \approx 0.96$), compressive strength ($R^2 \approx 0.94$), flexural strength ($R^2 \approx 0.96$) along with hardness ($R^2 \approx 0.84$) while less related to the water absorption ($R^2 \approx 0.08$) and bulk specific gravity ($R^2 \approx 0.37$).

Tests were performed on a wide wheel abrasion (WWA) apparatus based on EN 14157:2004 standards with varying the contact loads from 40N to 140N and speed ranging from 15 to 75 RPM. Results indicated that wear linearly increases with applied load while other factors were kept constant. Whereas with the increase in sliding speed, wear was initially increased, and then decreased while other factors were kept constant. In EN standards abrasive wear rate ranking of natural stones like marble are done according to their abrasive wear. But all the tests of standards are performed at fixed load and fixed sliding speed. Abrasion of marbles under the influence of foot traffic was found to be a function of sliding speed ($R^2 \approx 0.94$) and load ($R^2 \approx 0.80$) exerted on them by fine solid particles. It was also observed that change in applied load as well as change in the sliding speed while other factors were kept constant influenced the ranking

of marbles with respect to abrasion wear. This showed that the ranking of marbles at different load and different speed could results in different conclusions.

Also to understand the failure mechanism of marble, study of micro-cracks was carried out. It was studied that the environmental changes lead to formation of new micro cracks and can also lead to the expansion of existing ones. The calcite marble is more affected by the environmental changes than the dolomite marble. Large grain size and straight grain boundary result in more length and large connectivity cracks.

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ABBREVIATION

ASTM = American society for testing and materials	CSM = continuous stiffness measurement
Ha = Abrasive hardness rating	MR = modulus of rupture
EN = European standards	UTS = ultimate tensile strength
AR = Abrasive resistance	W_r = wear rate
CDOS = centre for development of stones	DSRW = dry sand rubber wheel test
WWA = wide wheel apparatus	CS = compressive strength
BA = Bohme apparatus	N = rebound number
UCS = uniaxial compressive strength	Sh = shore hardness index
BTS = Brazilian tensile strength	V_P = P-wave velocity
ITS = indirect tensile strength	LN = load index
LOV = loss of volume	FEPA = federation of European producers of abrasives
x = porosity of rocks %	
ISI = Indian standard institute	MVH = micro vicker hardness
MT = metric tonnes	FS = flexural strength
OGL = open general licences	BSD = bulk specific gravity
BMS = building management system	RPM = revolution per minute
PTV = pendulum test value	BIG1 = brittle Intergranular fracture type 1
WA = water absorption	Wt. = weight

Chapter-1

Introduction

1.1 Marble

Marbles are the widely used construction engineering material. The word marble has been derived from a Latin word **"**marmor**".** The word "marmor" itself comes from the Greek word **"**marmaros**"** which means a shining stone. Marble is a recrystallised, compact variety of metamorphosed limestone capable of taking polish. Marble is a crystalline rock whose main composition is either of calcite, dolomite or serpentine which can be cut into blocks, can be sawed and can be given good polish. Marbles can be considered as dimensional stone like granite, limestone and travertine. Any natural rock is known as dimensional stone if it satisfies the certain qualitative requirement and can be quarried in large blocks. These large blocks can be processed into specific dimension for a particular application.

Here two words of definition are important to the marble industry, they are metamorphic and recrystallised which means many marbles are developed by the process of recrystallization and metamorphism. Marble is generally formed when the limestone is subjected to pressure and heat of metamorphism. High pressure is required to develop the metamorphic marbles while recrystallized marbles can be developed from limestone under normal pressure in thick sedimentary sequences. Due to this high pressure formation metamorphic marbles are tighter, denser and more fracture free than other marbles.

1.1.1 Metamorphism

Metamorphism can be defined as a process in which chemical composition, texture or internal structure of the rock gets changed, due to its subjection to change in heat, Pressure or introduction of new chemical substance. The pre existing arrangement or texture of the mineral in rock gets changed. The change is a solid state change i.e. without the protolith (pre existing mineral or geological texture) melting into liquid state. Thus metamorphism simply means change in chemical composition and crystal structure of the minerals in a solid state which are present in rock. Metamorphic rocks have some specific minerals known as index minerals such as quartz, feldspars, micas, garnet, and sillimanite etc. Metamorphic rocks generally have five textures, these are as slaty (found in slate and phyllite), schistose (found in schist), gneissose (found in gneiss), granoblastic (found in granulite, marbles and quartz) and hornfelsic (hornfels and skarn).

Classification of metamorphism

Metamorphism can be classified into six types

(a) Contact metamorphism

In contact metamorphism change in rock occurs when magma is embedded into surrounding rock. Wherever the magma comes in contact with the rock, it causes greatest change due to high temperature at the boundary. Due to this a limestone may get change to yellowish, greenish, grey or siliceous marble.

(b) Regional or dynamic metamorphism

In regional metamorphism change occurs in larger area and masses of rock. Metamorphism occurs at great depths below the earth surface. Rock is subjected to high temperature and pressure caused by immense weight of the above rock layers.

(c) Catalytic metamorphism

In catalytic metamorphism two rocks slide against each other, heat is generated due to the friction of the sliding along a shear zone. Rock gets mechanically deformed, crushed, pulverized due to shearing.

(d) Hydrothermal metamorphism

Hydrothermal fluids altered the rock composition at moderate pressure and high temperature. Mg-Fe rich minerals are altered into talc, clay and serpentine. This metamorphism results in rich ore deposits.

(e) Burial metamorphism

When sedimentary rocks are buried to depth of 100 meters, temperature reaches to $300^{\circ}C$. New minerals are formed generally zeolites.

(f) Shock (impact) metamorphism

Whenever there is large volcanic eruption or meteorite or comet contact the earth, ultra high pressure is generated in the rock. This ultra high pressure produces minerals that are stable at high pressure only. Textures like shock lamella and shatter cones can also be produced. Metamorphism can be further classified into low grade or high grade metamorphism. Low grade required less burial temperature and pressure as compare to the high grade metamorphism. Low grade rocks have fine grained while high grade have coarse grained.

1.1.2 Recrystallization

In recrystallization the pre-existing mineral grains in rock are converted into new mineral grains by the solid state diffusion of ions due to the change in the temperature, pressure, or composition of the rock. The mineral chemistry remains the same and there is only change in the crystal size. Metamorphism is a chemical change process while recrystallization is a physical process. Limestone is a sedimentary rock which undergoes recrystallization and gets converted into marble. Similarly clay is converted into muscovite mica.

Table 1.1 various textures and their metamorphism type

Low grade rocks **Fine grained**				**High grade** rocks **Coarse grained**
Slate	**Phyllite**	**Schist**	**Genesis**	**Granulite**

1.1.3 Marble Composition

There are large variety of minerals in marbles which depends mainly on the geological origin and burial history of the marble. Marbles generally have fine to coarse grained, recrystallized Calcite ($CaCO_3$), and/or dolomite, ($CaMg(CO_3)_2$), which has a texture of relatively uniform crystals ranging from very large (inches) to very fine, small, uniform sized crystals. Generally Calcite is the dominant mineral of all the marbles. There are also traces of impurities present in the marbles which impart colour to them as well as land derived clays, slits and sands. Organic matter imparts grey to black colour; chlorite and epidote give light to yellowish green. Other minerals like magnesite ($MgCO_3$) are also found in metamorphic marbles but not in recrystallized marbles. Pyrites or iron sulphide (FeS_2) may also sometime found in marbles. Pyrite comes out on the face of cut and polished marble easily then it reacts with moisture in the atmosphere to form the undesirable and difficult to remove staining. It has brassy metallic luster.

1.2 Marble Industry in India

India has a wide varities of stones namely granite, marble, sandstone, limestone, slate, and quartzite. It is one of the largest producers of raw stone material. Marble deposits are found in many states in India especially in Rajasthan, Gujarat, Madhya Pradesh, Haryana, and Andhra Pradesh. Rajasthan is the main depository of marble accounts for over 90% of total marble production in India. Rajasthan is followed by the Gujarat, which produces some very fine marble followed by Madhya Pradesh. Recently some different kinds of marble are also being found in Bihar, Jammu & Kashmir, Maharashtra, Sikkim, and Uttar Pradesh & Bengal.

Rajasthan has the largest deposit of marble in India. Rajasthan is a hub of mineral in India with more than 50 types of minerals and rocks. It has vast deposits of natural rocks known as stones which include Granite, Marble, Sandstone, Limestone, Slate and Quartzite.

The stone industry has not only provided occupation to many people in the state but also endowed it with many different colours which can be seen on many historical building. Almost 90-95% of the marble in India is manufactured and processed in the Rajasthan. Rajasthan possesses large reserve of about 1100 million tonnes of good quality marbles.

Bureau of Indian standard (Indian standard institute i.e. ISI) (IS 1130-1969) has classified Indian marbles into ten groups on the basis of colour, shade and pattern. Rajasthan is the only state which has all ten groups. [36]

These ten groups are as follows

(a) Plain white marble
(b) White veined marble
(c) Black zebra marble
(d) Panther marble
(e) Plain black marble
(f) Green marble
(g) Pink marble
(h) Grey marble
(i) Brown marble
(j) Pink adanga marble

1.2.1 Marble Production

In India marble industry has evolved into the production and manufacturing of blocks, flooring slabs, structural slabs, monuments, tomb stones, sculptures, artifacts, cobbles, cubes, pebbles and landscape garden stones. Due to the development of simple and easy mining machinery & new mining fields has led to increase in marble production. Although India produces machinery, there is an excellent opportunity for exporting machineries for working stone cutting, sawing, grinding and polishing. India require almost 4.8 crore MT (metric tonnes) of rough marble every year while the domestic supply is only limited to 1.16 crore MT only. India meets its most of the marble requirement through imports. There is a need of new foreign trade policy in India so we can compete at the world level. Indian marble industry is about 20,000 crore and it is facing high risk of losses in foreign trade as well as jobs. Rough marble imports in Indian are limited to only those units which have been in the business for 5 years on or prior to 31 March 2013 and also have minimum Rs 5 crore turnovers during financial year 2008-2012 .This results in the black marketing and monopoly of big players. Marble exports by India in last 3 years are limited to about $300 billion. Various steps and methods are requiring for boosting and increasing its contribution in the world market. Marble industrialists have requested commerce and industry ministry for removal of quantitative restrictions on imports and allow easy imports under OGL (open general licences).

1.3 Marble Properties

Marble is one of the most widely used construction engineering material due to its unique properties like its abilities to take polished surface, to resist weather conditions and other environmental conditions, high load bearing capacity, as well as resistance to foot traffic. Since marble is the product of nature it's properties likely to vary due to atmospheric and environmental conditions. Hence same marble can have different values of the same properties.

1.3.1 Colour

Colour in a marble is generally determined by the substances which is present in the minor amount during formation. The presence of iron oxide imparts pinks, yellows, browns and red colour to the marbles. Most Grays, blue Grays, and blacks are of bituminous origin.

While the presence of micas, chlorites and silicates lead to the green colour in a marble.

1.3.2 Physical Properties

The value of physical properties of marble is determined by various standard test methods which are imposed by Dimension Stone Committee C18 of ASTM International. These values of physical properties are very useful for the Engineers and designers when Preliminary calculations are needed to be done.

The physical properties of marble are as follows:-

(a) Compressive Strength

Compressive strength of marble is also known as a crushing strength. The maximum stress require to crushed a standard marble specimen is known its compressive strength. The compressive strength of a marble can be determined according to ASTM C97 and EN 1926 test standards. The compressive strength of a marble is expected to lie in the range of 70-140 N/MM^2.

(b) Flexure Strength

Flexure strength is defined as the limit of the marble to withstand flexure stress without fracturing. It can be also termed as bending strength of the marble. It is one of the key properties which are required for the structural design of the marbles.

(c) Modulus of Elasticity

It is defined as the ratio of unit stress to the unit strain of a marble when subjected to a strain below its elastic limit.

(d) Density

Density of marble is expressed as specific gravity which is the density of the marble relative to the density of the water. Marble density generally lies in the range of 2.4 – 2.7 g/cm^3.

(e) Thermal Conductivity

Thermal conductivity is an intensive property and the ability of marble to conduct the heat. The value of thermal conductivity for marbles generally lies in the range of 2-3 W/mK. Marble is a better conductor of heat as compared to other floor lining materials.

(f) Modulus of Rupture

Modulus of rupture is the measure of the marble maximum load carrying capacity. It is the ratio of rupture bending moment to the section modulus. The modulus of rupture takes into account shearing stress along with the bending stress.

(g)Water Absorption

Water absorption is the proportion of water which can be soaked by a marble under a particular immersion conditions. Higher water absorption is an indication of poor weather ability of marble. This property also gives an indication about the porosity of marble that is volume of open pores accessible to moisture within the marble. ASTM C97 test standard and EN 13755:2008 are used to determine the water absorption capacity of marbles. A marble should have water absorption less than 0.5%.

1.3.3 Strength

The ability of a marble to resist the stress is known as its strength. The factors which affect the strength are rift and cleavage of the crystals, degree of cohesion, interlocking of crystals, any other materials present.

1.3.4 Fire Resistance

Marbles are non combustible material and can be treated as a fire resistance material. But due to its high thermal conductivity, heat is transferred very rapidly through them. Fire resistance evaluate whether a marble will catch fire or not, it also helps us to determine how much time will take by the nearby combustible materials to reach the temperature which will cause them to burn. The fire resistance of a marble can be improved by using insulating material as shown in table 1.2.

Fire resistance can be determined by "Fire Resistance Classifications of Building Construction," BMS92, National Bureau of standards.

Table 1.2 Insulating material used for improving fire resistance of marbles

S.No	Insulating Material	Time Improved In Fire Resistance
1	Paper Honeycomb	½ hour
2	Cement-Bonded Wood Excelsior	1 hour
3	Autoclaved Cellular Concrete	1½ hour

1.3.5 Abrasion Resistance

Abrasion Resistance is a property of a marble which gives an indication of the marble wearing quality when it is exposed to foot traffic. The property is tested according to the ASTM C241 M: 09 and EN 14157:2009 standards. Abrasion resistance is a property which is helpful in determining whether a marble is economically desirable and practical for floors and stairs. For this a marble should have high hardness and uniform wearing qualities. Marbles having abrasive hardness rating (Ha) of 10 or more can be used for flooring purposes. For Heavy traffic purposes such as in commercial floors, stair treads, and platforms, a marble should have Ha value of 12. When two or more marbles varieties are used for constructing surfaces of floors, in order to have uniform wear their Ha difference should not be greater than 5. If Ha difference value is more than 5 than the wear in marbles are not even and uniform.

1.3.6 Hysteresis

Hysteresis is a phenomenon in which marbles show small increase in volume after each rise in temperature from the starting point. Hysteresis causes differential expansion within the marbles, results in the bowing of marble panels ensues and produces compressive forces in the back of panels. This results in creep in the marble which in turn lead to the permanent deformation. Hysteresis also leads to the increase in the porosity of marble and make them vulnerable to corrosion from acids, and detrimental from freezing and thawing effects. For this minimum thickness of marble has to be determined to overcome the effects of hysteresis. This phenomenon is not found in each and every marble but instead it is present only in “True Marbles”.

1.3.7 Thermal Expansion

Almost all the marbles undergo thermal expansion. The thermal expansion becomes an important criterion when marble is used with dissimilar materials to form large units which are rigidly fixed. Almost each and every marble undergo a residual expansion of about 0.20% of the original size, when subjected to several cycles of heating and cooling. Clearances must be calculated accordingly to the expansion of the particular marbles.

1.3.8 Translucence

Translucence is a phenomenon of transmitting light. Translucence is one of the most distinguishable properties of a marble. This Phenomenon is not present in all the marbles and also the degree of translucence is different in all the marbles.

The factors affecting the translucence are as follows

(a) Crystal structure, only specific crystal structure marbles are able to transmit the light

(b) Colour, Lighter the colour more will be the translucence ability.

(c) Thickness, Greater the thickness lesser will be the translucence ability of the marble.

(d) Surface Finish, Translucency will be more in smooth finishes than in rough finishes.

1.3.9 Efflorescence and Staining

Efflorescence is a salt deposit, mostly white in colour that appears on the exterior surface of masonry walls. Efflorescence is caused by the sulphates of sodium, calcium, potassium, magnesium and iron. Efflorescence does not affect the marble. However, some of the salt crystals may form in the pores near the surface. Basically there is no difference in staining and efflorescence, expect that staining involves organic material. Staining leaves only an objectionable appearance and has no other effect on the marble.

1.4 Marble Testing

Many standards and test methods have been laid down in order to determine the suitability of different marbles for some specific applications in the construction industry. Marble's technical properties are generally related to its abrasion resistance, capability to resist external loads and low porosity which make it durable under various atmospheric conditions. The testing of various properties of marbles can be done according to three test standards. One of which is ASTM standards and other are EN and IS standards.

1.4.1 Water Absorption, Bulk Density, and Bulk Specific Gravity Testing

Water absorption, Bulk density, and bulk specific gravity testing of a marble is determined according to ASTM C97 test standard. In this method specimens are first heated to make them dry and then there weights are measured. After that these marble samples are submerged in water for almost two days so that they become saturated, there weights are measured while immersed in water and also in air while saturated. Water absorption can be determined by comparing the dry Weight and saturated weight obtained while samples submerged in water. Specific gravity and density can be determined by comparing the dry buoyant and the saturated weight obtained in air.

No. of samples = 08 in Nos.

Size of sample = 50×50×50 mm.

1.4.2. Compressive Strength Testing (ASTM C170)

Compressive strength testing of a marble samples are determined according to ASTM C170 test standard. The shape of sample can be cored drilled cylinder or a saw cut cubes. The samples are loaded in a calibrated test machine until they got fracture. The compressive strength of a tested sample can be calculated by dividing the maximum applied load to the loaded area of the sample. Usually five samples in both the wet and dry conditions are used.

The values of compressive strength of marbles are expected to lie in the range of 70-140 N/mm^2.

No. of samples = 5 to 10 in number in both dry and wet conditions.

Size of sample = 50×50×50 mm.

1.4.3. Modulus of Rupture (ASTM C99)

Modulus of rupture of a marble samples are determined according to ASTM C99 test standard. A single point load is applied in the middle of the span of length 180 mm. Almost 5 to 10 samples are tested in wet and dry conditions and load is also applied both parallel and perpendicular to the rift plane. This test provides bending strength of the marble similar to the ASTM C880 test standard but it does not consider actual thickness as well as exterior surface finish of the samples. It also has a shear component and hence gives higher evident strength of the marble rather than only the bending strength. Due to point load application the failure occurs only under the applied load and hence this test should not be used for design purposes.

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

Size of the sample = 200×100×60 mm

1.4.4. Flexural Strength (ASTM C880)

Flexure strength of a marble samples can be determined according to the ASTM C880 test standard. In this testing method marble samples are first cut from large panels or slabs. The load is applied at the quarter point of these specimens. This load is increased continuously until these samples get fracture. The maximum load at which the fracture occur is recorded and also flexural stress that occur at this load is recorded. Five samples are to be tested both in the dry and wet conditions as well as both parallel or perpendicular to the rift plane. During testing not 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 level as required. To completely understand the microstructure of marble samples testing in three orientations is necessary.

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

Size of the sample = 350×100×30 mm.

1.4.5. Slip Resistance Value with the British Pendulum Tester (ASTM E 303:2003)

Slip resistance testing is done to determine the coefficient of friction and gives an indication if there is any chance of slip and fall on the marble floor surface. This test is conducted to determine the slip resistance of a marble in both the wet and dry conditions. The pendulum tester has a standard dimension rubber piece which travel across the marble flooring sample for 124-126mm which is mounted on the pendulum device. When the pendulum arm is made to miss the floor sample completely, the pendulum arm swings up to point from where it has been started, and the pointer reads zero. If the floor is slippery then the pointer indicates readings nearby to zero, but if the flooring condition is anti-slip then the pendulum arm motion is blocked, giving results from zero to high numbers (35 or above) which gives an indication of anti slippery conditions. The level floor has a minimum PTV (pendulum test value) value of 36 for safety purposes.

No. of samples = 6 in Nos. (Polished or natural sample)

Size of the sample = 160×160×15 mm

1.4.6. Abrasion Resistance Testing (ASTM C241 & EN 14157:2004)

According to EN 14157:2004 there are three different tests to determine the abrasion resistance of natural stones (a) Wide wheel abrasion test (b) Bohme apparatus test (c) Amsler abrasion test. In wide wheel abrasion test sample is held against a rotating wheel, the abrasive particles fall between the wheel and the sample surface. The abrasive wear is determined on the basis of groove width. The abrasive particles should not be used more than three times. The Size of the sample is 100×70×70mm. For each stone six samples has to be prepared. According to ASTM C241, six samples of each stone having dimension of 50×50×25 is abraded by the rotating disc by an abrasive particle according to the standard conditions. The rotating disc is set for 45 revolutions per minute and a normal load of 20N is applied. The weight of the sample before and after testing is measured to determine the abrasion resistance.

1.5 Marbles under Investigation

1.5.1. Bhainslana Black Marble

Fig 1.5.1 Bhainslana Black Marble

The colour of Bhainslana black marble is black. The marble is given name as Bhainslana black since it is found near the Bhainslana village. Bhainslana is a village in Kotputli tehsil in Jaipur District of Rajasthan State, India. It is located 103 KM towards North from District head quarters Jaipur, 14 KM from Kotputli and 100 KM from State capital Jaipur. Bhainslana black is one of the very popular Indian marble in Europe. It has been exported to USA, Canada, Puerto Rico, UK, Poland, Russia, Ukraine, Costa Rica, Greece, Germany, Hungary, Netherlands, New Zealand, Serbia, Mexico, Lithuania, Slovenia, Bulgaria, Croatia, Australia and many more countries. The marble is widely accepted as a natural building stone material in these countries.

Table 1.3 Physical and mechanical properties of Bhainslana black marble, Sources: - Centre for development of stones (CDOS, Jaipur) [44].

S.No	Technical Information		Value	ASTM/INDIAN Standards
1	Water absorption(% by Weight)		0.03	C-97
2	Modulus of rupture (N/mm^2)	Dry Wet	22 21	C-99
3	Compressive Strength (N/mm^2)	Dry Wet	73 72	C-170
4	Flexure strength (N/mm^2)		21	IS 4860 Guidelines

1.5.2. Makrana Doongari Marble

Fig. 1.5.2 Makrana doongari marble

Makrana is one of the oldest and best quality marble in the world. It requires no reinforcement, can retain polishing well, has no change in colour and pin holes. It is also called as milky white marble. The colour of marble is white, gray and panther brown looks. Makrana is a village, in Naguar district of Rajasthan state. The Taj Mahal, Raudat Tahera, and Victorial memorial are built by this marble. Makrana has marble deposits of 56 MT. The total production of marble in Makrana is about 1.20 lakh tonnes per year with total revenue of Rs 36 crore per year. Makrana has many mining ranges, such as Doongari, Saabwali, Gulabi, Neharkhan, Matabhar, Kumari, Ulodi, Matabhar kumari, Chuck Doongari, Gulabi Chosira, and Devi etc.

Table 1.4 Physical and mechanical properties of Makrana Doongari marble, Sources: - Centre for development of stones (CDOS, Jaipur) [44].

S.No	Technical Information		Value	ASTM/INDIAN Standards
1	Water absorption(% by Weight)		0.04	C-97
2	Modulus of rupture (N/mm^2)	Dry Wet	15 17	C-99
3	Compressive Strength (N/mm^2)	Dry Wet	96 85	C-170
4	Flexure strength (N/mm^2)		17	IS 4860 Guidelines

1.5.3. Agaria White Marble

Fig. 1.5.3 Agaria white marble

Agaria marble is one of the finest quality marble found in Rajasthan. The colour of the marble is white. This marble does not require any chemical reinforcement. It has no pin holes, no colour change and polish loss. It has been used in India for the last 1000 years. There are 2500 marble seller units and 1500 gang saw units. Agaria has white colour with milky look along with the different figurative design and pattern. It has huge demand in the national as well as international market. It has been used for wall claddings, flooring, handicraft items etc. Agaria marble is found in Kishangarh city in Ajmer district of Rajasthan region.

Table 1.5 Physical and mechanical properties of Agaria white marble, Sources: - Centre for development of stones (CDOS, Jaipur) [44].

S.No	Technical Information		Value	ASTM/INDIAN Standards
1	Water absorption(% by Weight)		0.06	C-97
2	Modulus of rupture (N/mm^2)	Dry Wet	17 16	C-99
3	Compressive Strength (N/mm^2)	Dry Wet	106 102	C-170
4	Flexure strength (N/mm^2)		15	IS 4860 Guidelines

1.5.4. Green Udaipur Marble

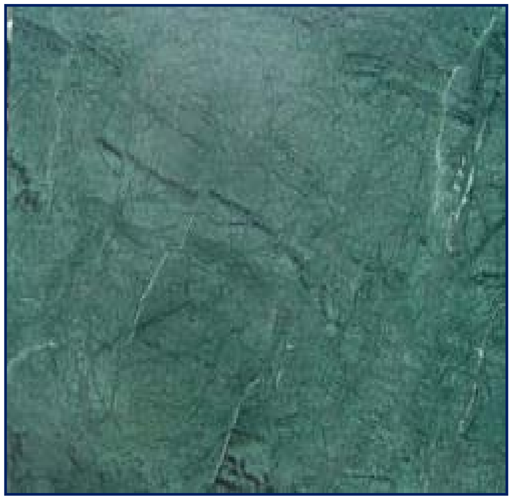


Fig. 1.5.4 Green Udaipur marble

Udaipur green marble is a marble quarried in Keshariya ji near Udaipur district in the state of Rajasthan. The city is located 403 kilometers southwest of jaipur capital city. It is also known as Verde India. The colour of the marble is green and hence the name. The marble is available in various colours such as forest green, jade green, oasis green, ocean green, mystic green, rainforest green etc. Udaipur green is a very strong and durable marble. This marble has been exported to 80 countries worldwide.

Table 1.6 Physical and mechanical properties of Green Udaipur marble, Sources: - Centre for development of stones (CDOS, Jaipur) [44].

S.No	Technical Information		Value	ASTM/INDIAN Standards
1	Water absorption(% by Weight)		0.07	C-97
2	Modulus of rupture (N/mm^2)	Dry Wet	42 35	C-99
3	Compressive Strength (N/mm^2)	Dry Wet	286 194	C-170
4	Flexure strength (N/mm^2)		35	IS 4860 Guidelines

1.5.5. Andhi Jhiri Marble

Fig. 1.5.5 Andhi jhiri marble

The marble is generally found near the capital city Jaipur of the state Rajasthan. Andhi is a dolomite marble with intrusions of tremolite. It is also known as pista or pistachio marble. The name pista is given due to its green color tremolite against white color background. The marble is used for flooring purposes. It is also exported to many other countries. It also has resemblance like famous Italy satvario marble.

Table 1.7 Physical and mechanical properties of Andhi jhiri marble, Sources: - Centre for development of stones (CDOS, Jaipur) [44].

S.No	Technical Information		Value	ASTM/INDIAN Standards
1	Water absorption(% by Weight)		0.08	C-97
2	Modulus of rupture (N/mm^2)	Dry Wet	14 17	C-99
3	Compressive Strength (N/mm^2)	Dry Wet	94 114	C-170
4	Flexure strength (N/mm^2)		16	IS 4860 Guidelines

Chapter – 2

Microcracks

Now a day, interest in research on microcracks in natural stones is on the rise for predicting and increasing the life of natural stones under application.

What is crack?

Any opening in rocks whose one or two dimensions are smaller than the third. If the one dimension is much less than the other two as well as width to length ratio also known as crack aspect ratio is less than 10^{-2} then this type of crack is known as flat microcrack. The length of the crack is typically of order of 100µm or less.

2.1 Causes of Microcracks

Whenever the local stress increases than the local strength of the natural stones, cracks are produced. The local stress may be increased by kink bands, stress concentrations at grain boundary and intracrystalline cavities, twin lamella and deformation lamella interactions. There is a decrease in local strength along grain boundaries, cleavage planes, and any internal surface due to corrosion by chemically active fluids.

Spatial and temporal temperature change results in differential thermal expansion between grains with different thermo elastic moduli and thermal conductivities, ultimately leading to microcracks in the stones. The quartz quantity has large affect on the thermally induced microcracks since it has large and variable thermal expansivity.

The hydrostatic pressure of 100 to 200 MPA will close all the cracks but the closure is not necessarily uniform if crack wall has asperities. The pressure stabilizes the cracks and cracks growth become more difficult. The number and average size of mechanically induced microcracks is greater in rock deformed at higher pressure. The mineralogy, rock type, and stress type are the major factors which tell about the relative amount of Intragranular and Intergranular cracking. The stress induced microcracks in rocks are mostly look to be extensional. Crack density increases when the macroscopic deviatoric stress increase above a threshold level. Crack size distributions can be either exponential or logarithmic. Fracture in rocks is a result of the concretion of many microcracks not only due to the growth of single crack under compressive loads. The main purpose of study is how microcracks affect the physical rock properties like compressibility, strength, permeability and electrical conductivity. Also how cracks are formed, they grow and interact, respond to different stress state, as well as their population and morphologies statistics. To study about the micro mechanics of fracture and fault formation the knowledge of microcracks is very important. They are the pathways for the transport of chemically active fluids.

2.2 Types of Microcracks

The microcracks can be classified into four main categories:-

(a) Grain boundary cracks (cracks associated with grain boundaries)

(b) Intergranular cracks (cracks which cross grain boundaries)

(c) Intragranular cracks (cracks which totally lie within the grain and do not extend over grain boundaries)

(d) Multigranular cracks (cracks which cross several grains and grain boundaries).

2.2.1 Grain Boundary Cracks

Grain boundary cracks are those cracks that are associated with the grain boundaries. They can be further subdivided into the coincident and non coincident with the actual crystal. It is very difficult to distinguish between these two types of grain boundary cracks. Non coincident extend for short distances into the grain. They are at a high angle to the grain boundary or can be close to and sub parallel to the boundary, may be running through the adjacent cement or grain boundary asperities. When the Coincident grain boundary cracks, are watched at high resolution, generally they are open space between the all or part of the crystal boundary and adjacent material. Most of the grain boundaries in an unstressed, virgin crystalline rock are partially healed and only a row of slot like elongated cavities marks the grain boundary. In diabase and gabbro the grain boundaries have no cracks, while in granites, the percentage of the grain boundary cracks can vary from granite to granite. In metamorphic rocks, grain mineralogy is a factor in determining whether grain boundaries are partially open or completely sealed. In thermally or mechanically stressed rock, grain boundaries are often highly separated or they may be crushed by pressure and loads applied normal to the boundary. Coincident grain boundary cracks in thermally or mechanically stressed rock may be continuous along the boundaries of several grains.

2.2.2 Intergranular Cracks

Intergranular cracks are those cracks which cross grain boundaries. They can also be termed as intercrystalline cracks. These cracks are longer and wider than the Intragranular cracks. However both the cracks are morphologically similar. Intergranular cracks are transgranular cracks which can be seen easily at low magnifications. It is a form of corrosive attack and follows the grain boundaries. Their orientations can vary approaching a grain boundary. These cracks can also be deflected by some other cracks or grain boundary. They are not clearly seen on the surface and are very destructive. They destroy the strength and specimen ability to be formed or shaped. In porous sedimentary rock, they may run from and through grain contact points and follow stress trajectories in each grain or merge with appropriately oriented grain boundary cracks. In mechanically stressed rock, the tip-to-tip inter crystalline crack orientations are usually subparallel to the macroscopic maximum stress direction. The cracks once originated can combine with other cracks or broadcast unstably due to stress concentration at the tip of crack. These types of crack have been described as BIF1 (Brittle Intergranular fracture type 1).

2.2.3 Intragranular Cracks

Intragranular Cracks are those cracks which are limited to the single grains. These cracks generally extend within the grain or at a grain boundary. These cracks are small, having length smaller than the grain diameter and width about 1μm or less. These cracks are generally occurring along with the plastic deformation within the grains. They generally have rough edged walls. These walls may be filled in or may be bridged by some other material. They can be filled partially or all. They have blunt tips and their aspect ratio can vary from 10^{-2} to 10^{-4}. Generally they are slots like activities within the grain. In some metamorphic rocks, cracks are unhealed in the same orientation. Also they are parallel to transgranular cracks having almost same morphology. But when these cracks are induced thermally or mechanically, they have sharp walls. The tips of the cracks are sharp or tapered instead of blunt. These cracks are twisted or tilted in 3-D or have curve traces in 2D. Most of the stress induced cracks are have less shear motion between the crack surfaces. They look like to be extensional.

2.2.4 Multigranular Cracks

Multi granular cracks are similar to Intergranular cracks but they cross several grains and grain boundaries. These are also known as transgranular cracks. These cracks generally occur when the strength of the framework and matrix are same, and then cracks nucleate within the matrix or in the framework. These cracks broadcast through successive grains and grain boundaries.

Chapter-03

Literature Review

Papers on abrasive wear and micro cracks in various machining and construction processes were identified and studied by using various journals like Elsevier, IMTDR, Springer link, IJET, IJEST etc and according to this, these papers are grouped into two main categories according to various similarities. These groups are i) Research in abrasion wear ii) Types of micro cracks and their effects. These research papers express what wear is, how it occurs, what are the factors which govern wear, what are the different types of micro cracks and how can they affect the materials.

3.1 Research in Abrasion Wear

Wear and friction are one of the old phenomenon's that exist in nature. In wear mechanism there is a relative motion between the solid surface and any other contact substance or substances. Due to this, solid surface gets damage by the continuous removal of material. Wear can be classified into five main categories abrasive wear, sliding wear, impact wear, erosive wear, and fretting wear. Several methods have been developed to measure different types of wear but whenever the testing is done, focus is mainly maintained on a particular type of wear at a particular time. Some wear tests are done to evaluate a material response to a particular type of wear and some tests checked the response of a material in a particular field application, surface treatments etc. Wear can cause damage to the components and equipments. Wear results in increase in maintenance costs as well as capital depreciation.

According to the EN 660-2 Standard, the floor covering are generally tested by the abrasive wear [1]. It is believed that abrasive wear, generally occurs whenever the hard particles slide on a softer solid surface resulting in a progressive removal of the softer material surface. Material removal can also take place whenever hard materials get embedded between two relative motion solid surfaces and also by hard protuberances. Hard protuberances will cause two- body erosion while the hard particles which can move freely between the contacting surfaces will results in third- body erosion. According to many studies, it has been confirmed that the two-body erosion has greater material removal (almost one order of magnitude) than the third-body erosion since loose abrasive particles keep on rolling about

90% of the time and only about 10% of time will abrade the solid surfaces. It is believed that wear mainly depends upon the working conditions, properties of the materials in interactions, and the type of sliding interaction. Thus wear may be controlled by controlling these factors. There are mainly two factors which are responsible for wear; i.e. load and motion between the surfaces. Since the life and performance of any material depends upon wear, it becomes one of the most important factors for engineer's consideration.

Karaca et al. [2] proposed that the load of the fine solid particles is the major factor which influences the abrasion of stone flooring material to foot traffic. Whenever stone tiles are used for floor applications, the abrasive wear mechanism is mainly third-body abrasion. Abrasion wear behaviour of twelve different stone materials has been studied when they are subjected to the varying contact loads from 100N to 500N with Bohme's testing (third body abrasion) while keeping the other parameters constant. Generally, Abrasions wear of all the stones increase as the load is increased. Some of the stones, exhibit linear relationship between the wear rate and the load while some not (especially granites). Marbles and carbonates present linear behaviour with more slope value than the limestones and granites. Hence lime-stones and granites are less sensitive to the increase in load. It has been found that the stones which are having high mechanical strength are less sensitive to the increase in loads. Stones ranking has been done in accordance with the different load apply to them. Also verification of famous Archard abrasive wear formula has been carried out. According to which abrasive wear rate is directly proportional to the sliding distance and normal load while inversely proportional to the hardness of the material. Some stones confirm to the formula while some disobey it.

Kuisama et al. [3] proposed that the abrasive wear is a system response and not any intrinsic material property. Hence abrasion wear of the same material can vary in different wear mechanisms which are tested under different test methods and conditions.

Gregolin et al. [4] proposed that wear affects direct production costs, production limitations and also indirect production costs. Due to wear we have to replace tear and worn parts, it leads to the over sizing of the components and also leads to the stoppage in production lines due to worn equipments.

Archard et al. [6] Abrasion rate of any natural stone can be expressed as the volume loss per specimen surface area. The material loss is directly proportional to the sliding distance (number of wheel revolutions) and normal applied load while it is inversely proportional to the hardness of the testing stone. It can be expressed by the well known Archard's abrasive wear formula V = K.S.F/H

Where V is the abrasive wear volume loss in (m^3), k is the wear coefficient, S is the sliding distance (m), F is the normal load (N) and H is the hardness of the tested material.

Marini et al. [7] proposed that abrasion can reduce the life of natural stones and with the increase in time its effects also keep on increasing. According to him abrasion does not only results in the removal of material from the stone surface but can also causes change in aesthetical properties like colour and brightness and decrease in various mechanical properties of stones. According to European Standard EN 14157: 2004, the abrasive material should not be used more than three times but Marini proposed that the performance of the abrasive material remains unchanged even after conducting many tests. The test has been done on marbles only having lower hardness than the abrasive particles and hence these results may vary for harder materials like granite or basalt. The abrasion resistance of the marble had been done with wide wheel abrasion test method according to EN 14157 standards. The granulometric and microscopic analysis had been done to confirm the result that abrasive particle can be used much more than three times.

Eyre et al. [5] proposed that wear results in the degradation of a material or components surface which results in continuously removal of material due to tribology processes. According to him almost 50% type of wear in the industries are abrasive type.

Das et al. [8] proposed that the abrasive wear of a material is related to cutting or ploughing at the wear surface. Both cutting and ploughing are deformation induced material removal phenomenon. Due to which deformation parameters like strength, hardness and ductility significantly affect the wear rate. Higher strength and hardness lower down the cutting efficiency of the abrasives. While higher ductility reduces tendency of fracture and fragmentation of flakes. On the other hand the higher load increases the cutting efficiency of abrasives. Thus wear rate mainly depends upon on the applied load, microstructure, ductility, hardness and toughness of the material. This cause larger material removal from the surfaces of the material and hence accordingly wear rate is also increased with the increase in the applied loads. Wear rate of a material decreases almost linearly with the hardness. At higher loads the effect of hardness is more predominant as compare to the lower load. Since at lower load only cutting type wear takes place but at higher load both cutting and ploughing wear occur. The wear of a material can be expressed as follows:-

$W_r = 1.85 \times 10^{-7} H^{-0.85} (UTS)^{-0.75} \varepsilon^{-0.15} P^{0.8}$

Where W_r is the wear rate of the material, H is the hardness, UTS is the ultimate tensile strength, ε is the percentage elongation of the material and P is the applied load.

The effect of percentage elongation on wear rate is not much significant as compare to the hardness and UTS.It is also believed that the micro structural refinement can also reduce the wear rate since it increases hardness, strength and percentage elongation.

Yilmaz et al. [9] proposed that for a particular application any natural stone must meet some specific requirements. These specifications or product requirements are mainly categorized into three categories (a) resistance to abrasion i.e. resistance of stone subjected to foot traffic (b) Resistance to external applied loads which in turn mainly depends on compressive strength, flexural strength and modulus of rupture of the stone (c) stone ability to resist different atmospheric conditions i.e. water absorption, frost resistance, and salt attack etc. In construction industry greater focus has to been maintained on these specifications for the selection of any natural stone for any particular application. However the acceptable values of these specifications as well as standard testing methods are different for different types of stones. To decide the suitability of any stone under various loads, determination of its mechanical properties becomes an important aspect. A statically significant correlation has been established between petrographic variables and mechanical strength properties of studied stones. It is also established that the knowledge of petrographic data is helpful in understanding the behaviour of the rocks.

Hawk et al. [10] proposed that to classify a wear as an abrasive wear, it is not necessary condition that the abrasive particles should be harder than the solid surface. Abrasive wear can be divided into two main types: high or low stress wear. During high stress wear the abrasive particles get embedded between two solid surfaces. The abrasive particles and solid surfaces have small contact region and high contact pressure. This high pressure produces indentations and scratching of the wearing surfaces. High stress abrasion can also be termed as third body abrasion but sometime two-body high stress abrasion also exists. During high stress wear abrasive particles are both broken and fractured. High stress abrasion is a combined phenomenon of cutting, surface fracture and plastic deformation on a macroscopic scale as well as by tearing, fatigue or spalling on microscopic scale. Abrasive particles are generally in contact with one other surface or component only. In low stress abrasion, abrasive particles impinge on and move across the surface. Low stress abrasion is a phenomenon of cutting and ploughing on a microscopic scale. In high stress load will fracture the abrasive particles but in low stress the abrasive particles do not get fracture. There is a correlation between the hardness and wear of the component, wear reduces as hardness of a component increase.

Yavuz et al. [11] proposed that the usefulness of any natural rock depends not only on its aesthetical properties but also on its technological properties. A stone must meet certain qualitative requirements to be considered as a dimensional stone. Dimensional stones are those natural rocks that can be quarried in large blocks and after that they can be given any shape, size or dimension for a specific application. Marbles, limestones, travertine are the dimensional stones. Now days in construction industry, researches are mainly focused on how long a natural rock will be able to maintain its aesthetical and technological properties. How long its surface can bear and keep its important and distinctive characteristics of appearance and strength in a specific atmospheric condition, manner, or purpose. Abrasion resistance of a stone is an important property to determine its suitability for larger cladding and flooring or paving applications. Generally friction, impact or both are the main cause of abrasion. Load and motion are the main driving forces for abrasion. Resistance of marbles against steps, flooring, pavements of railway station, airport areas, roads etc is generally determined by abrasion resistance. Some marbles are not very hard and wear easily on pavement applications. So it becomes necessary to determine the abrasion resistance of a marble. Third body abrasion is commonly studied for stones and is believed as the main process of material removal. A correlation is tried to establish between the abrasion resistance and physical and mechanical properties of rocks like density, porosity, compressive strength, hardness, p-wave velocity and the tensile strength through regression analysis. Abrasion resistance is directly proportional to the density and porosity. This means that if any stone has high density and porosity then its abrasion resistance will be more. But P- wave velocity is inversely proportional to the abrasion resistance which in turn depends on the mineral composition, density as well as porosity of the rocks. Abrasion resistance always increase with the hardness but the increase is not always linear as suggested by the

Archard. Compressive strength and tensile strength are also directly proportional to the abrasive resistance which means higher the compressive strength lower will be the abrasion rate. According to Yavuz, abrasion resistance can be calculated by knowing the hardness, compressive strength, tensile strength and the density.

Mezlini et al. [12] proposed that it is very important to control the loss of material through abrasive wear. Since it may fail the component permanently and thus final production cost increases. Abrasive wear depends on normal load, sliding distance as well as abrasive particles angularity. There exists a strong correlation between the abrasive wear and the abrasive particles abrasiveness. A repeated sliding process is generally referred to the particle abrasiveness. In this process wear mode undergoes change from cutting, then the mode is wedge formation and after that the mode is shear tongue formation which is followed by the ploughing. It is not always necessary that the hardest material resist the abrasive wear well. There is no well established correlation between the hardness and wear of a material. This is due to the fact that wear also depends upon the operating conditions, types of test, and configuration parameters. Many researchers conclude that the abrasive wear resistance increases with the hardness. But some conclude that the abrasive wear resistance decreases with hardness in third body wear. Abrasive particles get embedded in the soft material and generate scratch. Abrasive behaviour of the material also depends upon indenter geometry. Conical indenter has higher wear volume removal than the spherical one. Plastic deformation and ploughing are the main wear mechanisms in case of spherical indenter while in conical indenter the ploughing and shear tongue formation are the principal wear mechanisms.

Nahvi et al. [13] proposed that the test apparatus in any wear test are designed with a particular service application. In test methods abrasive particles are either loose or fixed. Whenever the abrasive particles are loose as it passes over the testing specimen then the abrasion is third body abrasion. While in two body abrasion, abrasive particles are fixed in orientation during passing over the testing specimen. The operating mechanism of wear is mainly function of the material properties such as hardness, flexure strength, ductility and toughness etc as well as the way abrasive particles move through the contact between the specimen and the wheel. In two body abrasion abrasive particles may get either embedded into the rubber wheel or slide across the specimen while in third body they roll between the wheel and the testing specimen. The mode of wear is different between fixed and free particle grooving. Fixed particles grooving can generate a wear factor which is ten times greater than the free particles. The main reason of this is that the attack angle of abrasive particles in fixed grooving will be high and due to this cutting is main mode of material removal. With low attack angle ploughing and wedge formation are modes of material removal resulting in lower material removal. The movements of particles through the contact zone affect the mode of wear. The motion of particles mainly depends upon the particle shape, applied load, counterbody and hardness of the testing specimen. The applied load changes abrasion mechanism from rolling to grooving as the load increases. Lower harder material has rolling motion whereas harder material has grooving motion. The motion of particles in the dry sand rubber wheel test (DSRW) is considered mainly the function of applied load and the hardness. Hardness is not the only property which affects the wear rate but other material properties can also affect the mode of material removal. There exhibits a non linear relationship between the applied load and the wear rate. The abrasive particles motion through the wheel and the testing specimen depend upon the specimen properties. High hardness and the applied load will favour particles sliding. Particles would move sliding if the anti clockwise moment is greater than the clockwise moment. For a particular load per particle the coefficient of friction decreases with the increase in the specimen hardness which will promote the sliding particles motion. The ploughing friction coefficient increases as the depth of indentation and the applied load increases. The motion of particles will change from rolling at low load to sliding at high load. It is also observed that the wear coefficients are not a strong function of the mode of particles motion through the contact.

Elalem et al. [14] proposed the relationship between the volume loss of a testing specimen and the sliding velocity as well as the applied load. With the increase in the load the wear loss also increases. It is believed that the volume loss of material is directly proportional to the load applied. So all the materials are generally tested at the fixed load and sliding speed. But wear is a complex phenomenon and it differs from one material to another and it is difficult to rely on one load testing methodology. Different materials show different response to the applied load, not necessarily obeying the linear relationship between the applied load and the wear loss. The wear load relation may also depend upon the hardness of the rubber rim, sand flow and the sliding speed. Therefore it is necessary to have careful observations to conclude the wear behaviour of any material. All these factors affect the wear rate simultaneously and their effects cannot be separated experimentally. According to elalaem volume loss of the material increases as the load is increased. But if a material has higher hardness, then its volume loss first increases with the load and then decreases as the load is increased regularly. As the hardness of the material increases, damage to the abrasive particles also increase and they become less effective to wear the testing material. If the material has its hardness closer to the abrasive particles, break up of asperities on the surface of the abrasive particles will take place and they become less angular which will further reduce the wear.

Original abrasive particles have smooth surfaces. Wear test will damage these surfaces to some extent. Low load causes less damage to these surfaces while the heavy load will cause high damage to these surfaces. If the lower sliding speed is used, then there will be an increase in the wear if the speed is increased. High sliding speed can also cause damage to the abrasive particles since they cannot bear high impact when they interact with the harder material. If the initial sliding speed is higher and is increased then no change in the wear is observed.

Ma et al. [15] Dry wheel abrasion tester is widely used in construction engineering to rank construction material for various applications. Effective correlation has been found between laboratory results and field tests. Test is generally performed under fixed loads and fixed speeds so that every material is evaluated under same condition. According to ASTM such test has to be done with fixed load and speeds for checking performance of materials in different situations. But the experimental parameters may be suitable for some materials and not for others; this may result in misleading information. According to Stevenson and Hutching wear behaviour of material varies with respect to the applied load, sliding speed, abrasive sand, and abrasive packing fraction. During wheel abrasion test some materials show wear loss follow linear relationship with applied load expect under very high load. An initial small increase in applied load will increase wear since it will increase contact stress which result in large surface damage. But with further increase in load a material wear may increase or decrease accord to the condition. Sliding speed is another parameter which may influence the wear, but it depends upon the material. Since some material wear change with the speed but some of them remain ineffective. High loads or high sliding speeds can cause microstructure or structural change in the surface layer which may strengthen the material or there might be change in abrasive sand condition. Many failures may occur of sand surface during high load and high sliding speed conditions. Therefore, if materials having close mechanical properties are ranked using fixed load and fixed sliding speed, misleading data could be generated. At high speeds, the abrasive particles may not withstand large impact and its surface failure would lead to less damage to material.

Trezona et al. [16] proposed that the wear volume V for any homogenous bulk materials depend upon sliding distance, normal contact load as V = kSN where k is wear coefficient m^3 $(N\ m)^{-1}$, the abrasive resistance is defines as k^{-1}. The measurement of k is useful only where wear volume is directly proportional to the sliding distance and the applied load. According to him in micro-scale abrasion test two body wear mechanism is dominating at high loads or less slurry concentrations while low load or high slurry concentration will result in third body abrasion. With intermediate load or slurry concentration the wear is two body at centre and third body at the sides. Wear volume exhibits non linear relationship with the slurry concentration. At low slurry concentrations the wear volume does not depend on load and is a function of slurry concentration only. Since the increase in load causes the particles to get embed more deeply. Thus at one stage particles are fully embedded and the additional load is supported by asperities or hydrodynamic film on the surface itself. Thus load increase has no effect on volume removal of the material by abrasion. The k can be increased only by increasing the slurry concentrations or in other words by increasing the numbers of particles in contact. For rolling wear, volume removal is proportional to the normal load while in grooving it is some power of load lower than the one. Also for both grooving and sliding wear volume is constant with sliding distance, since wear is independent to the load per particle. Wear coefficient can be compared only if it is obtained under the same fixed abrasive type and volume fraction. The values obtained at different sliding distance but all other conditions identical can be used for the wear mechanism. But For rolling mechanism only values obtained at varying loads but with fixed slurries can be compared.

Karaca et al. [17] proposed that abrasion resistance is the main test for deciding the suitability of any natural stone for pavement constructions and flooring applications. Thus abrasion resistance determination is an important task for the building and construction industry. The EN 14157 standard for determining abrasion resistance is a national standard for many European countries. The standard compromise three tests such as Bohme abrasion (BA) test, wide wheel abrasion (WWA) test and the Amsler abrasion test (AAT). All tests are third body or high stress abrasion test. A correlation between BA and WWA test has been established by using analysis of variance (ANOVA).

$WWA = 14.8 + 2.9\times 10^{-4}\,BA$

Where WWA are in mm and BA are in mm^3 respectively.

Any floor material should not only satisfy aesthetic appearance but it also satisfies technical specifications. This is very important criteria for places having intense foot traffic for e.g. shopping centres, railway platforms, queuing areas etc. Abrasion resistance determination becomes an important criterion, whenever we are using two or more stone materials for colour and design effects together. Abrasion resistance of the stones should match in that case. EN standard has not specified any value of abrasion resistance for different types of stones to be used within the same flooring areas.

Abrasion resistance of stones is a function of their mechanical properties and adopted test methods. Low Porosity of stones (< 1%) is not an indicator of abrasion resistance but in high abrasion resistance decreases with the increase in porosity. Abrasion resistance is directly proportional to UCS. Abrasion resistance is less correlated with BTS.

WWA method has disadvantage like it only simulate single direction foot traffic flow on floor coverings as well as 14 kg counter weight cannot remain constant throughout the abrasion period. The width of the groove in WWA test increase, as a result of this abrasion resistance of stone increase due to increase in contact area.

Marradi et al. classified stones based on WWA test data as follows

Little abrade materials: WWA is less than the 16 mm value.

Average abrades materials: WWA = lies between the 16–21 mm value.

More Abrade materials: WWA is greater than the 21 mm value.

Kilic et al. [18] proposed that the abrasion resistance is influenced by the strength, mineralogy, quartz structure and content. Wear loss is inversely proportional to the UCS, point load; P-wave velocity and Schmidt hammer rebound number. Hard rock will have less volume removal than the porous rock. There is an exponential relationship between the abrasion wear loss and the porosity of the rock. There exhibits a good relationship between the Schmidt rebound number and the volume loss as follows:-

$LOV = 136910\ N^{-2.361}$

$R^2 = 0.91$

Where LOV is the loss of volume ($cm^3/50cm^2$) and N is the rebound number.

The correlation is also established between the UCS (uniaxial compressive strength) and indirect tensile strength (ITS) with the other properties like shore hardness index, P- wave velocity, point load index, porosity and Schmidt rebound number as follows:-

$UCS = 0.159\ sh^{1.6269}$ (where sh = shore hardness index)

$UCS = 2.304\ Vp^{2.4135}$ (where Vp = P- wave velocity)

UCS = 100 LN (Is50) + 13.9 (where LN = load index)

$UCS = 147.16\ e^{-0.0835x}$ (where x = porosity of rock %)

$UCS = 0.0137\ N^{2.2721}$ (where N = Schmidt rebound number)

$ITS = 0.058\ sh^{1.2749}$

$ITS = 0.49\ Vp^{1.8743}$

ITS = 7.5 LN (Is 50) + 2.22

$ITS = 10.501\ e^{-0.4211}x$

Cozza et al. [19] proposed that the results obtained from different wear tests having different configurations cannot be compared easily. For comparison of any two wear tests different types, sizes or shapes of abrasive particles should not be used. An increase in the normal load would cause decrease in the degree of micro rolling abrasion.

Rendon et al. [20] proposed that the hardness play a very important role in controlling the wear of any material. Depending upon the wear tests, material can be ranked according to the wear resistance. In two- body abrasion wear loss is mainly control by the toughness and hardness of the material.

Nahvi et al. [21] proposed that movement pattern of the abrasive particles in DSRW test is function of hardness and applied load of the testing material. High loads and hardness would lead to the particle grooving (sliding). A model to describe the particle motion with respect to the sand wheel has been developed.

Abioye et al. [22] proposed that as the metamorphism level increases, Stress state, grains compaction, cementation and the brittleness of the stones also increase. In addition the value of the rock property also gets increase. Besides, both dynamic and static fragmentation is increased. The degree of metamorphism is the main factor which influences the stones property value. Therefore to evaluate the engineering performance of any stone it is necessary to understand the geology of rocks when it is used in mining and construction industry.

3.2 Research in Microcracks

The shape, size and orientation of microdiscontinuties affect greatly the mechanical response of crystalline rocks on macro scale.

Kranz et al. [23] proposed that micro cracks can be distinguished into four different types. These are grain boundary cracks (cracks associated with grain boundaries); Intergranular cracks (cracks which cross grain boundaries); Intragranular cracks (cracks which totally lie within the grain and do not extend over grain boundaries); multigranular cracks (cracks which cross several grains and grain boundaries).

Hughes et al. [24] proposed that rocks are generally treated as a homogenous media on macro scale having uniform mechanical properties. All the models which describe the behaviour of rocks under indentation do not take account the microdiscontinuties characteristics as well as their effect on the analysis and interpretation of the indentation data. These models only focus on the brittleness of these homogenous materials (rocks).

Bandini et al. [25] proposed that the crack unstable growth and crack initiation are the combined effect of both the extrinsic and intrinsic effects. The extrinsic effects depend on the Grain boundary and Intergranular defects develop due to the rock origin. They mainly occur at high scales of observation. The intrinsic effects depend on the rock material property like fracture toughness of the basic constituents and they demonstrate themselves in the fracture mechanism on nanoscale. According to him the strain and the fracture's mechanisms can be comprehensively understand only by using a multiscale and multidisciplinary experimentation technique, based on high- resolution nano-mechanical characterization and correlation with nanoscale deformation mechanisms and microstructures, a new technique has need to be developed in the rock mechanics.

Macroscale failure of any rock can be well understood only if we study the mechanical properties of rock on the micro and nano scale. Since it is believed that the failure mechanism of a rock begins on these scales. Method of nanoindentation in continuous stiffness measurement has been widely used in Material science for examining the strength and deformability but still innovative in the rock mechanics field. By this technique the mechanical behaviour (elastic modulus and hardness) and fracture mechanisms of materials can be analyzed dynamically during an indentation test. The analysis is done as a function of penetration depth with a resolution of nanometers. Thus this technique is helpful in studying the multiscale failure mechanisms of brittle materials. Nanoindentation has been limited to the study of mechanical properties of materials only but it can also be an effective measure to study the properties of rocks also. The micro fracture strongly depends upon micro condition near the indentation. With an increase in the penetration depth there is a decrease in the hardness and elastic modulus of the rock. The use of the CSM gives the complete elastic modulus and hardness versus indentation depth profile, and thus allows to correctly estimate the marble intrinsic properties as the extrapolation (e.g., by fitting with a polynomial function) of the profiles to zero depth.

Zhu et al. [26] was first one to proposed the correlation between the Hardness and Elastic modulus maps of different rock samples, by using Berkovich nanoindentation, to the mineralogy and structure of the rocks which form minerals grains, resulting from analysis with optical microscope as well as with the scanning electron microscopy. Granoblastic and Xenoblastic texture show a varying response under mechanical stresses, when subjected to indentation tests, although there mineral logical composition is almost mono mineral and the grain size does not vary much with the texture. The dependence of strength and deformability of the Xenoblastic and granoblastic marble on Intragranular cracks has been examined on the nanoscale by nanoindentation. These investigations lead to estimate the hardness and the elastic modulus of rock elements in Xenoblastic and granoblastic texture, as a function of the indentation depth. The hardness and Elastic modulus of the rocks in an indentation process can be calculated with the help of the method proposed by the Olive and Pharr. The CSM nanoindentation approach allows to examine the cracking network induced by the indenter penetration and, more specifically, by changing the structural conditions around the indenter and the orientation of the intragrain microcracks.

Olive et al. [27] proposed a method which is based on models to determine the hardness and elastic modulus of homogenous media. The method can also be used for non homogenous, anisotropic, brittle composite material since no model has been developed so far for them.

Sneddon et al. [28] proposed a model to calculate reduced elastic modulus that takes into account the elastic displacement that occurs in both the specimen and the indenter tip. It was calculated with the help of contact stiffness and contact area.

Lugue et al. [49] proposed that thermal change is the main decay agent in any marble. It leads to anisotropic expansion in calcite and dolomite crystals. Calcite crystals are harmed more than dolomite types. The micro cracks are Intergranular or transgranular. Due to microcracks transportation of elastic energy occurs and large concentration of elastic energy moves towards the boundaries between the grains. Great length and large connectivity cracks are produced in marbles having large grain size and straight grain boundaries.

3.3 Research Gap

1. All the abrasive wear testing on marble stones in Rajasthan is carried out at fixed load and sliding velocity where as wear is a complex phenomenon and it is difficult to rely on one load testing methodology. Hence research is needed to be done on the marbles at different load and sliding speed.

2. No well established correlation has been developed between the mechanical properties and the abrasive wear of the marbles available in Rajasthan.

3. Load wear relationship has been examined by Bohme test apparatus of some selected stone material but wear is not an intrinsic material property and same material can show different response to different test apparatus. However load-wear and speed-wear relationship has not been developed yet for the wide wheel abrasion test apparatus.

4. Whenever two or more marbles are used together for flooring purposes in order to obtain color and design effects the abrasion resistance of the marbles should match. Hence research is needed to be done on the marbles of Rajasthan to determine their abrasion resistance for using them together.

5. To understand the mechanism of failure of natural stones, it is important to study various mechanical properties on nano or micro scale, since the failure occurs at these scales. For this study is required to be done on marbles in order to determine the effect of micro cracks on the mechanical behavior of marbles.

3.4 Objective

1. To determine the hardness of various marbles grades of Rajasthan.

2. To determine the abrasion resistance of various marbles grades of Rajasthan for foot traffic according to the ASTM C241standards.

3. To study the abrasion behavior of various marbles grades of Rajasthan when subjected to wear under varying load and sliding speed conditions based on EN14157:2004 standard.

4. To establish a correlation, if any between the abrasion resistance and the various physical and mechanical properties of various marbles grades of Rajasthan according to ASTM standard.

5. To establish load-wear and speed-wear correlations for various marbles grades of Rajasthan by using wide wheel abrasion test based on EN14157:2004 standard.

6. To study the effects of micro cracks on the mechanical behavior of the various marbles grades of Rajasthan.

Chapter – 04

Methodology and Experimentation

4.1 Marble Selection

For carrying out of the study, five different marbles which are widely used for interior and exterior floor coverings has been selected from various marbles processing plants. These marbles have different percentage of minerals, grain size, mechanical properties, and colour. The marbles are dimensioned according to the necessity of the study. Laboratory testing has been carried out on these five marbles according to the various standards. The test marbles have been selected from various marble processing plants located around the Rajasthan region of India. Since marble is the product of nature and its chemical composition likely to vary by place, weather conditions etc. Hence all the samples of each marble have been prepared from the same blocks. Dimension marble samples are prepared by sawing marbles blocks. All the marbles are famous marbles of Rajasthan region and have been exported to other countries also. Commercial names, location, classes and colour of these marbles are given in Table 4.1

Table 4.1 Marbles under investigation

S.No	Marble Name	Class	Colour	Location
1	Bhainslana Black	Metamorphic	Black	Kotputli, Rajasthan
2	Makrana	Metamorphic	White	Doongari, Rajasthan
3	Agaria White	Metamorphic	Milky White	Kishangarh, Rajasthan
4	Green Udaipur	Metamorphic	Green	Udaipur, Rajasthan
5	Andhi Jhiri	Metamorphic	White	Jaipur, Rajasthan

4.2 Chemical Composition Testing

A titration test is done on the five marble samples to determine their chemical composition. For carrying out the test marbles were first crushed in powder form weighing 500 grams. Titration is a laboratory method of quantitative analysis which is used to determine the unknown concentration of known substance. Marble has unknown concentration of known substances such as quartz (SiO_2), Lime (CaO), Periclase (MgO), Haematite (Fe_2O_3), Corundum (Al_2O_3). In titration method a known volume of titrant reacts with a solution of analyte to determine concentrations. The result of the titration method is shown in Table 4.2.

Table 4.2 Chemical composition of Rajasthan marbles

S.No	Composition	Makrana Doongari	Bhainslana Black	Andhi jhiri	Green Udaipur	Agaria White
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, Haematite	Traces	1.99	0.3	Traces	Traces
5	Al_2O_3, Corundum	Traces	Traces	Traces	Traces	Traces
6	Loss due to ignition	46.76	40.20	43.71	37	44

4.3 Hardness Determination

According to many studies hardness is the major factor that affects the abrasion wear of the stones. Higher the hardness of the stone lower will be its abrasion wear. Abrasions wear decreases in a linear relationship with the increase in hardness of the stone. Micro Vicker's hardness test is done on the marble samples to determine their hardness. For this 50, 100 and 150 gram force is applied on the marble sample having size of 10×10×10mm. The results of hardness is given in the table 4.7

Table 4.3 Hardness of Rajasthan marbles.

S.NO	Marble Type	Micro Vicker's hardness
1	Bhainslana black	450
2	Makrana doongari	435
3	Agaria white	415
4	Andhi jhiri	411
5	Green Udaipur	490

4.4 Abrasion Resistance Subjected to Foot Traffic (ASTM C241)

To determine the abrasion resistance of marbles subjected to foot traffic, three samples of size 50×50×25 mm were prepared for five different marbles found in Rajasthan by sawing. Each sample surface has been made smooth, plane ant their edges was rounded so that the wear surface remain in complete contact with the rotating disc surface contact. The experiment procedure for the abrasion test was according to the ASTM C241 standard. Before the test the weight of the samples were measured and then they were dried in oven at 65 ^{o}C for 48 hours until the constant mass was reached. The samples were removed from the oven and cooled to the room temperature before testing. The weight of the samples was measured before testing. The three samples of each marble were then placed into the holding device of the abrasion testing machine. The rotating disc was then set for 45 revolutions per minute and a normal load of 20N was applied. The face of the sample which was in touch with the rotating disc was abraded by an abrasive material under the standard conditions. The abrasive material used for the testing was white fused alumina having grit size of 80.The abrasive material was stored in a hopper, fixed over top plate to feed abrasive through the delivery pipe. The abrasive material was fed continuously into the abrasion path so that it can remain uniformly distributed. The sample was subjected to 225 revolutions, after which machine stooped automatically. The abrasion resistance was measured from the weight differences of each three sample of the same marble before and after the 225 revolutions. To determine the abrasion resistance of each marble, their bulk specific gravity was also determined according to the ASTM C97 standard.

Calculation:-

(a) Bulk Specific Gravity $G = A/ (B-C)$

Where:

G = Bulk specific gravity

A = Weight of dried specimen

B = Weight of soaked and surface dried specimen in air.

C = Weight of soaked specimen in Water.

(b) Abrasion Resistance $Ha = 10G\ (2000 + Ws)/ 2000Wa$

Where:

Ha = abrasion resistance of each specimen

G = Bulk specific gravity

Ws = Average Weight of each specimen (original weight plus final Weight divided by 2) i.e.W1+W2/2

Wa = Loss of Weight during grinding operation i.e. W1-W2

Fig.4.4 Stone abrasion test rig TR-50 M

Abrasion Resistance testing according to ASTM C-241

4.4.1 Abrasion Resistance testing according to ASTM C-241for Bhainslana black marble

(a) Calculation for Bulk Specific Gravity

Table 4.4.1A Calculation of bulk specific gravity of Bhainslana black marble

S.No	Size	Weight Of Dried Specimen (A)	Weight Of Soaked And Surface Dried Specimen In Air (B)	Weight Of Soaked Specimen In Water (C)	Bulk Specific Gravity G= A/B-C
B1	50×50×25	159.52	158.22	100.65	2.78
B2	50×50×25	165.98	164.66	104.70	2.76
B3	50×50×25	162.68	162.00	103.83	2.78

(b) Calculation for Abrasion Resistance

Table 4.4.1B Calculation of abrasion resistance of Bhainslana black marble

S. No	Size L×B×H	Weight Before Oven (gm)	Weight After Oven (gm) A	Weight After Grinding (gm) B	Avg. Wt. (A+B/2) (gm) (Ws)	Weight Loss After Grinding (gm) (A-B= Wa)	Bulk Specific Gravity (G) (C-97)	Abrasion Resistance Ha = 10g(2000+Ws)/2000wa
B1	50×50×25	159.55	159.52	158.21	158.865	1.31	2.78	22.9
B2	50×50×25	166.03	165.98	164.60	165.29	1.38	2.76	29.86
B3	50×50×25	162.72	162.68	161.405	162.04	1.27	2.78	23.66
Average abrasion resistance value (Ha)								25.47

4.4.2. Abrasion Resistance testing according to ASTM C-241for Andhi jhiri marble.

(a) Calculation for Bulk Specific Gravity

Table 4.4.2A Calculation of bulk specific gravity of Andhi jhiri marble

S.No	Size	Weight Of Dried Specimen (A)	Weight Of Soaked And Surface Dried Specimen In Air (B)	Weight Of Soaked Specimen In Water (C)	Bulk Specific Gravity G= A/B-C
J1	50×50×25	160.03	158.942	103.81	2.93
J2	50×50×25	159.76	158.05	103.28	2.91
J3	50×50×25	159.90	159.07	104.30	2.92

(b) Calculation for Abrasion Resistance

Table 4.4.2B Calculation of abrasion resistance of Andhi jhiri marble

S.No	Size L×B×H	Wt. Before Oven (gm)	Wt. After Oven (gm) A	Wt. After Grinding (gm) B	Avg. Wt. (A+B/2) (gm) (Ws)	Wt. Loss After Grinding (gm) (A-B= Wa)	Bulk Specific Gravity (G) (C-97)	Abrasion Resistance Ha = 10g(2000+Ws)/2000wa
J1	50×50×25	160.05	160.03	158.41	159.22	1.62	2.93	19.52
J2	50×50×25	159.78	159.76	158.04	158.9	1.72	2.91	18.26
J3	50×50×25	159.92	159.90	158.22	159.06	1.68	2.92	18.76
Average abrasion resistance value (Ha)								18.84

4.4.3. Abrasion Resistance testing according to ASTM C-241for Makrana doongari marble.

(a) Calculation for Bulk Specific Gravity

Table 4.4.3A Calculation of bulk specific gravity of Makrana doongari marble

S.No	Size	Weight Of Dried Specimen(A)	Weight Of Soaked And Surface Dried Specimen In Air (B)	Weight Of Soaked Specimen In Water (C)	Bulk Specific Gravity G= A/B-C
M1	50×50×25	150.38	149.28	95.10	2.77
M2	50×50×25	147.60	146.08	92.99	2.78
M3	50×50×25	149.60	148.92	95.107	2.78

(b) Calculation for Abrasion Resistance

Table 4.4.3B Calculation of abrasion resistance of Makrana doongari marble

S.No	Size L×B×H	Wt. Before Oven (gm)	Wt. After Oven (gm) A	Wt. After Grinding (gm) B	Avg. Wt. (A+B/2) (gm) (Ws)	Wt. Loss After Grinding (gm) (A-B= Wa)	Bulk Specific Gravity (G) (C-97)	Abrasion Resistance Ha = 10g(2000+Ws)/2000wa
M1	50×50×25	150.39	150.38	149.26	149.82	1.12	2.77	26.58
M2	50×50×25	147.62	147.60	146.06	146.83	1.54	2.78	19.38
M3	50×50×25	149.63	149.60	148.16	148.88	1.44	2.78	20.74
Average abrasion resistance value (Ha)								22.23

4.4.4. Abrasion Resistance testing according to ASTM C-241for Agaria white marble.

(a) Calculation for Bulk Specific Gravity

Table 4.4.4A Calculation of bulk specific gravity of Agaria white marble

S.No	Size	Weight Of Dried Specimen (A)	Weight Of Soaked And Surface Dried Specimen In Air (B)	Weight Of Soaked Specimen In Water (C)	Bulk Specific Gravity G= A/B-C
A1	50×50×25	152.90	150.93	98.98	2.94
A2	50×50×25	154.43	152.90	100.29	2.93
A3	50×50×25	153.53	151.95	99.73	2.94

(b) Calculation for abrasion resistance.

Table 4.4.4B Calculation of abrasion resistance of Agaria white marble

S.No	Size L×B×H	Wt. Before Oven (gm)	Wt. After Oven (gm) A	Wt. After Grinding (gm) B	Avg. Wt. (A+B/2) (gm) (Ws)	Wt. Loss After Grinding (gm) (A-B= Wa)	Bulk Specific Gravity (G) (C-97)	Abrasion Resistance Ha = 10g(2000+Ws)/2000wa
A1	50×50 ×25	152.90	152.90	150.91	151.91	1.98	2.94	15.976
A2	50×50 ×25	154.44	154.43	152.89	153.66	1.54	2.93	20.48
A3	50×50 ×25	153.54	153.53	152.01	152.77	1.52	2.94	20.89
Average abrasion resistance value (Ha)								19.115

4.4.5 Green Udaipur marble.

(a) Calculation for Bulk Specific Gravity

Table 4.4.5A Calculation for bulk specific gravity of green Udaipur marble

S.No	Size	Weight Of Dried Specimen(A)	Weight Of Soaked And Surface Dried Specimen In Air (B)	Weight Of Soaked Specimen In Water (C)	Bulk Specific Gravity G= A/B-C
G1	50×50×25	122.52	122.61	78.05	2.75
G2	50×50×25	127.85	127.70	81.31	2.75
G3	50×50×25	125.50	125.04	79.237	2.74

(b) Calculation for Abrasion Resistance

Table 4.4.5B Calculation of abrasion resistance of green Udaipur marble

S.No	Size L×B×H	Wt. Before Oven (gm)	Wt. After Oven (gm) A	Wt. After Grinding (gm)B	Avg. Wt. (A+B/2) (gm) (Ws)	Wt. Loss After Grinding (gm) (A-B= Wa)	Bulk Specific Gravity (G) (C-97)	Abrasion Resistance Ha = 10g(2000+Ws)/2000wa
G1	50×50×25	122.64	122.52	122.13	122.325	0.39	2.75	74.82
G2	50×50×25	127.97	127.85	127.52	127.685	0.33	2.75	88.65
G3	50×50×25	125.51	125.50	125.10	125.30	0.40	2.74	72.80
Average abrasion resistance value (Ha)								78.75

4.5 Abrasion Resistance Determination Subjected to Varying Loads and Sliding Speeds (EN 14157: 2004)

Abrasion is an important ageing factor for natural stones which is caused by the elements that comes into contact with the stone surface. Abrasion also leads to decrease in mechanical and aesthetical properties of stones.

According to EN 14157:2004 there are three different tests to determine the abrasion resistance of natural stones (a) Wide wheel abrasion test (b) Bohme apparatus test (c) Amsler abrasion test. Any laboratory test for wear should match the real life tribological environment. In BA method the test specimen is subjected to three direction foot traffic since specimen is progressively rotated between each cycle to include directional effects on the test results. WWA test has disadvantages that it simulates only single direction foot traffic flow on floor coverings. Also the load exerted by the 14Kg counterweight on the abrasion wheel does not remain constant for the entire period leading to the larger groove width thus increasing resistance to abrasion. Even though it is standard method to determine the abrasion resistance of stones based on EN 14157:2004 standards.

The testing of marble samples was done by Wide wheel abrasion test. In wide wheel abrasion test sample as shown in Fig. 4.5B is held against a rotating wheel; the abrasive particles fall between the wheel and the sample surface. The abrasive wear is determined on the basis of groove width. The abrasive particles should not be used more than three times. The machine has components such as clamping trolley, Fixing screw, control valve, storage hopper, Flow guidance hopper, wide abrasion wheel, counterweight, slot, and abrasive collector. The apparatus also has to be calibrated against a reference sample of "Boulonnaise marble".

For each load and each sliding speed the test was repeated six times on each individual marble and the average value was taken as final reading.

For carrying out the study forty eight samples of each marbles of size 100×70×70mm were prepared by sawing. The marbles under examination was Andhi jhiri, Makrana Doongari, and Bhainslana black. The test sample was pressed against a rotating wheel with a controlled flow of abrasive grit that abraded the sample surface. Each sample was ground for making sure that the wear surface was in complete contact with the surface of rotating disc. The size of the abrasion wheel was 200mm outer diameter and 70mm wide and its speed was varied according to the requirements. The abrasive used for the test was white fused alumina with a grit size of 80 in accordance with standard FEPA 42F. The discharge rate of abrasive was 2.8 lit/min.

The testing procedure is described as follows:-

1. Preparation of test samples: - 48 samples of each three marbles and 2 Boulonnaise marble specimens were prepared with clean, flat, smooth surface and rectangular in shape . After that they were dried in an oven for 48 hours at 75 ^{o}C until their mass stabilized and their initial weight was recorded.

2. Marking of testing surface: - All the 50 marble samples were cleaned with a stiff brush and painted with the marker to facilitate measuring of the groove.

3. Abrasion testing on two Boulonnaise marble was done at 75 RPM and 70N load for calibration purpose.

4. Abrasion testing with respect to load: - The sample was then placed into the holding device of the testing machine. The rotating wheel was then set in motion at a speed of 75 RPM. The machine time was set for 60seconds after which the machine stopped automatically. The abrasive particle was continuously fed at the rate of 2.8lit/min. The testing was done for each 24 samples of three marbles at four different loads. The loads used for the testing was 40N, 70N, 100N and 140N.

5. Abrasion testing with respect to sliding speed: - The testing of the remaining each 24 samples of three marbles was done with respect to sliding speed. . The machine time was set for 60seconds after which the machine stopped automatically. The abrasive particle was continuously fed at the rate of 2.8lit/min. The load was fixed at 100N and RPM used for the testing was 15, 30, 45, 60 and 75 RPM respectively for all three marble samples.

6. Groove Measurement for samples: - Each sample was placed under the magnifying glass and external limit of groove was drawn by using ruler and pencil. A line was drawn in the middle of the groove perpendicular to central line of grove. The width of the middle line and extreme ends was measured with the help of the digital caliper. The average value of middle and extreme ends was the actual reading of the specimen (as shown in Fig.4.5A).

7. Abrasive value (mm) = actual reading in mm + (20 – calibration value)

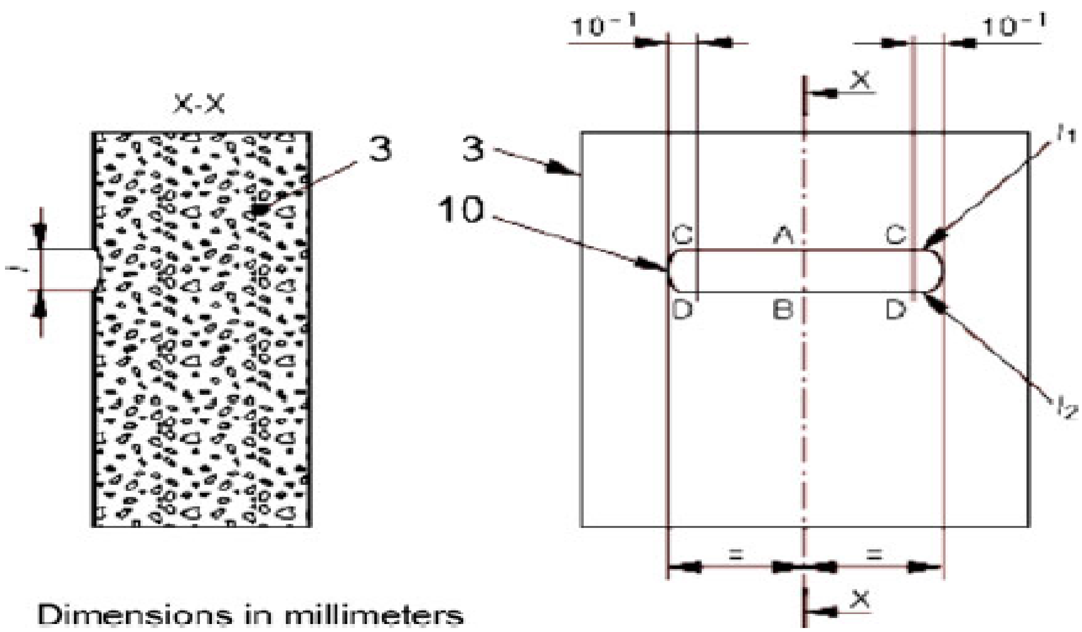
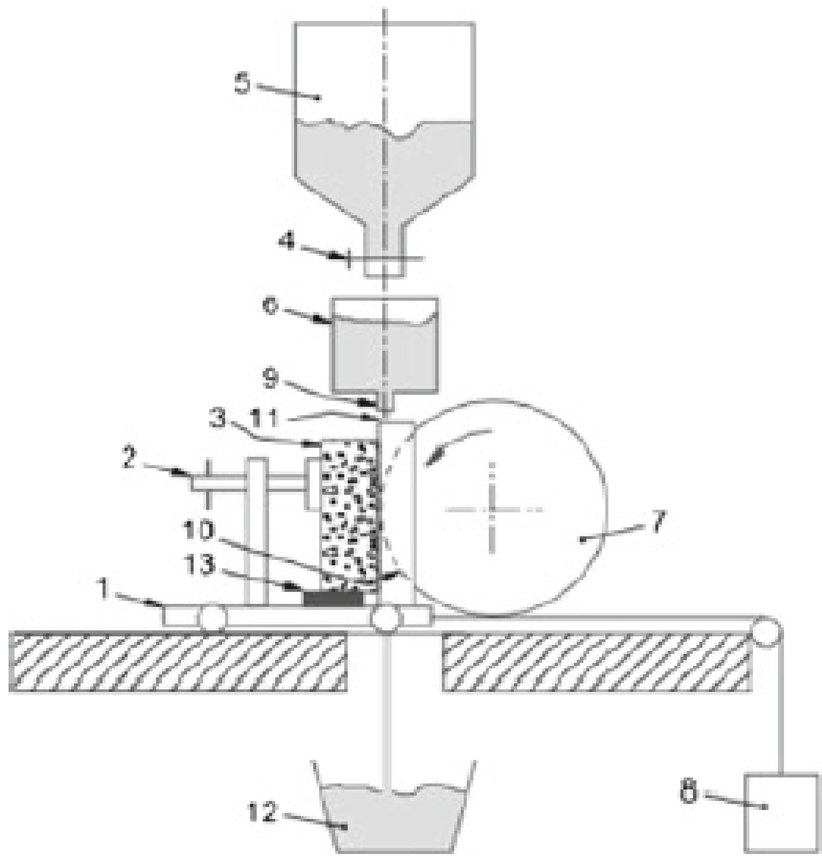


Fig.4.5A Groove measurement of a tested specimen (from EN 14157:2004) [29]



Key

1 Clamping trolley
2 Fixing screw
3 Specimen
4 Control valve
5 Storage hopper
6 Flow guidance hopper
7 Wide abrasion wheel
8 Counterweight
9 Slot
10 Groove
11 Abrasive material flow
12 Abrasive collector
13 Wedge

Fig.4.5B The wearing capon apparatus (from EN 14157:2004) [29]

Fig 4.5C Abrasion testing machine TR-52

Abrasion Resistance Testing (EN 14157:2004) With Respect to RPM

Firstly, the value of abrasive wear of Boulonnaise marble was calculated for the calibration purposes according to the standard. The testing was done at 70 N load and at 75 RPM on abrasion test machine TR -52 as shown in the Fig. 4.5C. The value of abrasive wear came out to be 19.83mm.

4.5.1. Abrasion Resistance Testing (EN 14157:2004) With Respect to RPM for Bhainslana black marble.

Table 4.5.1 Abrasion wear testing of Bhainslana black marble with respect to RPM

S.No	Size of Sample (mm)	RPM	Weight In Kg	Groove Width			Average Groove Width (mm)	Abrasion Resistance (mm) =
	L×B×H			A (mm)	B (mm)	C (mm)	(A+B+C)/3	Avg. groove width +(20-19.83)
1	100×70×70	15	10	12.36	12.40	12.76	12.506	12.67
2	100×70×70	30	10	15.55	16.01	15.66	15.74	15.91
3	100×70×70	45	10	18.08	18.7	18.46	18.41	18.58
4	100×70×70	60	10	18.17	17.98	17.89	18.01	18.18
5	100×70×70	75	10	19.33	19.81	19.84	19.66	19.83

4.5.2. Abrasion Resistance Testing (EN 14157:2004) With Respect to RPM for Andhi jhiri marble.

Table 4.5.2 Abrasion wear testing of Andhi jhiri marble with respect to RPM

S.No	Size of Sample (mm)	RPM	Weight In Kg	Groove Width			Average Groove Width (mm)	Abrasion Resistance (mm) =
	L×B×H			A (mm)	B (mm)	C (mm)	(A+B+C)/3	Avg. groove width +(20-19.83)
1	100×70×70	15	10	13.84	13.54	13.76	13.71	13.88
2	100×70×70	30	10	17.6	18.20	18.12	17.97	18.14
3	100×70×70	45	10	22.95	23.46	22.94	23.11	23.28
4	100×70×70	60	10	19.59	20.04	20.02	19.88	20.05

5	100×70×70	75	10	20.77	21.81	22.75	21.77	21.94

4.5.3. Abrasion Resistance Testing (EN 14157:2004) With Respect to RPM for Makrana Doongari marble

Table 4.5.3 Abrasion wear testing of Makrana doongari marble with respect to RPM.

S.No	Size of Sample (mm)	RPM	Weight in Kg	Groove Width			Average Groove Width (mm)	Abrasion Resistance (mm) =
	L×B×H			A (mm)	B (mm)	C (mm)	(A+B+C)/3	Avg. groove width +(20-19.83)
1	100×70×70	15	10	22.13	22.72	23.77	22.83	23.00
2	100×70×70	30	10	22.63	23.42	24.62	23.55	23.72
3	100×70×70	45	10	23.26	22.67	22.68	22.87	23.04
4	100×70×70	60	10	20.9	20.24	20.26	20.46	20.63
5	100×70×70	75	10	18.96	18.98	19.07	19.03	19.20

Abrasion Resistance Testing (EN 14157:2004) With Respect To Applied Load

4.5.4. Abrasion Resistance Testing (EN 14157:2004) With Respect to Applied Load for Bhainslana black marble.

Table 4.5.4 Abrasion wear testing of Bhainslana black marble with respect to load

S.No	Size of Sample (mm)	RPM	Weight in Kg	Groove Width			Average Groove Width (mm)	Abrasion Resistance (mm) =
	L×B×H			A (mm)	B (mm)	C (mm)	(A+B+C)/3	Avg. groove width +(20-19.83)
1	100×70×70	75	4	13.54	13.90	14.38	13.94	14.11
2	100×70×70	75	7	15.90	16.32	16.51	16.24	16.41
3	100×70×70	75	10	19.33	19.81	19.84	19.66	19.83
4	100×70×70	75	14	21.74	22.74	23.44	22.64	22.81

4.5.5. Abrasion Resistance Testing (EN 14157:2004) With Respect to Applied Load for Andhi jhiri marble.

Table 4.5.5 Abrasion wear testing of Andhi jhiri marble with respect to load

S.No	Size of Sample (mm)	RPM	Weight in Kg	Groove Width			Average Groove Width (mm)	Abrasion Resistance (mm) =
	L×B×H			A (mm)	B (mm)	C (mm)	(A+B+C)/3	Avg. groove width +(20-19.83)
1	100×70×70	75	4	17.56	17.57	18.12	17.75	17.92
2	100×70×70	75	7	18.81	18.50	18.48	18.59	18.76
3	100×70×70	75	10	20.77	21.81	22.75	21.71	21.88
4	100×70×70	75	14	24.37	24.36	25.04	24.59	24.76

4.5.6. Abrasion Resistance Testing (EN 14157:2004) With Respect to Applied Load for Makrana Doongari marble

Table 4.5.6 Abrasion wear testing of Makrana doongari marble with respect to load

S.No	Size of Sample (mm)	RPM	Weight in Kg	Groove Width			Average Groove Width (mm)	Abrasion Resistance (mm) =
	L×B×H			A (mm)	B (mm)	C (mm)	(A+B+C)/3	Avg. groove width +(20-19.83)
1	100×70×70	75	4	16.12	16.21	16.55	16.32	16.49
2	100×70×70	75	7	18.96	18.95	18.94	18.95	19.12
3	100×70×70	75	10	18.96	18.98	19.07	19.03	19.20
4	100×70×70	75	14	22.68	23.98	25.07	23.91	24.08

Chapter–05

Statistical Analysis

Regression analysis is a statistical technique for determining the relationship among the variables. The main focus is on the relationship between a dependent variable and one or more independent variables. Regression has many techniques for modelling and analysis many variables. It helps us to understand how the dependent variable value changes while the other independent variables values are fixed. It generally provides the average value of the dependent variable with respect to fixed independent variable. Regression function is a function of independent variables. The variation of the dependent variable around the regression function can also be described by a probability distribution. It helps to understand which independent variable is related to the dependent variable. Many techniques for carrying out regression analysis have been developed. Familiar methods such as linear regression and ordinary least squares regression are parametric, in that the regression function is defined in terms of a finite number of unknown parameters that are estimated from the data. Nonparametric regression refers to techniques that allow the regression function to lie in a specified set of functions, which may be infinite-dimensional.

Coefficient of determination (R^2) is a number which shows how well the data fit a statistical model. It is the ratio of the explained variation to the total variation. It values lies between $0\leq R^2\geq1$ and denotes the strength of linear association between dependent and independent variables. It denotes the % of data that is close to the line of best fit. If the regression line passes exactly through every point on the scatter plot, it would be able to explain all of the variation. The further the line is away from the points, the less it is able to explain.

P-value is the estimated is the estimated probability of rejecting the null hypothesis. Thus it may be considered the probability of finding the observed or more extreme. Before the test is conducted, a threshold value is chosen. It denotes the significance level of the test generally 0.05-0.10.

The regression analysis is used to determine the correlations between the abrasion resistance and the mechanical properties of marbles. It is also used for correlation between the abrasion resistance and load and speed.

5.1 Correlations between Abrasion Resistance and Mechanical Properties of Marbles.

5.1.1. Correlation between Abrasive Wear and Water Absorption.

AR = 12.9 + 357 WA and R^2 = 8.2 %, S = 28.5202

Coefficients

Term	Coef	SE Coef	T	P
Constant	12.92	40.57	0.32	0.771
WA	356.5	687.7	0.52	0.640

Where AR is abrasion resistance in Ha and WA is water absorption (% by weight)

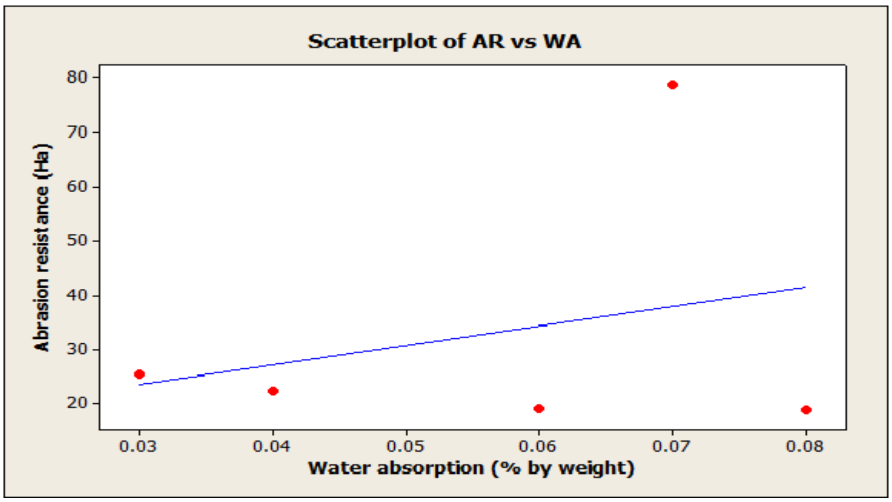


Fig. 5.1.1 Abrasion resistance v/s water absorption

5.1.2. Correlation between abrasion resistance and modulus of rupture.

AR = -15.1 + 2.18 MR and R^2 = 96.2 %, S = 5.80381

Coefficients

Term	Coef	SE Coef	T	P
Constant	-15.087	6.086	-2.48	0.089
MR	2.1804	0.2502	8.71	0.003

Where AR is abrasion resistance in Ha and MR is modulus of rupture in N/mm^2

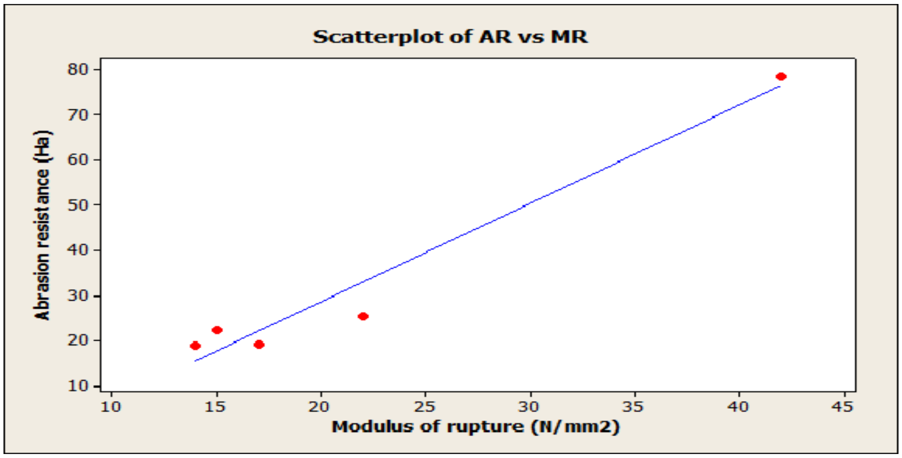


Fig 5.1.2 Abrasion resistance v/s modulus of rupture

5.1.3. Correlation between Abrasive Resistance and Compressive Strength.

AR = -4.68 + 0.287 CS and R^2 = 94.6%, S = 6.89567

Coefficients

Term	Coef	SE Coef	T	P
Constant	-4.678	6.014	-0.78	0.493
CS	0.28672	0.03941	7.27	0.005

Where AR is abrasion resistance in Ha and CS is the compressive strength in N/mm^2

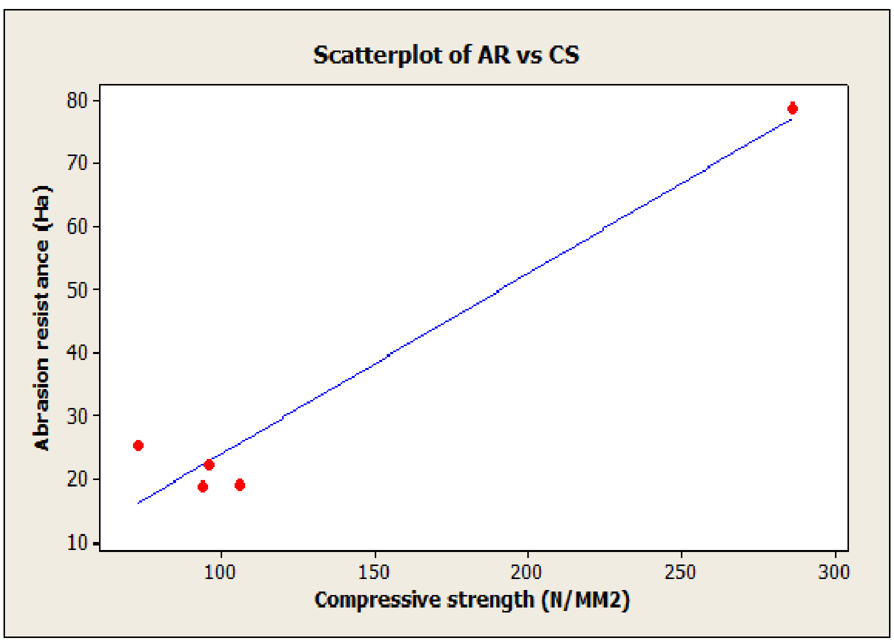


Fig 5.1.3 Abrasion resistance v/s compressive strength

5.1.4. Correlation between Abrasive Resistance and Flexural Strength.

AR = -31.0 + 3.07 FS and R^2 = 96.7 %, S = 5.399

Coefficients

Term	Coef	SE Coef	T	P
Constant	-30.978	7.215	-4.29	0.023
FS	3.0702	0.3269	9.39	0.003

Where AR is abrasion resistance in Ha and FS is the Flexural strength in N/mm^2

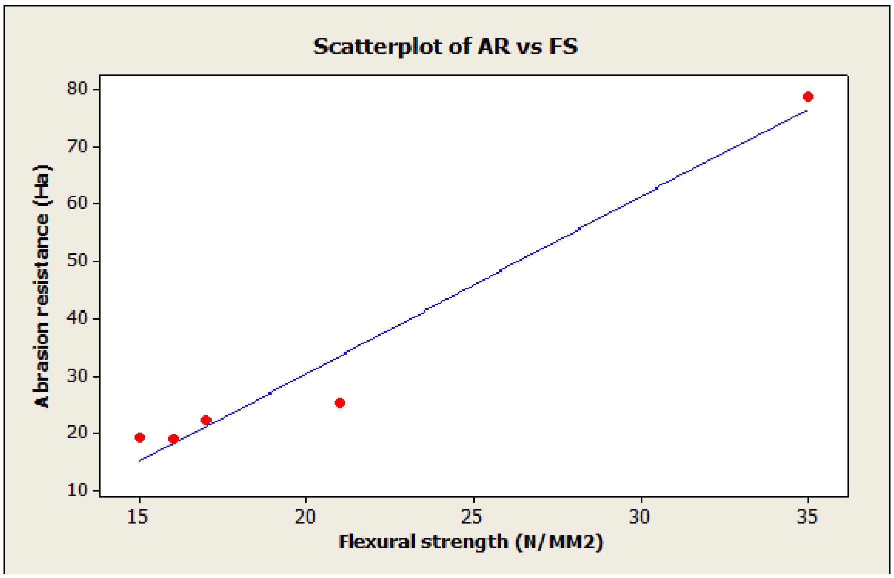


Fig 5.1.4 Abrasion resistance v/s flexural strength

5.1.5. Correlation between Abrasive Resistance and Bulk Specific Gravity.

AR = 531 - 176 BSG and R^2 = 36.7%, S = 23.6909

Coefficients

Term	Coef	SE Coef	T	P
Constant	531.3	378.3	1.40	0.255
MR	-175.9	133.4	-1.32	0.279

Where AW is abrasion resistance in Ha and BSG is bulk specific gravity.

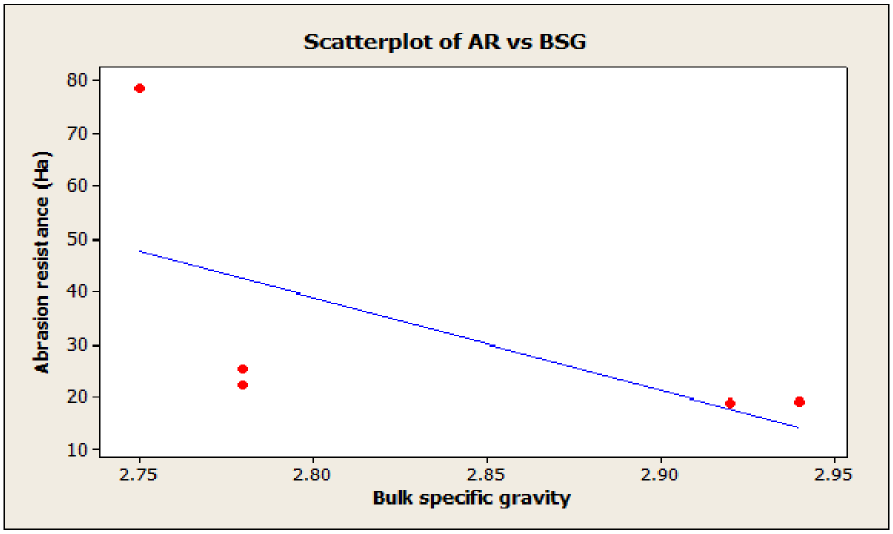


Fig 5.1.5 Abrasion resistance v/s Bulk specific gravity

5.1.6. Correlation between Abrasive Resistance and Micro Vicker's Hardness.

AR = -293 + 0.739MVH and R^2 = 84.1 %, S = 11.8846

Coefficients

Predictor	Coef	SE Coef	T	P
Constant	-292.50	81.97	-3.57	0.038
FS	0.7392	0.1858	3.98	0.028

Where AR is abrasion resistance in Ha and MVH is micro Vicker's hardness.

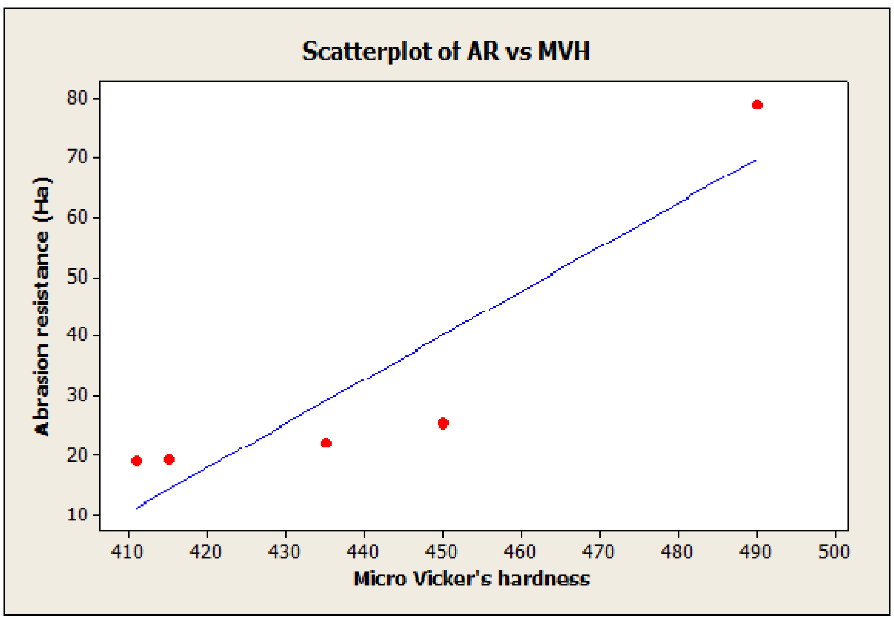


Fig 5.1.6 Abrasion resistance v/s hardness

5.2 Load-Wear and Speed-Wear Correlation.

5.2.1 Correlation between Abrasion Wear and Load for Bhainslana Black Marble.

WEAR = 10.5 + 0.0891 LOAD and S = 0.395082, R^2 = 99.3%

Predictor	Coef	SE Coef	T	P
Constant	10.4909	0.5072	20.68	0.002
MR	0.089132	0.005339	16.69	0.004

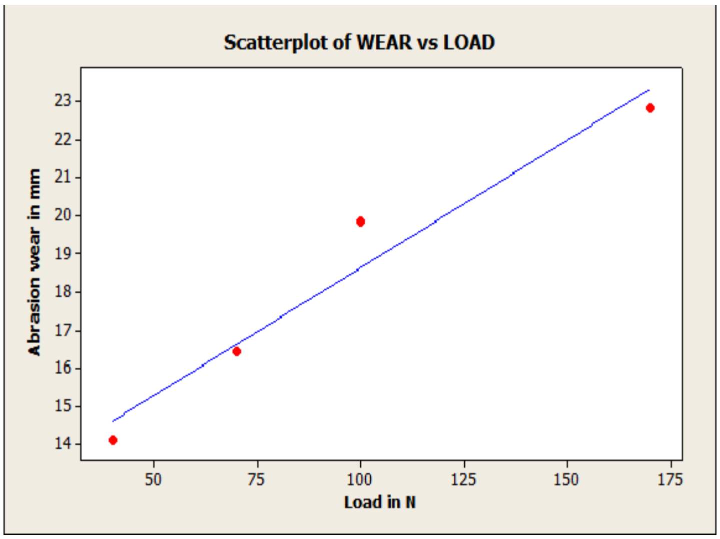


Fig. 5.2.1A Scatter plot of abrasion wear v/s load for Bhainslana black marble

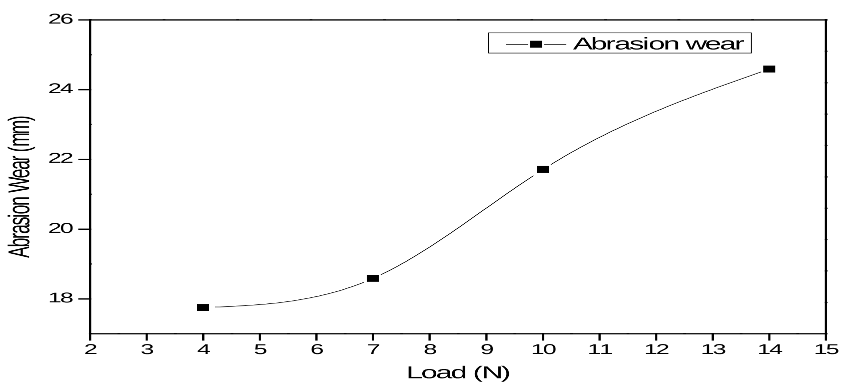


Fig 5.2.1B Abrasive wear v/s load for Bhainslana black marble.

5.2.2 Correlation between Abrasion Wear and Load for Andhi Jhiri Marble.

WEAR = 14.5 + 0.0719 LOAD and S = 0.071945, R^2 = 96.7%

Predictor	Coef	SE Coef	T	P
Constant	14.5348	0.8901	16.33	0.004
MR	0.071945	0.009369	7.68	0.017

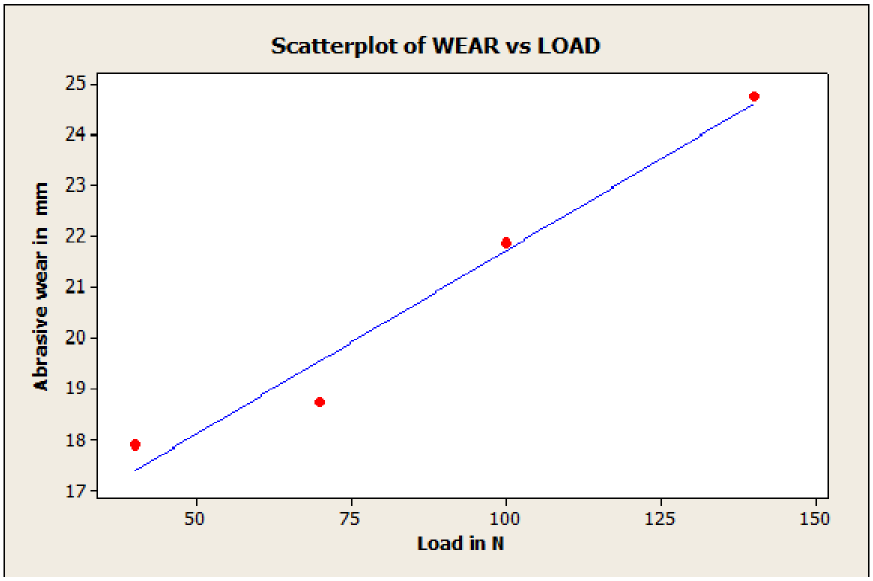


Fig. 5.3.2A Scatter plot of abrasion wear v/s load for Andhi jhiri marble

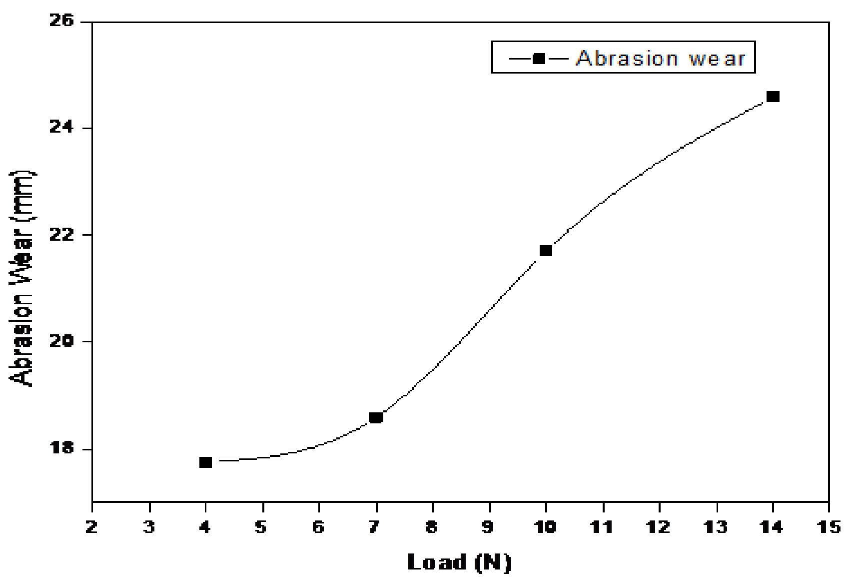


Fig. 5.3.2B Abrasion wear v/s load for Andhi jhiri marble

5.2.3 Correlation between Abrasion Wear and Load for Makrana Doongari Marble.

WEAR = 13.5 + 0.0706 LOAD and S = 1.18599, R^2 = 90.6%

Predictor	Coef	SE Coef	T	P
Constant	13.548	1.523	8.90	0.012
MR	0.07056	0.01603	4.40	0.048

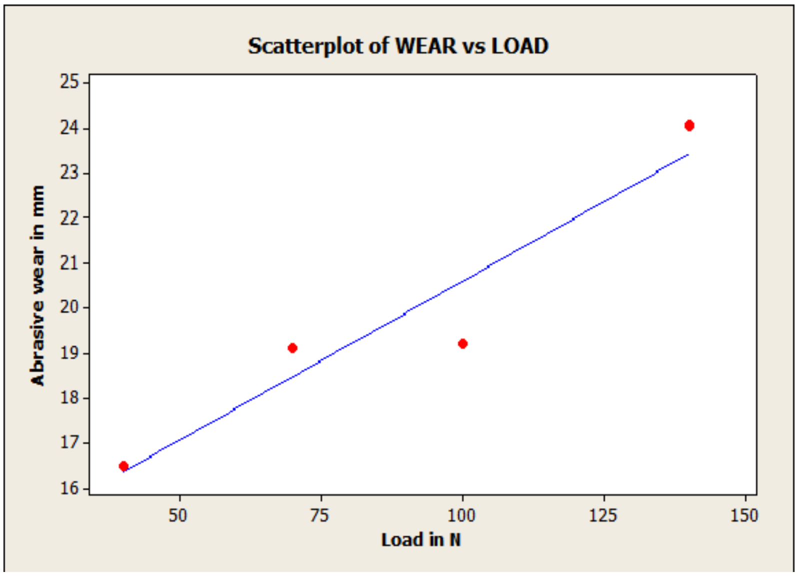


Fig. 5.2.3A Scatter plot of abrasion wear v/s load for Makrana doongari marble

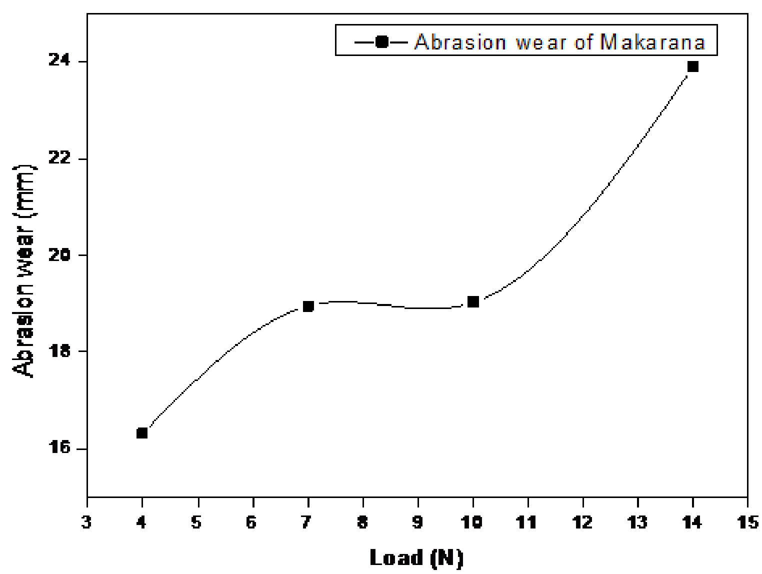


Fig. 5.2.3B Abrasion wear v/s load for Makrana doongari marble

5.2.4 Correlation between Abrasion Wear and RPM for Bhainslana Black Marble.

WEAR = 12.2 + 0.108RPM and S = 1.14072, R^2 = 87.0%

Predictor	Coef	SE Coef	T	P
Constant	12.217	1.196	10.21	0.002
MR	0.10793	0.02405	4.49	0.021

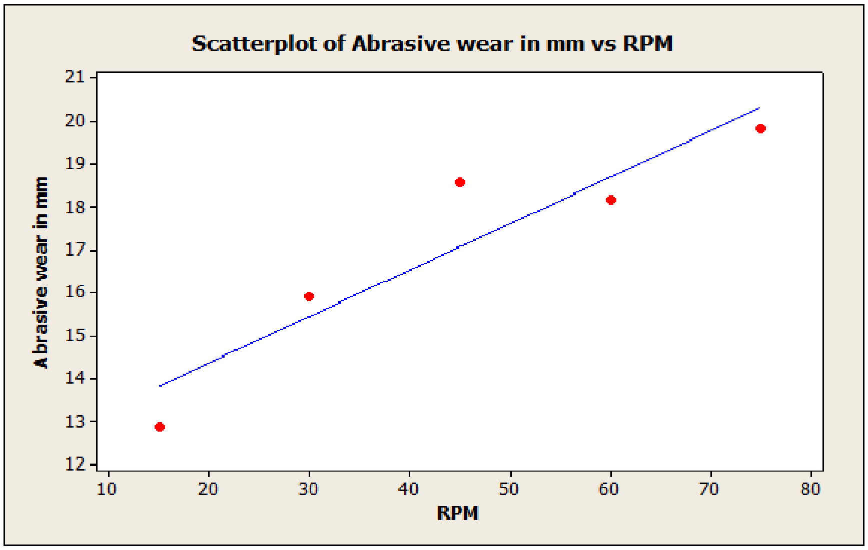


Fig. 5.2.4A Scatter plot of abrasion wear v/s RPM for Bhainslana black marble

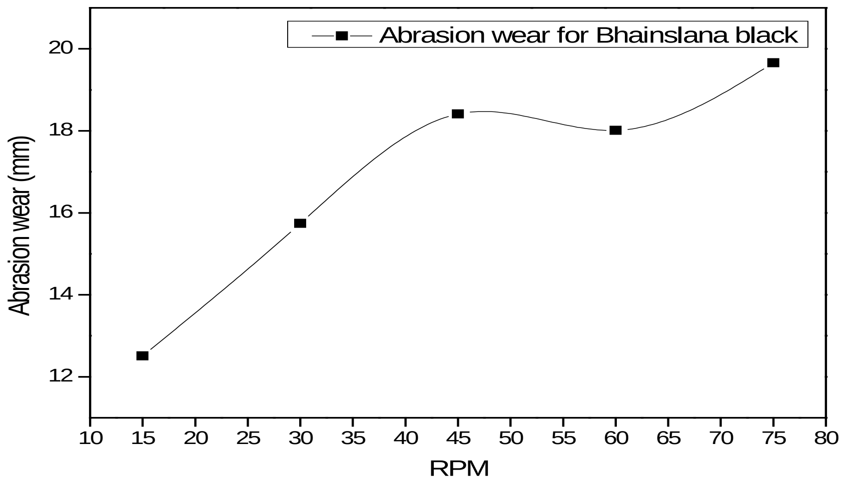


Fig.5.2.4B Abrasion wear v/s RPM for Bhainslana black marble

5.2.5 Correlation between Abrasion Wear and RPM for Andhi Jhiri Marble.

WEAR = 13.7 + 0.131RPM and S = 2.593, R^2 = 62.6%

Predictor	Coef	SE Coef	T	P
Constant	13.695	2.280	4.86	0.017
MR	0.13098	0.05842	2.24	0.111

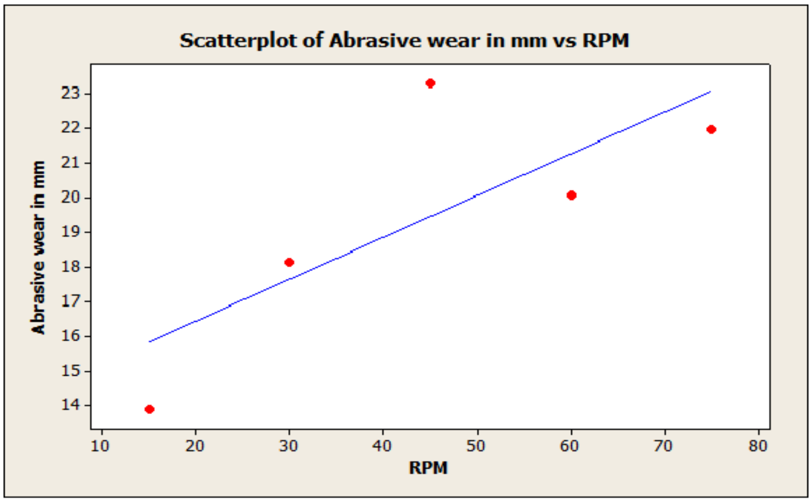


Fig. 5.2.5A Scatter plot of abrasion wear v/s RPM for Andhi jhiri marble

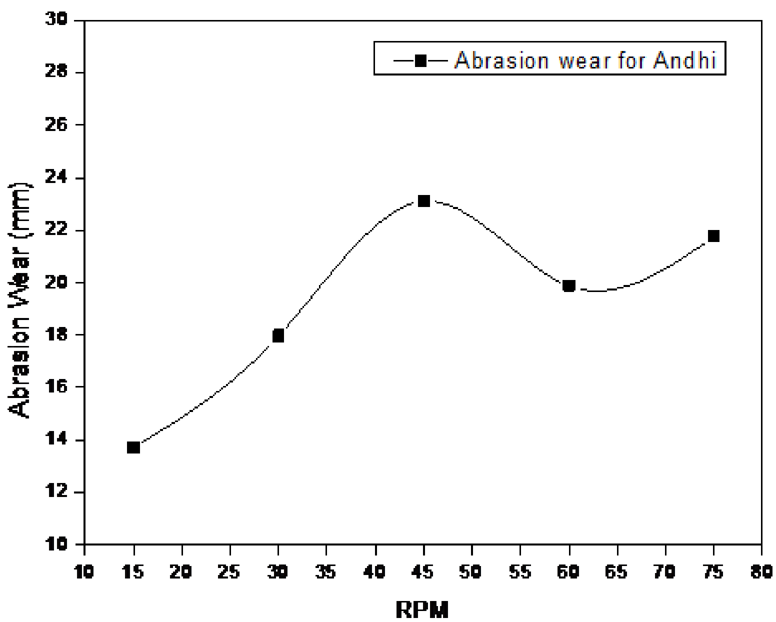


Fig. 5.2.5B Abrasion wear v/s RPM for Andhi jhiri marble

5.2.6 Correlation between Abrasion Wear and RPM for Makrana Doongari Marble.

WEAR = 25.1 – 0.0713RPM and S = 1.04812, R^2 = 77.6%

Predictor	Coef	SE Coef	T	P
Constant	25.125	1.099	22.86	0.000
MR	-0.07127	0.02210	-3.23	0.048

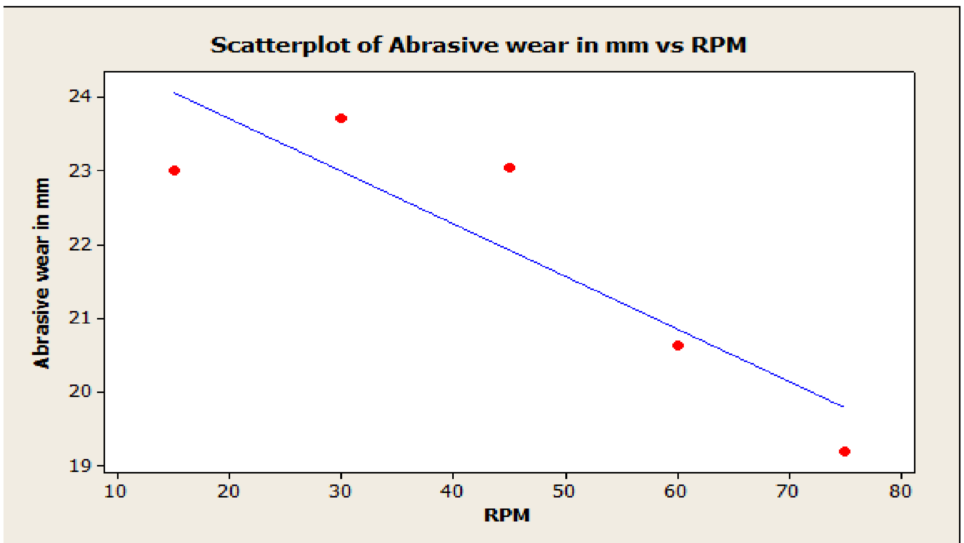


Fig. 5.2.6A Scatter plot of abrasion wear v/s load for Makrana doongari marble

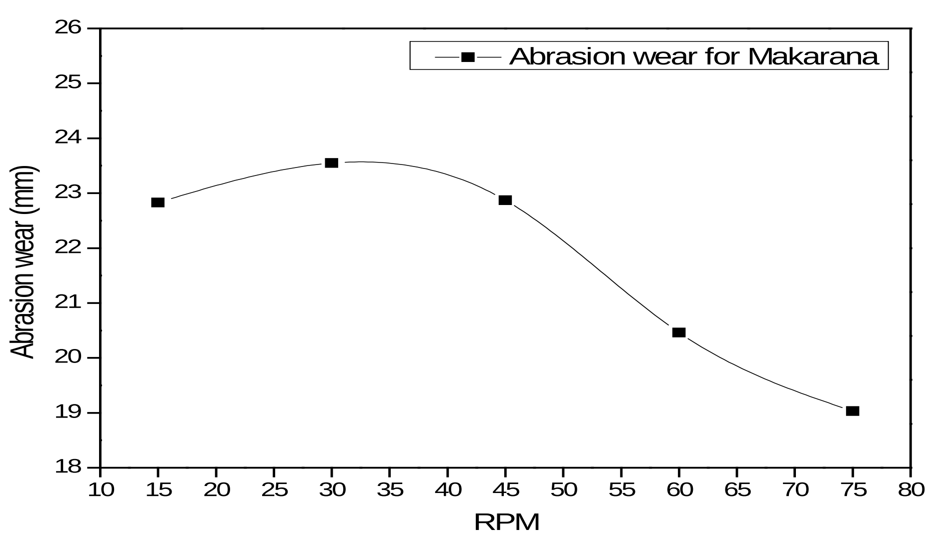


Fig. 5.2.6B Abrasion wear v/s load for Makrana doongari marble

Chapter – 06

Results and Discussions

6.1 Abrasion Resistance Value of Rajasthan Marbles and Their Applications for Internal Floorings and External Pavements.

Abrasion resistance is one of the key considerations in determining the suitability of a marble for internal floorings and external pavements applications. Marble having abrasion resistance Ha value of 10 or more are recommended for use as internal flooring. A minimum value of 15 Ha is recommended for heavy foot traffic like for railway platforms, airports, Showrooms etc. Although for decoration purposes whenever two or marbles are used their Ha value difference would not be more than 5. Table 6.1 shows the abrasion resistance value of five famous Rajasthan marble types determine according to ASTM C241 standard.

Table 6.1 Abrasion resistance value of marbles determine according to ASTM C241

Marble	Bhainslana black	Andhi jhiri	Agaria white	Makrana doongari	Green Udaipur
Abrasion resistance value (Ha)	25.47	18.84	19.12	22.23	78.75

From the table 6.1 followings results are discussed.

(a) Due to its high abrasion resistance Green Udaipur (78.75), Bhainslana black (25.47) and Makrana doongari (22.23) marble should be used for heavy traffic purpose like for railway platforms, airports, showrooms and shopping centres.

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

(c) Green Udaipur marble should not be used with any other marble for flooring purposes due to its high abrasion resistance value and hence wear will not be uniform in both marbles.

(d) Bhainslana black marble having Ha value 25.47 should be used with Makrana doongari marble having Ha 22.23 only for flooring purpose since their abrasion resistance values have difference less than 5.

(e) However Andhi jhiri, Makrana doongari and Agaria white marbles should be used together for flooring purposes due to their approximate same Ha value 18.84,22.23, and 19.12 respectively.

6.2 Mechanical Properties and Abrasion Resistance Correlationship

Abrasion resistances of marbles depend upon marble properties as well as on the adopted test method. Therefore various mechanical properties of marble were calculated according to ASTM standard in order to determine the dependence of abrasion resistance on them. Abrasion resistance of marbles was determined according to ASTM C241standard method. The regression analysis was carried out to determine the dependency of abrasion resistance on marble properties. The equation of the best fit line and coefficient of determination was determined for each regression. The abrasion resistance value was correlated with the water absorption, modulus of rupture, uniaxial compressive strength, flexural strength, bulk specific gravity and micro vicker hardness. The results of regression analysis are shown in table 6.2.

Table 6.2 Regression model showing relationship between abrasion resistance and mechanical properties of marbles

S.No	Regression equation	Coefficient of determination (R^2)	P- value
1	AR = 12.9 + 357 WA	0.082	0.640
2	AR = -15.1 + 2.18 MR	0.962	0.003
3	AR = -4.68 + 0.287 CS	0.946	0.005
4	AR = -31.0 + 3.07 FS	0.967	0.003
5	AR = 531 - 176 BSG	0.367	0.279
6	AR = -293 + 0.739MVH	0.841	0.028

Form the table 6.2 following results are discussed

(a) Correlation between abrasion resistance and water absorption.

Fig 5.2.1 shows the plot of abrasion resistance as a function of water absorption. Due to low value of R^2 (0.82), water absorption is not a reliable indicator of abrasion resistance. However the value of abrasion resistance decreases with the increase in water absorption in all marbles expect in green Udaipur marble which may be due to its high compressive strength, flexural strength and modulus of rupture.

(b) Correlation between abrasion resistance and modulus of rupture.

Fig 5.2.2 shows the plot of abrasion resistance as a function of modulus of rupture. According to the results abrasion resistance is directly proportional to the modulus of rupture. The regression model gave the best fit to data with coefficient of determination value (R^2) of 0.962. Thus modulus of rupture is highly correlated to abrasion resistance and under the influence of foot traffic greater damage should be expected in the case of relatively low modulus of rupture marble.

(c) Correlation between abrasion resistance and compressive strength.

Fig 5.2.3 shows the plot of abrasion resistance as a function of compressive strength. The abrasion resistance is highly correlated with the compressive strength with coefficient of determination (R^2) of 0.946. Abrasion resistance not necessarily increases with the increase in the compressive strength but at very high compressive strength it has large value and hence high strength marble should have low abrasion wear than low strength marble.

(d) Correlation between abrasion resistance and flexural strength.

Fig 5.2.4 shows the plot of abrasion resistance as a function of flexural strength. Flexural strength is also highly correlated with the abrasion resistance with R^2 value of 0.967. Abrasion resistance is directly proportional to flexural strength.

(e) Correlation between abrasion resistance and bulk specific gravity.

Fig 5.2.5 shows the plot of abrasion resistance as a function of bulk specific gravity. Abrasion resistance is inversely proportional to bulk specific gravity. Abrasion resistance decreases with the increase in bulk specific gravity. But the value of R^2 is 0.367 and hence bulk specific gravity is less correlated with the abrasion resistance.

(f) Correlation between abrasion resistance and micro Vickers hardness.

Fig 5.2.6 shows the plot of abrasion resistance as a function of hardness. Abrasion resistance is also well correlated with the hardness with R^2 value of 0.84. Abrasion resistance in ASTM standard increases with hardness, however it is a not a simple linear relationship as proposed by the Archard.

Thus according to the results of regression analysis modulus of rupture, compressive strength, flexural strength and hardness of marbles could adequately estimate the abrasion resistance of rocks whereas rough estimates could be made with the water absorption and bulk specific gravity.

6.3 Effect of Load on Abrasive Wear.

Abrasive wear loss of Bhainslana black, Andhi jhiri and Makrana doongari marbles was predicted with respect to the load using WWA test method and the results of experiments are illustrated in Fig. 6.3. It is seen that abrasion wear of all the marbles generally increased with the applied load. From the regression analysis equations as illustrated in the table 6.3, it can be observed that all the three marbles exhibited linear relationship between the abrasive wear and the applied load, which satisfy the Archard law [6]. These observations suggest that the abrasion wear of Rajasthan marbles can be expressed by the slopes of straight fit lines fitted through the experimental data points. However it is also observed that the Makrana doongari and Andhi jhiri marbles showed the linear behaviour with the reduced slope values than the Bhainslana black marble which indicates that they are less sensitive to increasing loads. This unusual behaviour may be explained on the basis of their high mechanical strength. As stated by Das et al. [8] abrasion wear is a function of cutting or ploughing action at the wear surface. These actions are deformation induced material removal phenomenon. Due to which the wear rate of material depends upon the deformation parameters such as strength and hardness. The efficiency of abrasive particles to remove material decreases with the increasing strength and hardness. The value of compressive strength is highest for Makrana doongari marble follow by Andhi jhiri marble and Bhainslana black marble respectively. Thus their relatively less sensitive wear behaviour relative loads (as shown by lower slope values) may be attributed to their high mechanical strength. Thus abrasive wear loss is inversely proportional to mechanical strength in marbles which is also earlier reported by some authors (11, 45, and 47).

Table 6.3 Regression models showing relationship between the applied load and abrasive wear

S.No	Marble name	Regression equation	Coefficient of determination (R^2)	P- value
1	Bhainslana black	WEAR = 10.5+0.0891LOAD	0.993	0.004
2	Andhi jhiri	WEAR = 14.5+0.0719LOAD	0.967	0.017
3	Makrana doongari	WEAR = 13.5+0.0706LOAD	0.906	0.048

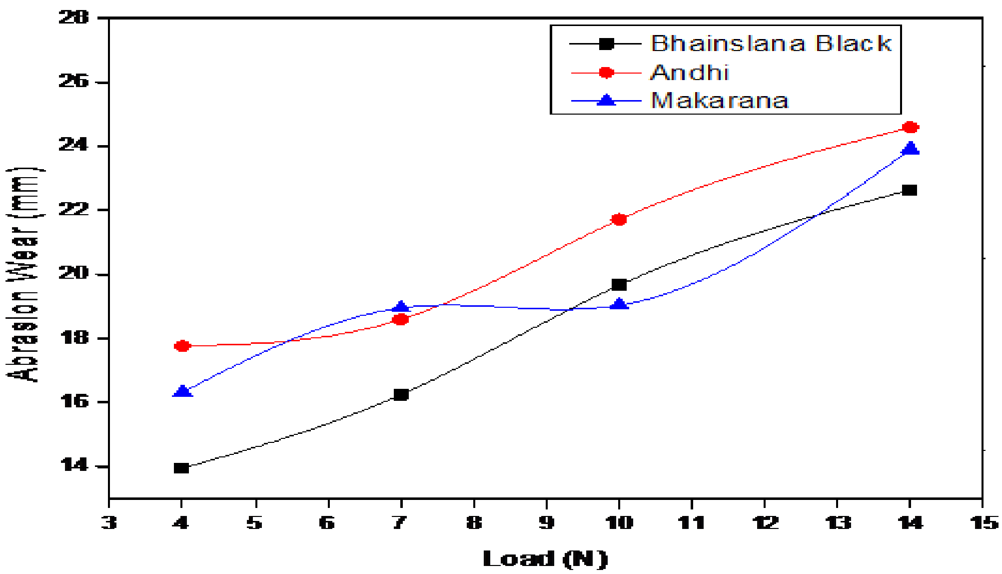


Fig.6.3 Effect of load on abrasive wear

6.4 Effect of Sliding Speed on Abrasive Wear

Abrasive wear loss of Bhainslana black, Andhi jhiri and Makrana doongari marbles was predicted with respect to the sliding speed using WWA test method and the results of experiments are illustrated in Fig. 6.4. In order to determine the effect of sliding speed on wear loss, five sliding speed was used for abrasion test. Abrasion wear of all three marbles at these five different sliding speeds under a load of 100N was measured. It is seen that abrasion wear of all the marbles first increased with the increase in sliding speed and then decreased. Thus abrasion wear of marbles increased in a linear function as a function of sliding speed initially and then started decreasing with further increase in the sliding speed. This is in contradiction with the wear formula as proposed by Archard [6] which implies a linear increase with the speed. This unusual behaviour may be due to two reasons. One possibility is that there may be change in abrasive particle condition. Another possibility is that the abrasive grits fail to fully entrain into the wear contact. As quoted by Marini [9] as far as the abrasive particles are concerned, that the same abrasive particles can be used more than the three times according to the standard almost about 20 times for marbles. Thus only possibility could be that with the increasing speed, abrasive grits failed to entrain 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. Thus the speed wear relationship as stated by Archard law might not be possible for marbles.

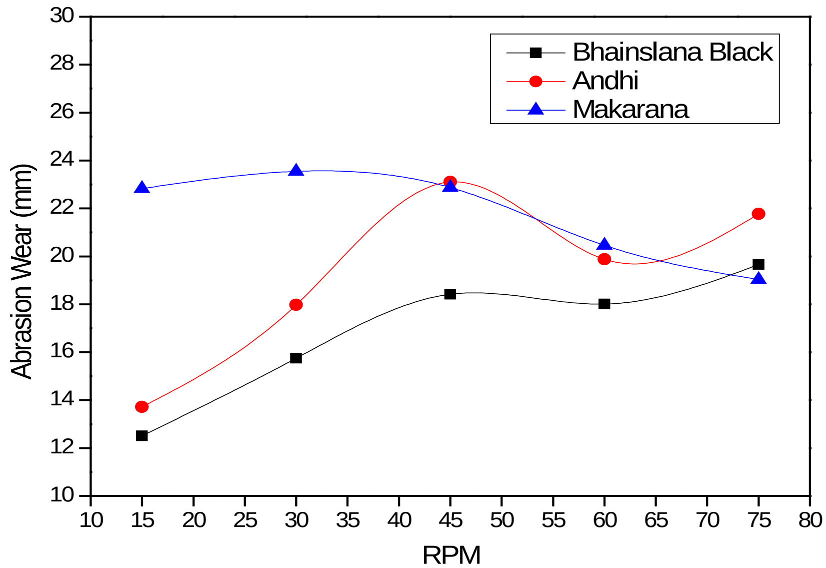


Fig. 6.4 Effect of speed on abrasive wear

From the regression analysis equations as illustrated in the table 6.4, it can be observed that abrasive wear is highly correlated with sliding speed and its effect cannot be neglected while calculating the abrasive wear for marbles. Bhainslana black marble is highly correlated with speed follow by Makrana doongari marble and Andhi jhiri marble respectively. According to the EN standard the testing is done at fixed load and 75RPM. But from the results, it can be concluded that 40-45 RPM will provide the better results at fixed load for marbles. However the results may be different for other stones like granites.

Table 6.4 Regression models showing relationship between the sliding speed and abrasive wear

S.NO	Marble name	Regression equation	Coefficient of determination (R^2)	P- value
1	Bhainslana black	WEAR = 12.2 + 0.108RPM	0.87	0.021
2	Andhi jhiri	WEAR = 13.7 + 0.131RPM	0.626	0.111
3	Makrana doongari	WEAR = 25.1 – 0.0713RPM	0.776	0.048

6.5 The Influence of Applied Load and Sliding Speed on the Abrasive Wear Rate Rankings of Marbles.

An attempt is done to examine whether variations in the applied load and sliding speed caused any differences in abrasive wear rate ranking, the abrasion wear of the tested marbles was listed in the table 6.5A with respect to applied load levels from 40 to 140N, and table 6.5B with respect to sliding speed ranging from 15 RPM to 75 RPM where '1'stands for the highest and '3' stands for the lowest wearing marble at each sliding speed level. It can be seen from the table that the ranking of any marble do not always maintain the same ranking at all loads and sliding speed. Thus the magnitude of abrasion wear differences between different marbles may show some variations depending upon the applied load and sliding speed. It can be shown from the Fig. 6.3 and 6.4 that the difference between the abrasion wear of these three marbles gradually changes with the variations in the applied load and sliding velocity. During practical applications when two or more marble varieties having different abrasion wear are used together for internal floorings and external pavements, it is very important that they should have uniform wear. All these results show that abrasive wear ranking of marbles using varying loads and sliding speeds may result in different conclusions. Abrasion ranking determination becomes an important criterion, whenever we are having two or more marbles available for the same flooring application. Abrasion rankings of three marbles can be determined at different loads and sliding speed from the Tables 6.5A and 6.5B. The tables are helpful in determine which marble should be used at different loading and speed conditions.

Table 6.5A Abrasion wear rankings of Rajasthan marbles with applied load

S.NO	MARBLE TYPE	LOAD IN N			
		40	70	100	140
1	Bhainslana black	3	3	2	3
2	Andhi jhiri	1	2	1	1
3	Makrana doongari	2	1	3	2

Table 6.5B Abrasion wear rankings of Rajasthan marbles with sliding speed

S.NO	MARBLE TYPE	SPEED IN RPM				
		15	30	45	60	75
1	Bhainslana black	3	3	3	3	2
2	Andhi jhiri	2	2	1	2	1
3	Makrana doongari	1	1	2	1	3

6.6 Effects of Micro Cracks on Mechanical Behaviour of Marbles

Various papers on micro cracks in marbles were studied and from them following results can be discussed. Due to its low porosity marble is an excellent construction and decorative material. Marble has almost no pores which make difficult for water or decay agents to penetrate the internal structure, hence increasing marble durability. Any temperature change can bring physical change in marble that cause in an increase in porosity which introduces new micro cracks and the expansion of existing ones. The cracks offer new paths into the marble which make it easier for solutions containing pollutants to penetrate the marble. Thermal change causes anisotropic expansion of calcite and dolomite crystals. The effect is more dangerous if marble is calcite and have straight grain boundaries. The micro cracks develops are generally Intergranular or multigranular. Cracks extenuate the elastic energy and cause elastic energy to move towards the boundaries between the grains. Large grain size and straight grain boundaries help in the formation of great length and large connectivity cracks.

When local tensile stress in marble is increased beyond the tensile strength leads to development of tensile cracks, a brittle deformation behaviour results. The shear crack growth is usually preceded by a formation of localized deformation bands, which are due to the process of damage accumulation and material deterioration, lead to ductile deformation behaviour. Failure modes of pre-flawed marble depend on the material parameters, loading conditions and flaw geometries.

By using the CSM technique, which gives the elastic modulus and hardness versus depth profile, the correct elastic properties of the rock can be deduced as the extrapolation of the profiles to zero depth. The knowledge of Intergranular cohesive force is very important to determine the macroscale strength of marble.

Chapter-07

CONCLUSIONS

In this study Abrasion resistance to foot traffic was determined for 5 different types of marbles found in Rajasthan according to ASTM C241 standard. The correlations between the abrasion resistance and marble properties were established according to ASTM standard. Abrasion wear rate of 3 different types of Rajasthan marbles was also analyzed under varied loads ranging from 40 to 140 N and under varied speed ranging from 15 to 75 RPM according to EN14157:2004 standard on wide wheel abrasion test apparatus. From the above mentioned experiments according to the standards the following conclusions can be drawn.

(i) Since, Green Udaipur, Bhainslana black and Makrana doongari marble have high values of abrasive resistance they can be used for railway platforms, airports, showrooms and shopping centers as flooring applications. For internal flooring purposes all five marble types are found suitable.

(ii) Combination of different marbles can be used for flooring purpose to increase color and design aesthetics. Abrasion resistance value Ha of all the marbles should not have difference more than 5 in such cases. Due to which Green Udaipur should be used alone for flooring purposes, while marbles like Bhainslana black and Makrana doongari can be used together. However due to almost same abrasion resistance value Andhi jhiri, Makrana doongari and Agaria white marbles can be used together.

(iii)According to the regression analysis results, it can be concluded that modulus of rupture, compressive strength, flexural strength and hardness of marbles could adequately estimate the abrasion resistance of rocks due to their high correlation whereas rough estimates could be made with the water absorption and bulk specific gravity due to low correlation.

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

(v) 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 Bhainslana black, followed by Andhi and Makrana marbles. The Makrana marble was less sensitive to increasing loads then other two marbles due to its high mechanical strength.

(vi)Abrasion wear of all marbles increased initially with the sliding speed and then decreased. With the increased speed, abrasive grits failed to entrain 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.

(vii) High correlations exist between the applied load and abrasion wear as well as between the sliding speed and the abrasion wear.

(viii) 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.

(ix) According to the EN standard the testing is done at fixed load and 75RPM. But from the results, it can be concluded that 40-45 RPM will provide the better abrasion wear results at fixed load for marbles. However the results may be different for other stones like granites.

(x) The micro cracks can be distinguished into four main categories such as grain boundary cracks, Intergranular cracks, Intragranular cracks and multigranular cracks. The cracks offer new paths into the marble which make it easier for solutions containing pollutants to penetrate the marble. Thermal change causes anisotropic expansion of calcite and dolomite crystals. The effect is more dangerous if marble is calcite and have straight grain boundaries. The micro cracks develops are generally Intergranular or multigranular. Cracks extenuate the elastic energy and cause elastic energy to move towards the boundaries between the grains. Large grain size and straight grain boundaries help in the formation of great length and large connectivity cracks.

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