Strength and Durability Studies on Concrete Containing Granite Cutting Waste as Partial Replacement of Sand

Ph.D. Thesis

Sarbjeet Singh

ID: 2013RCE9021

Department of Civil Engineering

MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY JAIPUR

JAIPUR-302017

November, 2016

Strength and Durability Studies on Concrete Containing Granite Cutting Waste as Partial Replacement of Sand

This thesis is submitted

as a partial fulfillment of the Ph.D. programme in Engineering

Sarbjeet Singh

ID: 2013RCE9021

Department of Civil Engineering

MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY JAIPUR

JAIPUR-302017

November, 2016

MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY JAIPUR

CERTIFICATE

This is to certify that the thesis report entitled "**Strength and Durability Studies on Concrete Containing Granite Cutting Waste as Partial Replacement of Sand**" which is being submitted by **Sarbjeet Singh**, **ID: 2013RCE9021**, for the partial fulfillment of the degree of **Doctor of Philosophy** in Civil Engineering to the Malaviya National Institute of Technology Jaipur has been carried out by him under my supervision and guidance. I consider it worthy of consideration for the award of the degree of Doctor of Philosophy of the institute.

(**Dr. Ravindra Nagar**) Supervisor	**(Dr. Vinay Agrawal)** Supervisor

The Ph.D. viva voce examination of Mr. Sarbjeet Singh has been conducted by the Oral Defense Committee (ODC) constituted by the Chairman SPGB, as per 9.4.3, vide letter No. F.4(P) PhD /Acad./MNIT/2016/1331. The ODC declares that the student has successfully defended the thesis in the viva-voce examination.

Dr. Ravindra Nagar Supervisor	**Dr. Vinay Agrawal** Supervisor	**Dr. Ashish Dhamaniya** External Examiner

MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY JAIPUR

CANDIDATE’S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled ‘**Strength and Durability Studies on Concrete Containing Granite Cutting Waste as Partial Replacement of Sand’** in partial fulfillment of the requirements for the award of the PhD and submitted to the Department of Civil Engineering, Malaviya National Institute of Technology Jaipur, is an authentic record of my own work carried out at Department of Civil Engineering during a period from July 19, 2013 to May 23, 2016 under the supervision of Dr. Ravindra Nagar, Professor, Department of Civil Engineeringand Dr. Vinay Agrawal, Assistant Professor, Department of Civil Engineering, Malaviya National Institute of Technology Jaipur.The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

Date: __________ (**Sarbjeet Singh**)

This is to certify that the above statement made by the candidate is true to the best of my knowledge.

(Dr. Ravindra Nagar)
(Supervisor)
Department of Civil Engineering,
Malaviya National Institute of Technology Jaipur.
Date: __________ Jaipur- 302017, Rajasthan, India.

(Dr. Vinay Agrawal)
(Supervisor)
Department of Civil Engineering,
Malaviya National Institute of Technology Jaipur.
Date: __________ Jaipur- 302017, Rajasthan, India.

Acknowledgement

I humbly grab this opportunity to acknowledge reverentially, may people who deserve special mentions for their varied contributions in assorted ways that helped me during my Ph.D research and the making of this thesis. I could never have embarked and finished the same without their kind support and encouragements.

First and foremost, I would like to express my sincere gratitude and praise to the Almighty GOD, who had showered his grace in the form of knowledge and wisdom and every other way for completing this thesis.

I would like to express my profound gratitude to my guides Dr. Ravindra Nagar, Professor, Department of Civil Engineering and Dr. Vinay Agrawal, Assistant Professor, Department of Civil Engineering Malaviya National Institute of Technology, Jaipur, Rajasthan, India for their supervision, advice, and invaluable guidance from the very early stages of this research. Their perceptual inspiration, encouragement, and understanding have been a mainstay of this work. From their busy schedule, they always spared time for assessing the progress of mywork. Their wide knowledge regarding the subject helped me in writing this thesis. I am indebted for their kind help and support which made it possible for me to stand up to the challenges offered by the task and come out successfully.

I am thankful to the Officers and Staff of academic affairs for their cooperation in academic work and help throughout the course of study. I am not able to find words in any of the dictionaries for thanking Prof. Gunwant Sharma, Prof. Y.P. Mathur, Prof. A.B. Gupta, Prof. A.K.Vyas, Prof. Sudhir Kumar and Dr. Sandeep Choudhary, Department of Civil Engineering, MNIT Jaipur for their valuable guidance, unfailing encouragement, keeping my moral high during the course of the work and helped me out whenever I needed them.I am extremely thankful to members of DGPC and DREC, for their support and guidelines regarding my thesis work. I am also thankful to Dr. Urmila Brighu, DPGC Convener, Dr. Mahesh Jat, Dr. S.K Tiwari, Dr. Pawan Kalla, Dr. Arun Gaur, Prof. Rohit Goyal, Prof. B.L. Swami, Dr. M. K. Shrimali, Dr. S.D.Bharti, Dr. J.K. Jain, Dr. Rajesh Gupta, and all other faculty members of Malaviya National Institute of Technology Jaipur.

I extend my deep sense of gratitude to Director, Head, Civil Engineering Department, Dean Academics, and Dean R&C of MNIT Jaipur for strengthening the research environment of the Institute and for providing me with the environment and space to carry out my research work. I give my thanks to Mr. Rajesh Saxena, Office-in-Charge, Civil Engineering Department, MNIT

Jaipur, Mr. Ramjilal Meena and Mr. Sapan Gaur, who were always ready to extend me every possible help throughout my work.

I can never forget the assistance extended to me by CDOS (Centre for Development of Stone) for providing the required raw material and backing the research with financial remuneration.

Last but not the least I extend my heartfelt gratitude to my parents- Mr. Surjeet Singh and Mrs. Narinder Kaur for their unshakable faith in my capabilities and impeccable mental support throughout the course of the research.

Dated: __________ **(Sarbjeet Singh)**

Student ID: 2013RCE9021

Abstract

The ever increasing pace of globalization, production and consumption have led to a situation where the nature is experiencing tremendous strain to meet the demands of raw material to try and satisfy the insatiable appetite of the industry to produce more. Moreover just to aggravate the situation further the worsening, handling and disposal capabilities for the heaps of industrial byproducts generated is becoming a serious handicap in the path of realizing the goal of a comprehensive sustainable growth. A tremendous amount of efforts have been put forth by the researchers in the past as well as still going on in figuring out the effective and efficient ways to handle and absorb the quantum of waste generated.

One of the unilaterally accepted frontrunner among the contributors to the waste generated has been the construction industry. With the kind of lifestyle and living standard changes going across the globe stone industry have emerged as one of the foremost cause of concern with respect to the quantum of waste generated. Marble and Granite waste have been the significant portion of the total stone waste. Concrete by many matrices is by far and likely to remain one of the largest consumed material in the world. Concrete is remarkably a versatile material which has shown commendable affinity to absorb a variety of industrial byproducts as partial to full replacement of fine aggregates and cement in it.

Quite significant research has already been done that establishes the credentials of Marble as a substitute for fine aggregate and cement upto optimum percentage as reported by various researchers. However a comprehensive and concluding research assessing the capability of the Granite Cutting Waste as a partial replacement for fine aggregate in concrete with parametric w/c ratio was still missing and therefore the thesis attempts to address and deliver the same.

The experimental methodology included making the detailed assessment of rheological, mechanical and durability characteristics of Granite cutting waste substituted concrete and explaining the phenomenon observed with the assistance of

Information gathered from the microstructural studies conducted. Thirty six concrete mixes were cast in two series at 0.30, 0.35, 0.40 (Series-I) and 0.45, 0.50, 0.55 (Series-II) water cement ratio by substituting 0%, 10%, 25%, 40%, 55% and 70% river sand by GCW. It was found that the replacement of fine aggregate with GCW leads to the reduced workability of the resulting concrete mix and this was clearly reflected by the decrement in the observed values of slump. The observations for mechanical properties were made by evaluating the response of specimens casted in terms of compressive strength, flexural strength and split tensile strength. The results have been found to be very encouraging as these strength parameters showed increment over the values observed for the control concrete up to a certain optimum percentage replacement (25-40%). The durability of the concrete was evaluated using various tests including permeability, water absorption, carbonation, corrosion, chloride penetration, shrinkage, acid attack and corrosion. The test result clearly showed that GCW substituted concrete exhibits enhanced resistance to carbonation chloride penetration, acid attack at optimum GCW replacement of 25%. No loss in weight was observed at all duration of $MgSO_4$ solution. The specimen with 25% GCW replacement exhibits greater intensity and peak area for hydration productas compared to control specimen. It was observed that replacement with GCW leads to enhanced properties of the concrete as far as the aforementioned tests are concerned. Concrete matrix becomes more dense and compact with optimum percentage of GCW substitution. To deliver the detailed explanations for the improved behavior of Granite Cutting Waste substituted concrete specimens SEM and XRD tests were carried out. To study the extent of hydration water present concrete was exposed to elevated temperatures ranging 30-900 C and gravimetric observations were then made and analyzed to seek appropriate explanations for the behavior observed.

Contents

List of Figures

List of Tables

List of Symbols and Abbreviations

GCW	Granite Cutting Waste
W/C	Water-cement Ratio
SEM	Scanning Electron Microscope
XRD	X-ray Diffraction
TGA	Thermo Graphic Analysis
DMG	Department of Mines & Geology

Chapter 1

Introduction

- **General**
- **Waste Generated by Stone Industry**
- **Properties of Granite Cutting Waste**
- **Significance and Objective of the Research Endeavour**
- **Organization of Thesis**

1.1 General

Concrete is one of the most widely utilized material globally with total production of about 25 billion tonnes per annum. Its key ingredients are cement, fine aggregate, coarse aggregates, water and admixtures etc. With rapid surge in the growth rate of globalization and urbanization comes the insatiable demand for the raw materials in the concrete industry. The exponential demand for the fine aggregate i.e., natural sand exerts tremendous stress on the natural reserves of sand i.e., river beds. As per calculations, world consumes 5-7.5 billion tonnes of river sand every year for construction purpose. The excessive consumption of river sand has depleted the river beds and adversely affected the surrounding flora and fauna. The excessive mining of sand has resulted in reduced water storage of stream, lower water tables, and unstable substructure of river bridges and eroded river beds. Thus, authorities in some countries have banned or constrained the usage of river sand as construction material. The limited supply of river sand on one hand and enhanced infrastructural development throughout the country has compelled the researchers and concrete manufacturers to look for other viable alternatives. The Rajasthan high court also imposed a ban on sand mining from river Banas in 2013, the ban was later lifted and provisional sanction was given due to sand requirement for ongoing Jaipur Metro Project [India Times, 2015].

Researchers have assessed and tried to establish the feasibility of a wide range of industrial waste products such as slag, rubber tyre, recycled glass, pond ash, waste foundry sand, plastic waste, stone waste etc. as a substitute or partial replacement for fine aggregate in the concrete production. In 2012 the world's total production of dimension stones including granite came out to be 125 million tons India is enriched with deposits of all types of dimension stones. As one of the largest producer of stones in the world, It is endued with ample variety of granite comprising over 200 shades. The humongous amount of stone waste generated globally provides the possibility of being utilized as a potential substitute for the natural sand in the concrete production. GCW (Granite cutting Waste) is one such stone waste that seeks attention and invites in-depth research courtesy to the large amount of this waste getting generated every year and structural and functional similarity to the natural sand being replaced.

1.2 Waste Generated by Stone Industry

Rajasthan is the largest state in India in terms of geographical area and at the same time it possesses the largest share in the Indian stone industry. It owns a plethora of stone varieties including marble, sandstone, granite, limestone and kota stone etc., and these resources fuel the economy of the state. More than 30% of the state`s income is sourced by the stone industry. This industry engages about one third of the total population of the state. But in the last few years this industry has faced serious setbacks courtesy to the repeated forced restrictions and limitations on the mining activities by the government. One of the prime reasons for such a series of restrictions is lack of proper disposal mechanism for the waste generated alongside machining operations encompassing variety of activities like cutting, sawing and polishing etc.

The table below details the concerned scenario:

Table 1.1: Waste generation in stone industry

(Source: DMG Rajasthan Report, 2011)

Stone waste generated	**%out of total**
Quarrying (ungraded or undersized material, overburden, side burden & inter burden)	50.00
Processing (Dressing, cutting and polishing)	15.00
Transportation	0.500
Total waste	**65.50**

It can be readily inferred from the table that more than 50%of the stone is lost as waste slurry, grit or fines before it is ready for use at the consumer end. A lack of proper waste disposal site invariably leads to huge mounds of waste lying around in the open causing air pollution and range of health problems like asthma, irritation, nausea etc. This slurry which is usually dumped on open grounds or near highway scan render their surface slippery when wet, may cause waterlogging and disturb the ecology of the area. Also the very fine powder can cause a variety of health and visibility problems. At times the waste is even dumped on seasonal river beds threatening the porosity of aquifers. Water logging can also take place in due course of time. Considering the threat this waste pose to the entire ecosystem in a variety of ways be it affecting human health, or damaging the natural traits of the watersheds and aquifers such as porosity etc. it has become imperative to find appropriate means of efficient and effective disposal mechanism.

1.2.1 Granite Cutting Waste

In 2012 the world's total production of dimension stones including granite came out to be 125 million tons. From the data of **Indian Minerals Yearbook 2013** the India's contribution in granite reserves on 1.4.2010 came about 46,230 million cubic meters. Of this Rajasthan has allocation of 20% of the total share of granite in India which is around 8479 million cubic meters (as per the DMG Rajasthan report)**.**

Figure 1.1: One of the heaps of GCW in shahpura industrial Area

granite processing which includes sawing and polishing by using blade cutters leads to the generation of enormous amount of solid waste which is more than 30% by volume of the final product. This huge waste needs to be properly disposed of in specially allotted land fill sites according to the Hon’ble Supreme Court of India by its order dated 14/10/2003 in the Writ petition No. 657/95. (CPCB, 2013). The disposal of these slurries leads to drastic reduction of water due to evaporation and percolation leaving behind granite fines as airborne particles which is pernicious to health. Also because of lack of availability of area the factories are now disposing these wastes around there own factory surroundings creating respiratory and allergy problems for both workers and people living nearby.

This growing heap of stone waste is plaguing the Rajasthan stone industry which has now entered into legal disputes with various administrative bodies over the environmental impacts of this waste. The mining industry has even been facing temporary ban from High Court which has put thousands of people out of job.

1.3 Properties of Granite Cutting Waste

1.3.1 Physical Attributes

The particles of granite dust are irregular, angular, and porous and have rough and crystalline surface texture. The particle size resembles fine sand. Granite dust particles exhibit interlocking characteristics. The specific gravity of granite dust varies from 2.36 to 2.72 depending upon its source stone. Table shows the specific gravity, water absorption and fineness modulus of various granite dust as reported by various researchers.

Table 1.2: Physical attributes of granite cutting waste

Physical properties	Donza et al. (2002)	Arulraj and Kannan (2013)	Vijaylakshmi et al. (2013)	Elmoaty * (2013)	Williams et al. (2008)	Adigun (2013)	Kala (2013)
Specific gravity	2.69	2.61	2.386	2.50	2.6-2.8	2.72	2.58
Water absorption (%)	-	-	-	-	0.5-1.5		
Fineness modulus	3.15	-	-	-	-	3.69	2.43

1.3.2 Chemical Attributes:

Granite cutting waste is primarily composed of silica, alumina and potassium with minor quantities of calcium and magnesium. The chemical composition is invariably controlled by the parent rock characteristics. Table exhibits the comparative study of chemical composition of granite dust acquired from different sources of granite stone.

Table 1.3: Chemical attributes of granite dust

Chemical composition (%)	Vieira et al. (2004)	Hojamberdiev et al. (2011)	Abukersh and Fairfield (2011)	Vijaylakshmi et al. (2013)	Li et al. (2013)	Elmoaty (2013)
SiO_2	67.14	65.10	61.40	72.14	57.58	85.5
Al_2O_3	14.92	14.00	16.30	17.13	10.42	2.10
Fe_2O_3	4.40	4.34	3.66	-	2.06	0.40
CaO	1.91	6.04	3.69	-	1.89	4.90
MgO	0.73	1.12	1.70	-	-	2.50
Na_2O	2.93	3.51	3.62	-	3.29	-
K_2O	5.18	2.75	3.75	-	3.42	-
TiO_2	0.73	-	-	-	-	-
SO_3	-	-	0.05	-	-	1.80
LOI	0.50	3.14	5.01	-	-	1.10

1.4 Significance and Objective of the Research Endeavour

1.4.1 Significance

With exponential hike in the rate of generation of industrial by-products arises the need for efficient and effective solid waste disposal mechanism. The scarcity of the land space for waste disposal along-with tremendous quantum of waste generated makes it tedious to facilitate economical waste disposal. Besides, the increasing demand for raw materials in the construction industry is causing a major upwards shift in the price thus making it eventually challenging to meet the demands with limited financial means. A variety of industrial by-products generated in abundant quantities put forward the possibility of reutilization within concrete industry. Granite Cutting Waste is one such waste. The reutilization of this waste in concrete industry as a partial replacement for sand aggregate will not only facilitate economical alternative to the need of raw material in the industry but at the same time will address the threatening problem of efficient and effective waste disposal.

1.4.2 Niche in the Research

India’s share in granite production in the year 2014 was roughly about 45-55 million sqm / year and waste produced during granite cutting was about 15% by weight, which is a fairly large quantity [World Natural Stone Association, 2014]. Rajasthan accounts for about 20% which is around 8479 million cubic meters national granite productions [CDOS, 2015]. The granite is cut and polished prior to its usage. Cutting and polishing operations generate large amount of cutting and polishing waste. Granite cutting waste (GCW) has become a serious problem in its mining regions throughout the state. Jaipur, Jalore, Barmer, Pali, Sirohi, Alwar, Jhunjhunu, Tonk, Ajmer, Bhilwara, Sikar and Udaipur being the most affected areas During the cutting process, granite mass lost is approximately 30% in the form of fine dust. Every year 250-400 tons of granite waste is generated at site (Rajgor and Pitroda, 2013).

The huge quantum of waste generated invites serious research endeavour to assess the feasibility of Granite Cutting Waste as a potential substitute or partial replacement for sand in the concrete manufacturing process. The literature review ahead clearly put forth the fact that in past only limited scope studies have been attempted and necessitate the need for a detailed study encompassing GCW feasibility assessment on strength and durability grounds with parametric w/c ratios supported by microstructural attributes study.

1.4.3 Research objectives

Considering the niche in the research area, the final objective of the research endeavour is to assess the strength and durability of the concrete obtained with variable w/c ratios of 0.30, 0.35, 0.40, 0.45, 0.50 and 0.55 respectively and view the results obtained in the light of microstructural studies.

The final objectives of the research endeavour are:

1. Characterization of Granite cutting waste and natural sand.
2. Study of incorporating GCW various hardened concrete tests including compressive strength, flexure strength, pulls off strength etc. for different w/c ratios.
3. Durability assessment of concrete in terms of response to various durability tests including permeability, acid attack, sulphate attack, carbonation corrosion and exposure to elevated temperature (TGA).
4. In-depth microstructural study of the incorporating GCW concrete highlighting features at molecular scale.

1.5 Organization of Thesis:

The thesis has been divided in five chapters:

Chapter 1: This chapter introduces the realm of the problems of GCW disposal and economical procurement of the raw material in concrete manufacturing. The chapter includes identification of niche in the industry for the utilization of GCW and concludes with the research objectives.

Chapter 2: This chapter presents a critical review of the existing literature on the possibility of use of Granite cutting waste as a partial replacement for natural sand in the concrete.

Chapter 3: This chapter presents a detailed study of the raw material used and the methodology adapted for the various strength and durability tests performed during the course of research work.

Chapter 4: The chapter details the results and observations of the tests performed including compressive test, flexure strength test, acid attack, sulphate attack, carbonation, abrasion, chloride-ion penetration, corrosion, shrinkage etc. performed on specimens with variable w/c ratios.

Chapter 5: The chapter concludes the findings of the research endeavour and makes recommendations for appropriate replacement of natural sand via Granite Cutting Waste in the concrete manufacturing process.

References: All the references have been duly mentioned under this heading at the end of the thesis.

Chapter 2
LITERATURE REVIEW

- **General**
- **Quarry Waste**
- **Literature Review Concerned with Utilization of Granite Waste in Concrete**

2.1 General

Increased demand for the raw material and their limited availability at the same time invites a huge paradigm shift in the way manufacturing of concrete is being carried out. Loads and piles of unattended waste raise concerns for the effective and efficient waste disposal mechanism. This is where the need for the utilization of this waste arises. Concrete has been one of the most dynamic construction material ever used in the industry and it presents a huge possibility for absorbing this waste as a potential partial replacement for the aggregate in the manufacturing process. A variety of industrial by-products have been attempted in the past as a replacement for sand as key ingredient in the concrete. This huge plethora of by-products include fly –ash, coal bottom ash, crumb rubber, glass aggregates, silica fume, coal bottom ash, stone waste etc. Recent studies showed that attempts have been made to substitute aggregate with stone waste resulting in a sustainable concrete.

2.2 Quarry Waste

Quarry waste generated throughout the world poses a variety of ecological threats including respiratory problems, water logging, damage to vegetation, slippery highways etc. India is one of the largest producers of finished processed stones throughout the world.

Hamza et al. (2011) estimated global quarry waste production to be about 75 million tonnes.The research work carried out on the effective and efficient utilization of different stone waste as replacement of fine aggregate in concrete manufacturing has been reviewed.

Sravani et al.(2014) replaced fine aggregate with quarry dust waste in increments of 25% .It was observed that up to 75% replacement, the values of compressive strength were within permissible limits.

Nagabhushana and Bai (2011) investigated the strength of concrete with partial replacement of natural sand with CRP (Crushed rock powder) in steps of 20%, 30%, and 40% respectively. It was observed that the compressive strength, flexure strength and split tensile strength were not significantly affected up to 40% replacement of natural sand with CRP and thus sand could be effectively replaced up to 40% with CRP without compromising the strength of the concrete.

Vijayalakshmi et al. (2013) assessed the strength and durability attributes of concrete on partial replacement of fine aggregate with granite industry waste. Fine aggregate was replaced with Granite Powder waste in proportions of 0%, 5%, 10%, 15%, 20% and 25% respectively. It was observed that workability decreased consistently as the percentage replacement increased. Compressive strength was maximum at optimum percentage replacement of 15%. Split tensile strength and flexure strength exhibited decrement with increasing percentage replacement. These parameters were found to be comparable to control concrete at a percentage replacement of 15%. Also, the optimum values for chloride penetration and Ultra Pulse Velocity were observed at 15% replacement. Thus, overall optimum replacement of fine aggregate with Granite Powder Waste was found to be 15%.

Corinaldesi et.al. (2009) studied the effect of partial replacement of natural sand and cement with marble dust. Concrete mixes exhibited maximum compressive strength and comparable workability as that of the control concrete at 10% replacement of natural sand with marble dust. Therefore, it was recommended that 10% replacement would be ideal to obtain concrete having good strength and remarkable durability properties. Alyamaç and Adin (2015) attempted a study to find out the maximum possible percentage replacement of natural sand with marble powder for comparable properties as that of the control concrete (the one with 0% replacement). They performed various tests including compressive strength, split tensile strength, water absorption, sorptivity and abrasion resistance. Besides, a cost analysis was also performed. The maximum possible percentage replacement was found to be 40 %.

In another study Rana et al. (2015) investigated the effect of partial replacement of fine and coarse aggregates with recycled Kota stone aggregate. It was found that use of recycled stone aggregates in place of natural coarse aggregates led to enhanced compressive strength and lesser permeability as compared to the control concrete.

Also, the use of recycled stone manufactured sand enhanced the aforementioned properties of the concrete mix. Thus, it was concluded that the natural coarse aggregates and natural sand can be effectively replaced by the recycled Kota stone aggregates and recycled Kota stone manufactured sand respectively.

Rana et al. (2016) investigated the possibility of utilizing dimension limestone as a replacement for natural sand in concrete. They observed enhanced strength, reduced permeability, and bleeding for the concrete with a mix of 85% crushed solid stone waste and 15% slurry as fine aggregate.

Thus, it can be established from the above studies that the partial substitution for natural sand in concrete can be made with granite cutting waste, granite slurry, Kota stone slurry, marble slurry respectively up to an optimum percentage replacement. The enhanced strength and durability parameters may be attributed largely to the physical and chemical properties of the particles of this waste. While the chemical similarity with sand is important, the physical properties of the waste particles like fineness, shape, and surface texture also play a major role in determining the strength and long-term durability of the resulting concrete.

2.3 Literature Review Concerned with Utilization of Granite Waste in Concrete

Besides the variety of wastes mentioned above, Granite Waste is a waste of critical importance owing to the huge quantum of these waste generated and striking similarities with fine sand. Vijayalakshmi et al. (2013) , Adigun (2013) , Kala (2013) , Joel (2010), Kanmalai et al. (2008), Arulraj et al. (2013) , Elmoaty (2013) , Divakar et al. (2012), Marmol et al. (2010), Li et al. (2013) , Ramos et al. (2013), Allam et al. (2014), Kala and Senthuraman (2013), Williams et al. (2008) assessed the impact of partial replacement of fine aggregate by Granite Cutting Waste on the rheological, mechanical and durability aspects of concrete.

2.3.1 Attributes of fresh granite dust concrete

2.3.1.1 Workability

Water required for desired workability of concrete mostly depends upon the properties and quantity of fine aggregate particles. Granite dust particles are angular and rough textured and porous. The particles of size smaller than 75μm are in higher percentage in granite dust. Therefore on using granite dust as replacement for fine aggregate in concrete, the number of rough textured, fine and irregular particles increases. The increased inter particle friction and surface area might be a reason for the poor flow characteristics of fresh concrete. Secondly since the granite dust has much higher water absorption ratio as compared to natural aggregate, the internal water absorbed by the granite dust particle reduces the availability of water for lubrication of cement paste which hinders the process of achieving desired workability. Hence for constant water cement ratio, the workability of granite dust concrete reduces as compared to the control concrete. In other words, to achieve the same slump of concrete the water requirement of granite dust concrete is higher. A summary of relevant studies is presented in subsequent paragraphs.

Falade (1999) the effect of using different grain sized granite fines on the properties of the concrete. Seven different size ranges namely 4.75-0.063 mm, 4.75-3.35 mm,3.35-2.36 mm, 2.36-1.70 mm,1.7-1.18 mm,1.18-0.3 mm,0.30-0.063 mm and 4.75-0.063 mm were used. It was found that as the particle size of the granite fines being utilized decreased, corresponding workability of the concrete mix decreased.

Joel (2010) observed that workability of concrete mixtures containing varying percentage from 10% to 100% of crushed granite dust as sand replacement, improved with respect to control concrete mixture. While upto 50% replacement the slump values were equivalent, at higher replacement levels the rise in workability was observed.

Vijayalakshmi et al. (2013) studied the effect of granite powder on the slump of concrete. Fine aggregates were partially replaced with 0, 5, 10, 15, 20 and 25% granite powder respectively. Fixed water cement ratio was considered in all mixes.

Slump values were calculated for all the concrete mixes. The slump losses were calculated at different time range from immediate mixing, i.e. 30 minute and 60 minute. However, there is some contrary data also in the published research which is against the concept of decreased workability on use of granite dust as sand replacement in concrete. The published literature which indicate increase in workability are discussed below.

Adigun (2013) observed the contrary results when crushed granite dust was used to replace natural sand in varying percentages from 0% to 100%. he observed that for fixed water cement ratios of 0.42 and 0.45 for two different nominal mixes consisting of nine trial mixes, the slump value increased with increase in crushed granite powder content.

Kala (2013) examined the effect of granite powder as sand replacement at levels of 0%, 25%, 50%, 75% and 100% by mass at three different water cement ratios, on workability of concrete. Mineral admixture was used to replace cement by 27.5%. They observed that the slump values increased with increase in granite powder content in the concrete mix. This was attributed to the higher granite dust particle quantity along with mineral admixture.

Sukesh et al. (2013) observed that as the percentage replacement of sand with granite quarry dust increases, workability of concrete decreases. The higher water absorption of granite quarry dust is a major factor behind the decreased workability of the concrete.

Raghavendra et al (2015) investigated the effect of granite fines on the workability of the concrete. It was observed that for all the percentage replacements upto 25% granite substituted concrete exhibited comparable workability to that of the control concrete.

Harur et al. (2015) observed the workability of concrete when natural sand was replaced by granite powder for fixed w/c ratios of 0.55, 0.45 and 0.40. The concrete mixtures containing varying percentage from 10% to 50% of granite powder as sand replacement recorded improved slump values as compared to control concrete.

Raghvendra et al. (2015) found that workability in terms of slump value decreases with the increase in the replacement level of fine aggregate with granite powder. They found that the slump value reduced from 85mm to 70mm when the replacement level was increased from o to 25%.

Singh et al. (2016) assessed the impact of replacement of fine aggregate by granite cutting waste on a host of mechanical and durability characteristics. The experiments were carried out with the 0.3, 0.35 and0.4w/c ratios and for the percentage replacements of 0%, 10%, 25%, 40%, 55% and 70% respectively. It was found that as the percentage replacement increased the workability of the concrete matrix decreased slightly. It was stated that the loss of workability could be easily make up by the use of superplasticizers.

Thus it can be concluded from the results reported by the majority of the researchers that as the percentage replacement for natural sand by granite dust in concrete increases, the corresponding workability of the concrete mix decreases.

2.3.2 Properties of hardened granite dust concrete

2.3.2.1 Compressive strength

The ultimate resistance offered by the concrete block before yielding to the applied compressive load can be termed as the compressive strength of the concrete.

The development of strength in concrete is governed by water cement ratio and the bond at the interface of hydrated cement paste and aggregates. The strength of the individual constituent material in concrete mix also has some influence on the strength of concrete mix. The investigation shows that the granite particles are comparable in strength with natural sand particles. The matrix or microstructure of the granite dust concrete is dense and has better dispersion of cement grains which ultimately results in better compressive strength of granite dust concrete mix at lower replacement ratios.

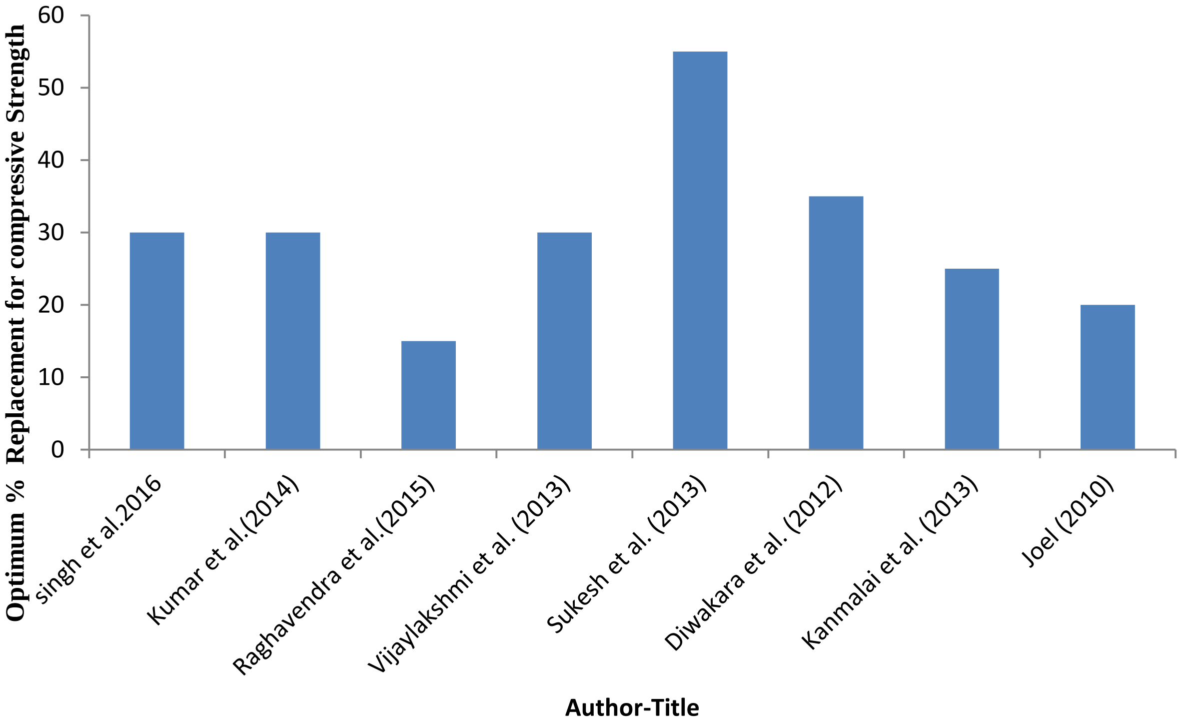


Fig.2.1 . Optimum Percentage replacement proposed by various researchers for maximum compressive strength

F.Falade (1999) studied the effect of using different grain sized granite fines on the compressive strength of the concrete. Seven different size ranges namely 4.75-0.063 mm, 4.75-3.35 mm, 3.35-2.36 mm, 2.36-1.70 mm,1.7-1.18 mm,1.18-0.3 mm, 0.30-0.063 mm and 4.75-0.063 mm were used in the study. The maximum compressive strength was observed for 1:1.5:3 mix for granite fines particles size range of 0.3-1.18 mm. The compressive strength for this mix was found to be 14% higher than the concrete mix containing granite fines with particle size of all the ranges. H. Donza et al. (2002) studied the effect of using a variety of fine aggregates on the properties of concrete. It was observed that G-530 (Granite sand concrete with 530 kg/m3 Granite sand) exhibited higher strength at all ages than the S-530 (Natural sand concrete with 530 kg/m3 Natural sand).Assuming all other factors as constant this was attributed to the higher intrinsic strength of granite sand particles and the strong paste-fine aggregate interface.

Oyekan and Kamiyo (2008) studied the effect of inclusion of Granite fines on the compressive strength of the sandcrete blocks. The compressive strength of the concrete specimens was found out to be maximum for a percentage replacement of 15% of the total volume of fine aggregates by granite fines. Beyond 15% replacement the compressive strength of the granite fines concrete began declining gradually.

Kanmalai et al. (2008) investigated the effect of granite dust with varying levels from 25% to 100% as sand replacement on properties of concrete and observed that concrete mix with 25% granite dust exhibited highest strength increment of 2% to 7% for all days of curing. The mixes with higher replacement levels showed lesser compressive strength than the control concrete.

Joel (2010) studied the effect of granite dust as partial and full replacement of sand and observed that compressive strength increased with increase in amount of crushed granite dust replacement up to 20%. Further addition of granite beyond 20% led to decrease in compressive strength at all ages such as 7, 14 and 28 days. However at 100% replacement the compressive strength was better than the 30% to 90% substitutions.

Marmol et al. (2010) demonstrated that use of granite slurry as cement replacement from 0% to 20% has detrimental effect on compressive strength of mortar at both 7 and 28 days of curing period. When the granite slurry is used to replace natural sand at 0% to 100% replacement, the compressive strength shows a gradual improvement at all substitution levels.

Felixkala and Partheban (2010) studied the properties of concrete with granite powder as partial replacement for fine aggregate in the concrete. It was found that the maximum compressive strength was obtained for a percentage replacement of 25%.The compressive strength was found to be greater than the control concrete at all ages of curing by 2-9%. The replacements beyond 25% resulted in a significant decrement in the value of compressive strength relative to the control concrete.

Rao et al. (2011) investigated the effect of varying percentage replacement of natural sand with crushed granite stone on the mechanical properties of the concrete being casted for studying mode-II fracture. It was found that the compressive strength exhibited increment with increasing percentage replacement and the maximum compressive strength was observed corresponding to a percentage replacement of 50%. Beyond 50% replacement there was a slight decrease in the values of compressive strength, however it was still higher than the control concrete even at 100% replacement of natural sand with crushed granite stone aggregate.

Olaniyan et al. (2012) assessed the impact of replacement of fine aggregate by granite fines on the compressive strength of the sandcrete blocks. The percentage replacements made were 0%, 5%, 10%, 15%, 20%, 25% and 100% respectively. They found that the maximum compressive strength was exhibited by the concrete with optimum percentage replacement of 15%.

Divakar et al. (2012) studied the effect of granite dust as fine aggregate replacement varying from 0% to 50%. The increment in the compressive strength was 22% with 35% replacement of fine aggregates with granite dust, with 50% replacement the compressive strength increment was only 4%.

Vijaylakshmi et al. (2013) examined the influence of Granite powder as a partial replacement for fine aggregate on the compressive strength of concrete, up to the age of 90 days. Fine aggregates were partially replaced with 0, 5, 10, 15, 20 and 25% of granite powder. As reported the addition of granite dust have no significant influence of the compressive strength of the concrete up to 15% replacement. Moreover the compressive strength of the concrete increased upon aging as usual .

Kala (2013) observed that at different water cement ratio, the compressive strength increased with increase in the granite dust content at all ages. However the concrete was designed with 27.5% mineral admixtures replacing cement. The improvement in compressive strength could be attributed to the fact that use of mineral admixtures also helped in the densification of microstructure. He concluded that 25% of granite dust as sand replacement exhibited 6.12 to 22.14% increase in compressive strength than control mix and it is optimum amount to get favorable strength.

Adigun (2013) demonstrated that development of compressive strength in crushed granite dust concrete is higher than control mixtures till 75% replacement and comparable at higher substitutions. The early strength gain was also higher in granite dust concrete. The increase in compressive strength is attributed to the fact that rough and irregular granite particle fill the void and have higher frictional resistance.

Vitoldas Vaitkevičius et al. (2013) assessed the impact of partial to full replacement of quartz sand with Granite rubble waste on the properties of the ultra-high performance concrete. It was observed that the granite rubble concrete specimens observed a decrement in the values of compressive strength than the control concrete. The reduction in the compressive strength was minimum for the percentage replacement of 10%.

Arulraj et al. (2013) studied the effect of granite dust as fine aggregate replacement varying from 0% to 25% in concrete on compressive strength of M20, M30 and M40 grade concrete at 28 days. As presented in Table 5, they observed that the compressive strength increased with the increase in granite dust content in concrete mix till 20% replacement. The highest values of compressive strength was obtained when the sand replacement was 15% by granite dust.

Elmoaty (2013) studied the effect of granite dust as partial replacement and addition of cement in concrete and observed that when cement was replaced by granite dust the compressive strength decreased with increase in amount of granite dust. The utilization of granite dust up to 5% improved the concrete`s compressive strength by 8.2% at the age of 56 days. Concrete mixes with 7.5%, 10% and 15% granite dust as cement replacement recorded 5.5%, 11.5%, and 8.2% reduction in compressive strength at the age of 56 days. The reduced cement content might be the reason behind the reduction in compressive strength. The concrete`s compressive strength showed increment up to 10% addition of granite dust. The increase in compressive strength at 56 days curing period was 1.0%, 11.9%, 12.2% and 4.6% having 5.0%, 7.5%, 10.0% and 15.0% granite dust as cement addition as compared to control mix concrete.

Li et al. (2013) investigated the use granite dust with fly ash magnesium oxychloride cement, and they observed that incorporation of small amount of granite dust such as 10% can increase the strength of fly ash magnesium oxychloride concrete.

Ramos et al. (2013) studied the effect of granite dust and superfine granite dust with levels of 5% and 10% as cement replacement on properties of concrete. They observed that 10% cement can be replaced with granite dust without significant losses.

Sukesh et al. (2013) concluded the ideal percentage of replacement of natural sand with granite quarry dust as 55% for optimum compressive strength.

Shaik and Reddy (2013) investigated the effect of replacement of natural fine aggregate by granite aggregate on the compressive strength of geo polymer concrete. They observed that 28 days compressive strength increased with increase in granite aggregate content and maximum increment was observed for 15% sand replacement and its values was 20.8%.

Allam et al. (2014) examined the effect of addition of 10%, 17.5% and 25% granite dust as fine aggregate replacement on compressive strength of concrete. They observed that compressive strength increased by 11% at the age of 28 days when sand was replaced by 17.5% of granite dust, however at the age of 90 days the compressive strength decreased.

Kumar et al. (2014) examined the impact of granite fines substitution on the compressive strength of the concrete. It was observed that the maximum compressive strength was exhibited by the concrete specimens with percentage replacement of 30% of the natural fine aggregate by the granite fines.

Garas, GL. et.al (2014) studied the effect of incorporation of granite and marble as replacement of fine aggregate in the manufacturing of green concrete. It was found that upto 30% replacement with RGD (Red Granite Dust) produced concrete with compressive strength comparable to the pulverized fly ash concrete. Any further replacement beyond 30% was found to cause a significant reduction in the strength.

A. Arivumangai and T. Felixkala (2014) assessed the properties of concrete with partial replacement of natural sand by granite powder and partial replacement of cement by fly ash, silica fume, slag and super plasticizer. It was observed that the maximum increment in the value of compressive strength occurred for the percentage replacement of 25%. Further replacement led to decrease in the value of compressive strength however even at 50% replacement the value of compressive strength was still higher than the control concrete.

Reddy et al. (2015) investigated the impact of replacement of fine aggregate by granite fines on the mechanical properties of the resultant concrete mix. The percentage replacements made were 2.5%, 5%, 7.5% and 10% respectively. It was found that concrete specimens with 7.5% replacement percentage exhibited maximum increment in the compressive strength. The concrete specimens with 10% replacement were found to have comparable compressive strength to that of the control concrete.

Raghavendra et al (2015) investigated the effect of granite fines on the compressive strength of the concrete. It was observed that the maximum compressive strength was shown by concrete at the optimum replacement of 15% at all ages of curing.

J.Jayavardhan .Bhandari and Seetharam Munnur (2015) examined the compressive strength of concrete with partial replacement of fine aggregate by granite fines .Replacement was made in steps of 5% beginning from 0% and a maximum of 20% replacement was made. The maximum value of compressive strength was found out to be corresponding to the percentage replacement of 15%.

Harur et al. (2015) investigated the effect of granite powder on compressive strength of concrete at curing ages of 7 and 28 days. They observed that the percentage of granite powder strongly affected the compressive strength of concrete. They found 50% of granite powder as the optimum percentage replacement for natural sand.

Senthil et al. (2015) observed that compressive strength of granite slurry concrete was higher than that of control concrete till 30% replacement. At higher percentage a gradual decrease was observed however the compressive strength of granite slurry concrete was higher than that of control concrete.

Raghvendra et al. (2015) observed that concrete mixes prepared with granite powder replacing natural sand showed higher compressive strength as compared to reference concrete.

Singh et al. (2016) assessed the impact of replacement of fine aggregate by granite cutting waste on a host of mechanical and durability characteristics. The experiments were carried out with the 0.3, 0.35 and 0.4 w/c ratios and for the percentage replacements of 0%, 10%, 25%, 40%, 55% and 70% respectively. The optimum percentage replacements for the w/c ratios 0.3 & 0.35, 0.40 were found out to be 25% and 40% respectively.

Thus from the above literature review it can be established that in the majority of the cases, the replacement of natural sand by granite dust upto optimum percentage replacement increases the compressive strength of the concrete. The optimum percentage replacement varies for different types of granite dust procured from different source stones.

2.3.2.2 Flexural strength

Flexural strength of concrete is the resistance offered by the concrete block before failing under the application of bending (flexure) stresses induced by appropriate loading mechanisms.

F.Falade (1999) studied the effect of using different grain sized granite fines on the flexural strength of the concrete. Seven different size ranges namely 4.75-0.063 mm, 4.75-3.35 mm, 3.35-2.36 mm,2.36-1.70 mm,1.7-1.18 mm,1.18-0.3 mm,0.30-0.063 mm and 4.75-0.063 mm were used in the study. The maximum flexural strength was observed for 1:1.5:3 mix for granite fines particles size range of 0.3-1.18mm.The flexural strength for this mix was found to be 15% higher than the concrete mix containing granite fines with particle size of all the ranges.

Divakar et al. (2012) studied the effect of granite dust as fine aggregate replacement varying from 0% to 50%. The flexural strength increase was 5.41% with 5% replacement of fine aggregates with granite dust. With 15%, 25%, 35% and 50% replacement a significant decrement in the flexure strength was observed.

Vijaylakshmi et al. (2013) examined the influence of Granite powder as a partial replacement of fine aggregate on the flexural strength of concrete, up to the age of 90 days. Fine aggregates were partially replaced with 0, 5, 10, 15, 20 and 25% of granite powder. As reported the addition of granite dust showed slightly lower flexure strength of the concrete up to 15% of substitution rate however beyond 15% replacement a significant loss in flexure strength was observed.

Ramos et al. (2013) observed the impact of granite replacement for cement in proportions of 5% and 10% in mortar. It was observed that the split tensile strength values observed a continuous decrease with increase in the percentage replacement.

Kala (2013) observed that at different W/C, the flexural strength increased with increase in the granite dust content at all ages. The concrete was designed with 27.5% mineral admixtures replacing cement. The improvement in flexural strength could be attributed to the fact that use of mineral admixtures also helped in the densification of microstructure. He concluded that 25% of granite dust as sand replacement exhibited 12.5% to 19.88 % increase than control mix and it was optimum amount to get favorable strength. Even at 100% replacement of natural sand with granite dust the increase in flexural strength observed was 0.65% to 4.78% for various curing ages.

Shaik and Reddy (2013) observed that concrete specimen containing 20% granite aggregate showed improved flexural strength over control specimen at the curing age of 28 days.

Senthil et al. (2015) observed that 28 days flexural strength of 30% granite slurry concrete was highest. With the increase in natural fine aggregate replacement level beyond 30% the flexural strength was found to be reduced.

Reddy et al. (2015) investigated the impact of replacement of fine aggregate by granite fines on the mechanical properties of the resultant concrete mix. The percentage replacements made were 2.5%,5%,7.5% and10% respectively. It was found that concrete specimens with 7.5% replacement percentage exhibited maximum increment in the flexural strength. The concrete specimens with 10% replacement were found to have comparable flexural strength to that of the control concrete.

J.Jayavardhan .Bhandari and Seetharam Munnur (2015) examined the flexural strength of concrete with partial replacement of fine aggregate by granite fines .Replacement was made in steps of 5% beginning from 0% and a maximum of 20% replacement was made. The maximum value of flexural strength was found out to be corresponding to the percentage replacement of 15%.

Thus it can be inferred from the research work of the majority of the researchers that the replacement of fine aggregate by the granite dust upto an optimum percentage replacement results in a concrete with either comparable or better flexural strength than the control concrete.

2.3.2.3 Split tensile strength

Split tensile strength is the ultimate resistance offered by the cylindrical concrete specimens before disintegrating under the application of a transverse load acting perpendicular to the longitudinal axis of the cylinder. Granite dust influences the development of split tensile strength to a larger extent than flexural strength of concrete.

Kanamalai (2008) observed that granite substituted concrete exhibited increment in split tensile strength over control concrete at a replacement level of 25%.However beyond 25% further addition of granite powder led to the decreased split tensile strength giving values even lesser than that of the control concrete.

Felixkala and Partheban (2010) studied the properties of concrete with granite powder as partial replacement for fine aggregate in the concrete. It was observed that a percentage replacement of 25% resulted in a slight increment in the value of the split tensile strength over that of the control concrete. However the strength began to reduce with further replacement beyond 25%.

Joel (2010) studied the effect of granite dust as partial and full replacement for sand and observed that split tensile strength increased with increase in amount of crushed granite dust replacement up to 20%. The additions of higher amount of granite dust than 20% led to decrease in compressive strength at all ages such as 7, 14 and 28 days.

Babafemi Adewumi John and Olawuyi Babatunde James (2011) studied the impact of partial replacement of sand with granite fines on the strength attributes of the PKSC concrete (Palm Kernel Shell Concrete).The trend observed for the split tensile strength was similar to that for the compressive strength. The optimum value of split tensile strength was found to be at the percentage replacement level of 25%.

Divakar et al. (2012) studied the effect of granite dust as fine aggregate replacement varying from 0% to 50%. The split tensile strength remained same for 0%, 25% and

35% replacement of fine aggregates with granite dust. At 5%, replacement the increment in split tensile strength was 2.4%. However at 15% replacement level the reduction in tensile strength was 8% when compared to control mix concrete.

Vijaylakshmi et al. (2013) examined the influence of granite powder as a partial replacement of fine aggregate on the split tensile strength of concrete, up to the age of 90 days. Fine aggregates were partially replaced with 0, 5, 10, 15, 20 and 25% of granite powder. As reported the addition of granite dust shows little lower split tensile strength of the concrete up to 15% of substitution rate however a significant decrease in split tensile strength was observed beyond the replacement level of 15%.

Arulraj et al. (2013) studied the effect of granite dust as fine aggregate replacement varying from 0% to 25% in concrete on split tensile strength of M20, M30 and M40 grade concrete at 28 days. They observed that the split tensile strength increased with the increase in granite dust content in concrete mix till 20% replacement. The highest value of split tensile strength /was obtained at 15% replacement of sand by granite dust.

Elmoaty (2013) studied the effect of granite dust as partial replacement and in addition of cement in concrete and observed that when cement is replaced by granite dust the split tensile strength decreased with increase in amount of granite dust. The use of 15% granite dust slightly decreased the concrete split tensile strength by 8% at 56 days. The reduction in compressive strength decreased with the increase of curing period. Reduced cement content caused reduction in split tensile strength. The concrete split tensile strength showed increase when 10% of granite dust was used as cement addition. The increase in 56 days split tensile strength was 4.6% with 10.0% granite dust as cement addition as compared to control mixes.

Kala (2013) observed that at different water cement ratios, the split tensile strength decreased with increase in the granite dust content at all ages. The concrete was designed with 27.5% mineral admixtures replacing cement. He concluded that 25% of granite dust as sand replacement exhibited 14.88 to 21.95 % increase over control mix and it was optimum amount to get favorable strength. The split tensile strength decreased with increase in sand replacement level beyond 25%.

Shaik and Reddy (2013) observed that split tensile strength of geopolymer concrete samples containing 30% granite aggregate as sand replacement was higher than control concrete.

A. Arivumangai   and T. Felixkala (2014) assessed the properties of concrete with partial replacement of natural sand by granite powder and partial replacement of cement by fly ash, silica fume, slag and super plasticizer. It was observed that the maximum increment in the split tensile strength was observed for the percentage replacement of 25%. Any increment beyond 25% induced decrement in the split tensile strength.

J.Jayavardhan .Bhandari and Seetharam Munnur (2015) examined the split tensile strength of concrete with partial replacement of fine aggregate by granite fines .Replacement was made in steps of 5% beginning from 0% and a maximum of 20% replacement was made. The maximum value of split tensile strength was found out to be corresponding to the percentage replacement of 15%.

Reddy et al. (2015) investigated the impact of replacement of fine aggregate by granite fines on the mechanical properties of the resultant concrete mix. The percentage replacements made were 2.5%, 5%, 7.5% and 10% respectively. It was found that concrete specimens with 7.5% replacement percentage exhibited maximum increment in the split tensile strength. The concrete specimens with 10% replacement were found to have comparable split tensile strength to that of the control concrete.

Senthil et al. (2015) observed that up to 30% natural fine aggregate replacement exhibited an increment in the split tensile strength. A noticeable decrement in the split tensile strength was reported beyond 30% replacement with granite slurry content.

Thus the literature review establishes the fact that in most cases the partial replacement upto optimum percentage replacement of the natural sand by the granite fines led to an increase in split tensile strength of the concrete. The reduction in split tensile strength in a few cases might be due to the presence of external impurity in the granite dust been used.

2.3.2.4 Modulus of elasticity

Modulus of elasticity is a physical parameter that reflects the mechanical behaviour of any material in response to the induced stresses due to loading.

Kanamalai (2008) observed that the modulus of elasticity of the granite substituted concrete specimens was more or less similar to that for the control concrete. Moreover at 25% replacement at 90 days of curing modulus of elasticity value observed 2% increment over that of control concrete. This was attributed to the increment in strength with curing age.

Felixkala and Partheban (2010) studied the properties of concrete with granite powder as partial replacement for fine aggregate in the concrete. It was observed that the modulus of elasticity exhibited similar trend as observed that for the split tensile strength. The value of modulus of elasticity at 25% replacement was slightly higher than the control concrete. However any replacement beyond 25% let to a reduction in the value as compare to the control concrete.

Vijaylakshmi et al. (2013) observed that the modulus of elasticity decreases when the substitution rate is increased. The elastic modulus value of modulus of elasticity of the mixtures having 5%, 10% and 15% granite dust were comparable to control concrete.

Kala (2013) designed concrete with 27.5% mineral admixtures replacing cement. He found that 25% of granite dust as sand replacement exhibited 10.16 to 18.54 % increase in modulus of elasticity than control mix and it was therefore the optimum amount to get favorable strength.

Only a few studies have been conducted on assessing the effect of natural sand replacement by granite dust. Among these studies mixed kind of results have been reported in the sense that some researchers reported increase while others reported decrement in the values of modulus of elasticity when sand was partially replaced by granite dust.

2.3.2.5 Drying shrinkage

The loss of moisture from the concrete matrix on drying induces shrinkage and this can be termed as drying shrinkage. Limited literature is available on drying shrinkage properties of granite dust concrete. The drying shrinkage strain of granite dust concrete increases as the percentage of granite dust increases.

Kanamalai (2008) studied the drying shrinkage characteristics of the granite substituted concrete. It was found that with the increment in the percentage replacement there occurred a sustained rise in the values of drying shrinkage. The observed increment in the drying shrinkage value for GP25 (With 25% Granite Powder Replacement) was marginal.

Williams et al. (2008) studied drying shrinkage from 1 day to 90 days of granite dust concrete with 0% to 100% natural sand replacement. The drying shrinkage in all granite dust concrete was similar to control mixture.

Felixkala and Partheban (2010) studied the properties of concrete with granite powder as partial replacement for fine aggregate in the concrete. It was observed that the replacement with granite powder leads to increase in the values of drying shrinkage. Also it was found that values of drying shrinkage were increasing with increase in the curing age.

Kala and Senthuraman (2013) observed that for W/C ratio of 0.35 and different curing temperatures of 32°C and 38°C, the drying shrinkage values of granite dust concrete were higher than that of control mixture. The shrinkage in concrete with

25% replacement of natural sand by granite dust was 60% more than that of control concrete specimen.

The prominent published research studies unanimously establish the fact that the partial replacement of natural sand with the granite dust leads to increased drying shrinkage.

2.3.2.6 Density

Density or unit weight of a material is a physical property which directly or indirectly conveys the state of compactness and denseness within the material concrete matrix to some extent. Very less data related to the measurement of the density of the granite substituted concrete is available in the published literature. The data reported shows that when granite waste is utilized as fine aggregate in concrete there is a slight decrease in the unit weight of concrete. Singh et al. xfines being utilized decreased, corresponding density of the concrete mix decreased.

However Harur et al. (2015) observed that the density of concrete containing upto 50% granite powder as fine aggregate replacement for w/c ratio of 0.55, 0.45 and 0.40 exhibited slight increment over that of the control concrete.

The literature study reveals that the replacement of natural sand by granite dust generally leads to the decrease in the unit weight of the resulting concrete.

2.3.3 Durability properties of granite dust concrete

2.3.3.1 Permeability

As the name suggests permeability of a material is a parameter reflecting the extent of allowance to the flow of any fluid across the interconnected pores /voids present in the matrix of the material.

The permeability of the aggregates and the pore size distribution in the cement paste plays an important role in the concrete permeability. The reported research indicates that as compared to natural sand concrete, granite dust concrete has higher permeability. With the increase in granite dust content in concrete its permeability increases.

Williams et al. (2008) found that the water permeability of granite dust concrete was better than control concrete at 25% and 50% replacement of natural sand by granite dust. It was also observed that water penetration value was decreasing when the curing age was increased.

Kanamalai (2008) observed that water penetration increased for granite substituted concrete over control concrete at all values of percentage replacement .It was also observed that as the curing age increased a noticeable reduction in the values of water penetration was observed.

Vijaylakshmi et al. (2013) reported that as per ASTM C1202-97 specifications, the chloride permeability of granite dust concrete is higher than that of control concrete mix at the ages of 180 and 365 days. the chloride permeability of the concrete was found to be directly proportional to the substitution rate. The water permeability test exhibited compliance with the RCPT test result and showed that increasing percentage of granite dust caused higher permeability. The rise in permeability was attributed to the increased specific surface area and density.

It can be inferred from the literature review that as the percentage replacement for natural sand by granite dust increases, the corresponding permeability of the concrete generally increases.

2.3.3.2 Resistance to sulphate attack

It is the resistance and resilience of the concrete on exposure to sulphate containing chemical agents.

Vijaylakshmi et al. (2013) studied the influence of granite dust in concrete on its long term durability. In the investigation carried out they established that concrete containing granite dust showed significant losses in compressive strength as compared to control mixes and the increase in substitution rate caused increase in sulphate attack. It was predicted that the durability was influenced by a reactive material present in granite dust hence some treatment for granite dust was advised.

2.3.3.3 Carbonation depth

It helps in determining the extent of penetration of carbonate within the concrete matrix and is thus an indirect measure of quality of concrete matrix.

Vijaylakshmi et al. observed the carbonation depth of granite dust concrete at the age of 180 and 365 days. Upon investigation it was found that increase in granite dust content increases carbonation depth, however the increase in depth is not proportional. The carbonation depth values for substitution rate of 15%, 20% and 25% were 7.7 mm, 8.9 mm and 10.2 mm which is closer to the cover of reinforcing steel bars which can cause corrosion. The substitution rate greater than 15% is not advisable for structural concrete.

2.3.3.4 Electrical resistivity

The electrical resistivity is a measure of resistance offered by the concrete matrix to the flow of ions through it.

The electrical resistivity of concrete is related to the pore structure of matrix. For higher electrical resistivity, the corrosion resistance is more. Vijaylakshmi et al. (2013) demonstrated that with increase in substitution rate, the specific surface area increases. As a result, the electrical resistivity of concrete mixtures is reduced.

2.3.3.5 Water Absorption and Sorptivity

Both the parameters are indicators of the extent of porosity of the concrete matrix.

GL Oyekan and OM Kamiyo (2008) studied the effect of inclusion of Granite fines on the water absorption & sorptivity of the sandcrete. The water absorption and sorptivity of the sandcrete specimens were found out to be minimum for a percentage replacement of 15% of the total volume of fine aggregates by granite fines.

J.Jayavardhan .Bhandari and Seetharam Munnur (2015) examined the water absorption and porosity of concrete with partial replacement of fine aggregate by granite fines. Replacement was made in steps of 5% beginning from 0% and a maximum of 20% replacement was made. The minimum value of water absorption was found out to be corresponding to the percentage replacement of 15%.

Harur et al. (2015) demonstrated that at same w/c ratio the water absorption and sorptivity of the concrete mixes decrease with increasing percentage of granite powder upto 50% replacement of natural fine aggregate.

This can be inferred from the literature that as the percentage replacement for natural sand by granite increases, the water absorption and sorptivity generally decreases.

2.3.3.6 Chloride-ion Diffusion

Ramos et al. (2013) observed the effect of replacement of cement in mortar by PG (powdered granite from quarries) and PGS (superfine Granite powder from quarries) in proportions of 5% and 10%. It was found that lower values of chloride resistance were observed for the coarser PG mortar matrix. However the fine PGS mortar matrix exhibited an increase in the value of chloride resistance. The increase in the chloride resistance over that of control concrete was observed to be 67% and 70% respectively for PGS5%, PGS10% respectively. Literature review showed huge potential of granite waste as a replacement of natural fine aggregate.

Literature on the utilization of granite dust in concrete is not extensive. Only few studies have been reported on the strength and durability properties of concrete. There is untouched part for microstructure and effect in elevated temperature of concrete. Therefore, present studies important and its findings will be very useful in concrete technology area, wherein, fine aggregates are to be replaced with industrial byproducts in making structural grade concrete.

Chapter 3

EXPERIMENTAL PROGRAM

- **Materials Used**
- **Mixture Details**
- **Properties of Concrete**

The detailed analysis of physical and chemical attributes of a substance is necessary to gain insight to the behavior of the concrete. Physical assessment includes studies on particle size distribution, specific gravity, water absorption. Chemical assessment includes monitoring minute details of the chemical elemental composition of the substance and is of vital importance in understanding the mechanical and durability behavior of the material. The chemical assessment these days is being increasingly carried out using accurate and sophisticated X-Ray based techniques.

The first half of the chapter explains the details of mix proportions, physical chemical and morphological attributes of the material. The second half of the chapter explains in detail the experimental methodology adapted in compliance with detailed guidelines issued by competent authorities and relevant codes. This chapter presents details of experimental methodology for the measurement and assessment of attributes and characteristics of fresh concrete (workability) and hardened concrete (Mechanical and durability properties). Also, the procedural details for the microstructural studies (SEM and XRD) have been explained along with TGA (Thermo Graphic Analysis) for the prepared concrete specimens.

The details on physical and chemical attributes seek to provide appropriate explanations for the mechanical and durability behavior mentioned in the chapters ahead. The research has been carried out on concrete specimens for six different water cement ratios ranging between 0.3 to 0.55 in increment of 0.05 fetching large sample sizes to attain statistical control and accuracy in the behavior observed. The morphological studies were based on the SEM (Scanning Electron Microscope) images captured for the specimens. These images provide deeper understanding of the morphological characteristics of various ingredients. The TGA (Thermo Graphic Analysis) test was carried out to study the change in behavior of the concrete on exposure to elevated temperatures of the order of up to 900°C.

3.1 Materials Used:

3.1.1 Cement

Ordinary Portland Cement of grade 43 confirming to IS 8112-1989 was used in the experiments being carried out.

3.1.2 Fine Aggregate [River Sand and Granite Cutting Waste (GCW)]

For the experimental study the locally available Banas river sand with a maximum aggregate size of 4.75mm was used. GCW was procured from stone industries in Shahpura, Jaipur . The comparative assessments of the attributes of the river sand and GCW have been tabulated as follows:

3.1.2.1 Particle size distribution

Particle size distribution (or Gradation of aggregates) of GCW and sand was determined using sieve analysis as per the procedure mentioned in IS: 2386 (Part 1)-1963 [BIS, 1963]. The sample was dried before weighing and sieving. Each sieve was shaken separately for at least 2 minutes and finally the weight retained on each sieve and percentage passing was determined. Grading zone to which GCW and sand conforms to, was determined using IS: 383-1970 [BIS, 1970].

Particle size distribution of river sand and GCW aggregates are shown in Table 3.1 and 3.2. Fineness modulus of GCW and river sand comes out to be 2.573 and 3.36 respectively. Thus, GCW and river sand belong to Zone IV and Zone III as per grading limits of fine aggregates mentioned in IS: 383 - 1970.

Table 3.1: Sieve analysis of River sand

I.S. Sieve Size	Weight retained (grams)	Percentage weight retained	Cumulative percentage weight retained	Percentage passing	IS:383-1970 Requirement for Zone III
10.0 mm	00	00	00	100	100
4.75 mm	39.50	3.95	3.95	96.05	90-100
2.36 mm	25.00	2.50	6.45	93.55	85-100
1.18 mm	89.00	8.90	15.35	84.65	75-100
600 µm	161.50	16.15	31.50	68.50	60-79
300 µm	522.00	52.20	83.70	16.30	12-40
150 µm	126.00	12.60	96.30	3.70	0-10
75 µm	25.00	2.50	98.80	1.20	-
PAN	7.50	0.75	99.55	0.1	-

Table 3.2: Sieve analysis of GCW

I.S. Sieve Size	Weight retained (grams)	Percentage weight retained	Cumulative percentage weight retained	Percentage passing	IS:383-1970 Requirement for Zone IV
10.0 mm	00	00	00	100	100
4.75 mm	2.50	0.25	0.25	99.75	95-100
2.36 mm	0.50	0.05	0.30	99.70	95-100
1.18 mm	6.50	0.65	0.95	99.05	90-100
600 µm	14.50	1.45	2.40	97.60	80-100
300 µm	622.50	62.25	64.65	35.35	15-50
150 µm	263.50	26.35	91.00	9.00	0-15
75 µm	68.00	6.80	97.80	2.20	-
PAN	19.50	1.95	99.75	0.25	-

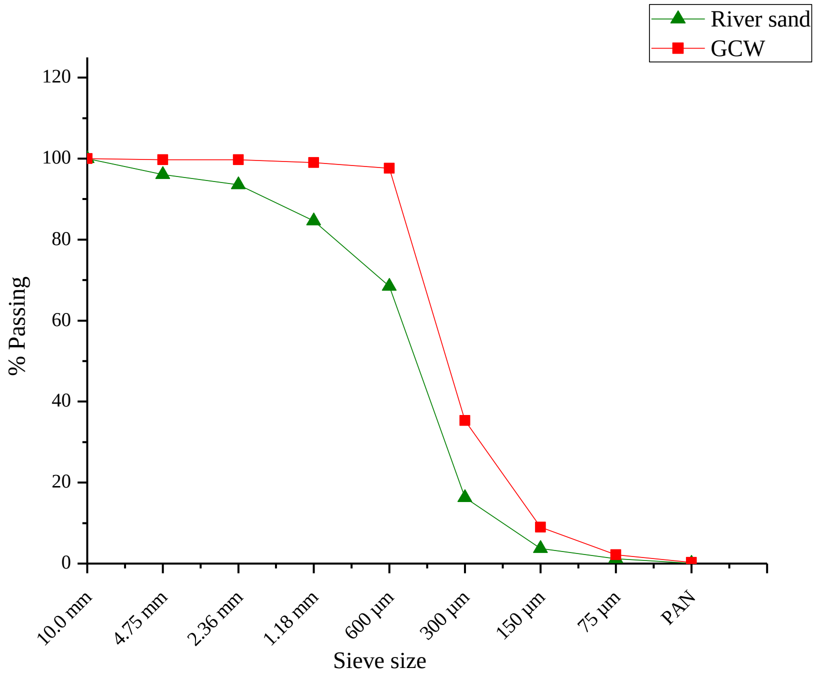


Figure 3.1:. Gradation Curve of Fine Aggregates

Fig.3.1 shows gradation of GCW and river sand. GCW has larger proportion of fine particles compared to river sand. Proportion of particles finer than 75 µm is higher in case of GCW compared to sand. Also, sand is well graded fine aggregate compared to GCW as it has larger proportion of particles of varying sizes. Thus, concrete prepared using sand as fine aggregate requires minimum cement paste for filling up the voids [Mehta and Monteiro, 2006; Mindess, 2003] as sand contain minimum voids. If concrete is prepared using GCW as partial replacement of sand (optimal % of GCW), overall performance of concrete gets improved [Vijayalakshmi et al., 2013; Ramos et al., 2013; Kala, 2013] and concrete produced is even better than conventional concrete. Use of GCW as partial substitute of sand results in filling up of voids in cement-aggregate matrix (filler action) and thus strength and durability of concrete increases and also cement paste requirement decreases which means there is less requirement of water and cement to produce concrete [Vijayalakshmi et al., 2013; Kala, 2013; Mehta and Monteiro, 2006]. Thus, utilization of optimal proportion of GCW with sand helps in producing concrete of high strength, greater durability, lower shrinkage and better resistance to freezing and thawing effect [Mindess, 2003; Shetty, 2005; Neville, 1981].

Better gradation of fine aggregates (mixture of GCW and sand) results into reduction of voids which means excess amount of cement paste is available for better lubrication effect and hence aggregate particles (of varying sizes) easily slide over one another with minimal amount of compacting effort and thereby improving the workability of concrete [Mehta and Monteiro, 2006; Mindess, 2003; Shetty, 2005]. Although gradation of river sand is better than GCW but interlocking of particles of river sand is very poor [Mehta and Monteiro, 2006] due to the fact that sand particles are round in shape and thus, compressive strength of concrete is less compared to concrete mix with partial replacement of sand by GCW.

3.1.2.2 Specific gravity and density

Specific gravity of GCW and sand was determined in compliance with IS: 2386 (Part-3)-1963 [BIS, 1963]. 0.5 Kg of clean and dry aggregate sample was taken in pycnometer which was filled with distilled water. Proper care was taken so as to eliminate entrapped air by rotating the pycnometer on its side after covering the hole in the apex of the cone by a finger and then the jar was completely filled by water up to the brim of pycnometer. Finally, the surface of pycnometer was cleaned and as per the procedure mentioned in IS: 2386 (Part-3)-1963, the specific gravity of both GCW and river sand was determined separately.

Unit weight or bulk density of GCW and sand were also determined using IS: 2386 (Part-3)-1963 [BIS, 1963]. Aggregates were filled in the container and then compacted using a standard manner as per the guidelines of the code. Thus, the weight of the aggregates gives the value of bulk density in Kg/litre or Kg/m^3.

Specific gravity of aggregates helps in determining the strength and material quality of aggregate [Mindess, 2003; Murdock, 1960]. Specific gravity of aggregates is also used in design calculations involved in concrete mix proportioning, thus when specific gravity of each constituent is known, the weight of the aggregates can then be converted into solid volume occupied by the aggregates in the concrete mix. This helps in determination of theoretical yield of concrete per unit volume. Specific gravity and porosity are also related to each other as volume of voids in the aggregates can also be determined if specific gravity of aggregates is known [Shetty, 2005; Neville, 1981].Specific gravity also helps in determining the compaction factor of concrete (required to determine workability of concrete mix).

Specific gravity of GCW and river sand comes out to be 2.624 and 2.7 respectively. This means that for a given weight of aggregates (GCW and sand), the volume occupied by GCW aggregates is larger than that of sand as volume is inversely proportional to specific gravity of aggregates. Moreover, larger volume of GCW indicates that specific surface area of GCW particles is higher than that of sand [Vijayalakshmi et al., 2013]. Hence, the water demand of GCW increases due water absorption and if in concrete production w/c ratio is kept constant and cement content is kept constant then workability of concrete containing GCW (G mix - concrete mix with GCW as partial replacement of FA i.e. sand) comes out to be lower than that containing sand as fine aggregate (NC mix normal conventional concrete mix without GCW) [Vijayalakshmi et al., 2013]. Also, due to higher solid volume of GCW (compared to sand), cement requirement increases so complete replacement of sand by GCW is not economical.

Bulk density of GCW and river sand was 1682 Kg/m^3 and 1886 Kg/m^3 respectively. Since bulk density of GCW is less than that of sand because of angularity of GCW particles, hence % voids or void ratio is slightly higher in case of GCW. So, GCW cannot be used as complete replacement of sand but its use in conjunction with sand as partial replacement is highly beneficial as it would result in higher strength and durability of concrete mix (G- mix) compared to NC mix because of dense and compact matrix obtained in case of GCW [Vijayalakshmi et al., 2013; Ramos et al., 2013; Kala, 2013; Siddique, 2011]. In general, cement paste requirement is more in case of GCW as specific surface area is high in case of GCW compared to sand, hence use of GCW along with sand is preferable in production of concrete of high strength and durability but workability of this mix is still lower compared to control mix as water demand of GCW is higher on account of higher angularity and rough texture of these particles [Day, 2003].

3.1.2.3 Water Absorption

Water absorption of aggregates was determined by noting down the difference in weight of the oven dried sample of aggregate when immersed in water for a period of 24 hours. Water absorption of fine aggregates (GCW and sand) was determined by following the procedure and guidelines of IS: 2386 (Part-3)-1963 [BIS, 1963].

Water absorption of fine aggregate is an important physical property of aggregate which helps in determination of net w/c ratio required in production of concrete mix. Water absorption (% by weight) of GCW and sand was 4.36 % and 2.9 % respectively whereas moisture content was 0.68 % and 0.35 % respectively. Since water absorption of GCW is higher than sand, the amount of water required to produce concrete mix is more in case of GCW (as fine aggregate). Prominent reason behind high water requirement of GCW is due the fact that GCW particles are more angular and elongated compared to sand particles which are round and generally water requirement increases with increase in angularity of grains of aggregate [Hughes, 1954; Murdock, 1960]. Moreover, GCW particles have higher specific surface area because of angularity of particles and this enhances the cohesion and friction between particles of aggregate but at the same time, water requirement for concrete production also increases [Mehta and Monteiro, 2006; Day, 2003]. Higher water absorption, decreases the workability of concrete and hence to maintain workability additional quantity of water is required. But addition of more water increases w/c ratio which adversely affects the compressive strength of concrete, so use of admixture in place of water is preferable. Higher water absorption indicates an increase in drying shrinkage and reduction of freezing and thawing resistance of concrete [Mehta and Monteiro, 2006; Mindess, 2003; Shetty, 2005; Day, 2003]. Since, GCW has a filler action in cement aggregate matrix, hence densification of matrix retards ingress of water and thus decreases drying shrinkage and enhances the freezing and thawing resistance of concrete compared to conventional concrete mix. Therefore, utilization of optimal % of GCW (as partial replacement of sand) has beneficial effect on performance of concrete but an adverse effect on workability.

3.1.2.4 Chemical Composition

Chemical composition of GCW and sand was determined experimentally in CDOS Lab, Rajasthan (India).

Table 3.3: Chemical composition of River sand and GCW

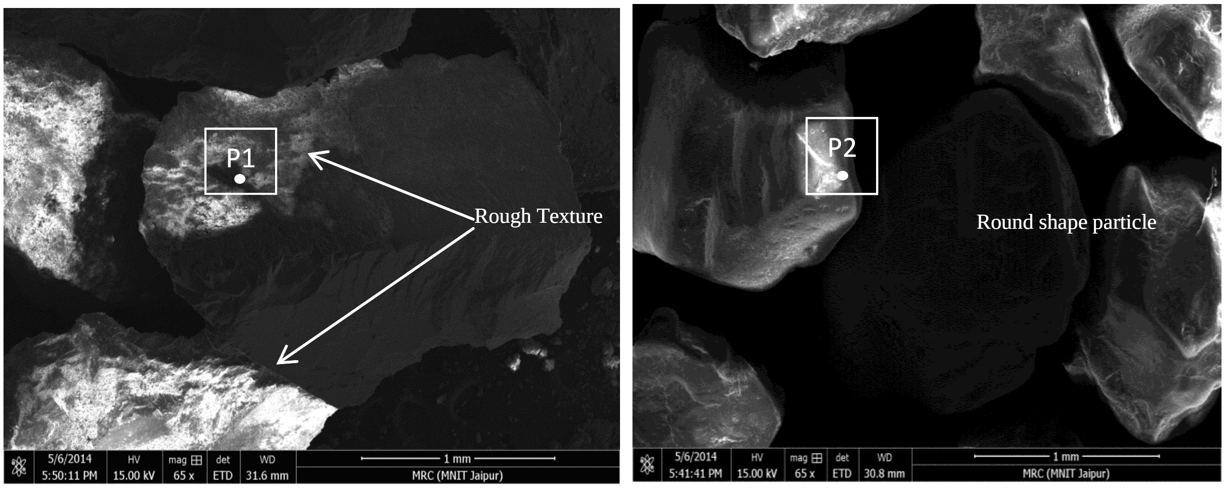
Chemical Compounds	**% (by weight)**	
	GCW	**River Sand**
SiO_2	72.57	84.73
Al_2O_3	15.63	10.66
MgO	0.83	1.33
Na_2O	4.21	-
K_2O	6.76	3.28

Table 3.3 clearly shows that amount of silica present in GCW is relatively lesser compared to that in river sand. On the other hand, proportion of alumina is higher in case of GCW. Also, magnesium oxide (magnesia) is present in minute quantities in both GCW and river sand. Similarly, small percentage of potassium oxide is also

present in GCW and sand. One major difference is the absence of sodium oxide in river sand. Thus, chemical composition of sand and GCW are comparable without any significant difference in quantities of different compounds. So, chemical analysis of GCW shows that it is suitable for concrete production. Moreover, using optimal GCW content along with sand in concrete production has significant changes in performance of concrete (enhancement of strength and durability) [Vijayalakshmi et al., 2013; Kala, 2013; Adigun, 2013].

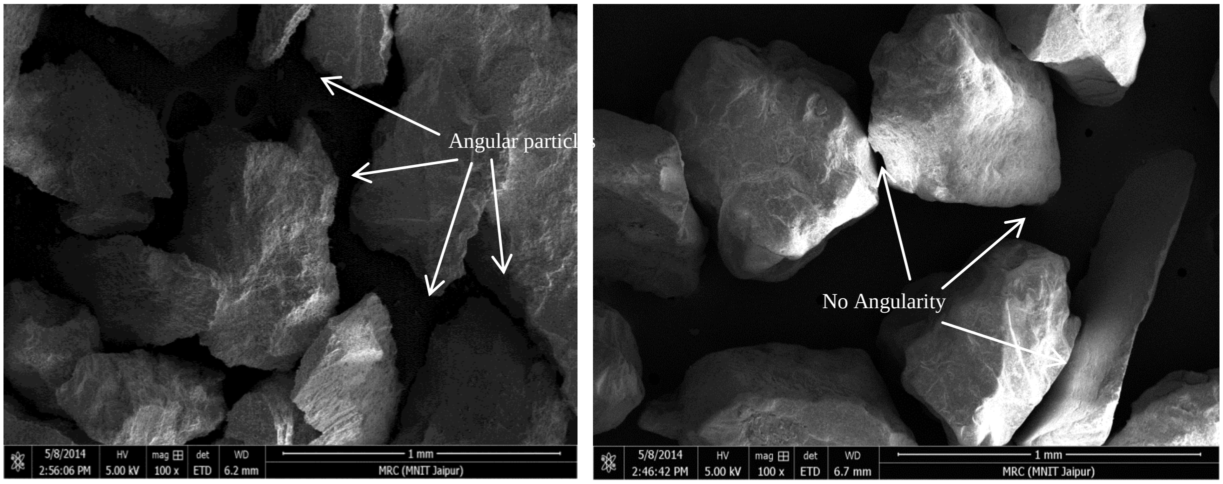
3.1.2.5 Morphology of river sand and GCW (SEM Analysis)

Scanning electron microscope, Nova Nano FE-SEM 450 (FEI), was used for taking SEM images of sample of fine aggregates i.e. GCW and river sand at different magnifications. In SEM analysis, electron beam was directed towards the surface of specimen (of GCW and sand) and after striking the object, electron beam was either absorbed or scattered and finally the responses were collected as SEM image [EDS Analysis, 2015]. SEM images of sample were taken at different magnifications so as to closely examine the morphological characteristics of GCW and river sand such as particle size, shape, and surface texture.



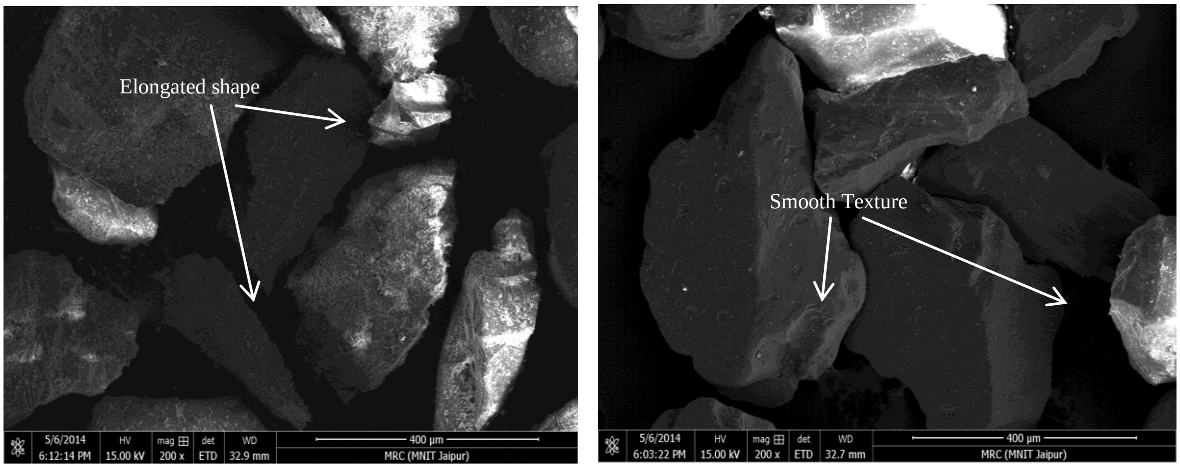
(a) (b)

Figure 3.2: SEM image of (a) GCW and (b) Sand particles passing 2.36 mm and retained 600 µm sieves (65X)



(a) (b)

Figure 3.3: SEM image of (a) GCW and (b) Sand particles passing 600 µm and retained 300 µm sieves (100X)



(a) (b)

Figure 3.4: SEM image of (a) GCW (b) Sand particles passing 300 µm and retained 150 µm sieves (200X)

SEM images clearly depict the particle shape and surface texture which significantly affects the workability of fresh concrete and strength and durability of hardened concrete. Generally, GCW particles are more angular and elongated compared to river sand particles which are predominantly round in shape [Ramos et al., 2013; Mehta and Monteiro, 2006; Ho, 2002].

SEM image of GCW and river sand particles of different sizes are shown in Figs. 3.2, 3.3 and 3.4. SEM images were taken at 65 X, 100 X and 200 X magnifications so as to clearly demonstrate the morphology of GCW and sand particles. SEM images shows that GCW particles are irregular in shape and are more angular and elongated compared to sand particles which have regular shape with smooth surface. Also, sand particles are nearly round in shape compared to GCW particles. Moreover, GCW particles have a rough and angular texture which means that these particles have higher water absorption compared to sand particles. Angularity of the grains increases the water absorption % [Hughes, 1954; Murdock, 1960] which means that on addition of GCW in concrete the workability of fresh concrete decreases on account of higher water demand of particles [Mehta and Monteiro, 2006; Mindess, 2003; Day, 2003]. Higher angularity of the GCW particles has a positive influence on compressive strength of concrete because of higher cohesion and friction between these particles compared to sand particles [Vijayalakshmi et al., 2013; Ramos et al., 2013; Kala, 2013; Day, 2003]. Angular aggregate (GCW particles) exhibits better interlocking effect in concrete resulting in higher bond strength and thereby enhancing the strength of concrete to a greater extent compared to concrete mix without GCW [Mehta and Monteiro, 2006; Day, 2003] whereas smooth textured round particles of sand yield poor concrete due to the absence of proper bond between sand particles of smooth surface and cement paste. Moreover, adherence of cement paste will be higher in case of rough textured GCW particles which would result into higher strength of bond between aggregates [Shetty, 2005; Day, 2003].

Rough texture of aggregate also means that more amount of cement paste (water and cement) will be required to produce concrete of high strength [Mehta and Monteiro, 2006; Mindess, 2003] which is uneconomical and less cost effective. But when GCW is used as partial replacement of sand in concrete production, then it will have a filler action which helps in reduction of voids in the matrix and thereby reduces the quantity of cement paste required to establish high strength bond between aggregates. The only disadvantage of using GCW in concrete production is the reduction in workability of concrete, but this can be compensated by addition of admixture (super plasticizer) which improves the workability of concrete [Vijayalakshmi et al., 2013]. Therefore, utilization of optimal % of GCW improves overall performance of concrete [Vijayalakshmi et al., 2013; Ramos et al., 2013; Kala, 2013; Ilangovana et al. 2008] with an additional advantage of cost effectiveness [Adigun 2013] in concrete production coupled with reduction in transportation cost and disposal problems. Moreover, conservation of river beds can also be ensured as an additional benefit by incorporation of this waste in production of concrete.

3.1.2.6 EDS Analysis

EDS analysis was performed to detect the presence of various elements in granite cutting waste and river sand. It helps in identification of elements and their relative proportion in the sample of aggregates. EDS was carried out along with SEM analysis. Several points were selected on SEM image of the sample (i.e. GCW and sand separately), and were analysed using EDS technique. EDS identifies the presence of elements in the sample by detecting X-rays emitted by specimen itself [EDS Analysis, 2015]. EDS collects the X-ray photons emitted by the specimen and finally intensity (counts) vs emission voltage graph was obtained. Basically, total number of counts for an element in the sample is proportional to the quantity of that element present in the specimen [Sarkar et al., 2010; Ogwuegbu et al., 2011].

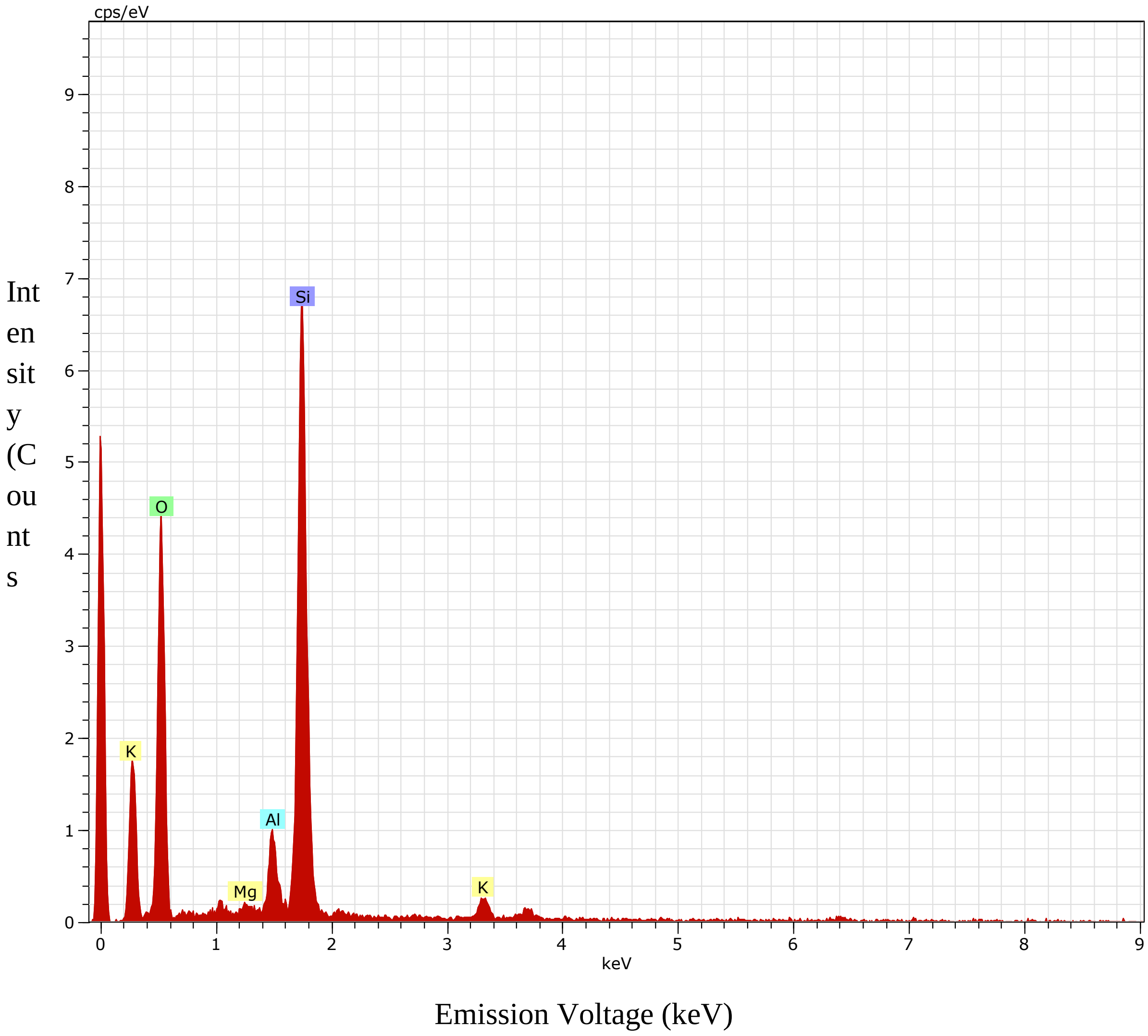


Figure 3.5: Energy Dispersive Spectra of river sand

EDS helps in detection of elements in the GCW and sand. EDS is carried out along with SEM analysis of the sample and EDS at some specific points or regions of SEM image of GCW and sand are shown in Figs. 3.5 and 3.6.

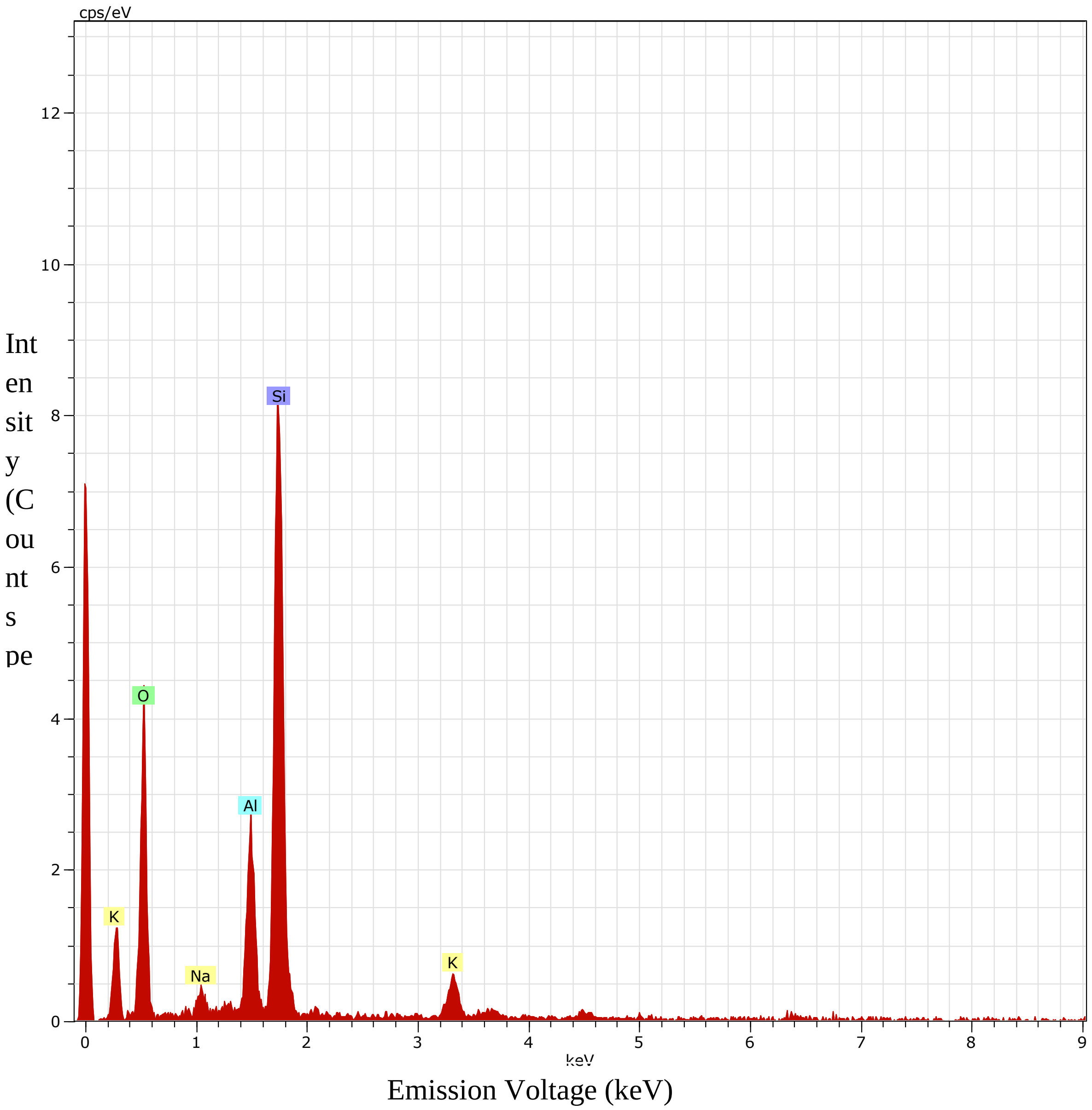


Figure 3.6: Energy Dispersive Spectra of GCW

EDS analysis proves that the river sand contains the elements such as potassium (K), magnesium (Mg), aluminium (Al), silicon (Si), and oxygen (O). Predominant sharp peaks of Si, O, Al, and K are observed in EDS spectra of river sand [Fig. 3.5.] which means that these elements are present in significant amount in river sand whereas small and broad peak of Mg is also observed in the spectra. Predominant peaks also signify the presence of silica and alumina in river sand whereas small-broad peak of Mg indicates the presence of MgO (magnesium oxide) in very small amount in river sand. Moreover, absence of peak of sodium (Na) in EDS spectra indicates that Na_2O is not present in significant amount in river sand [Fig. 3.5].

Fig. 3.6. shows the EDS spectra of GCW. EDS spectra clearly indicates the presence of elements such as Si, O, K, and Al in significant proportion (sharp narrow peaks) compared to Na and Mg which present in trace amounts in the sample. Fig. 3.5 and 3.6. shows EDS spectra at a specific point or region marked on SEM image [P1 and P2 points marked on SEM images].

3.1.2.7 XRD Analysis

PANalytical X pert PRO Powder diffractometer was used for performing XRD analysis of powdered sample of GCW and sand. During the analysis, radiation source (copper electrode- Cu kα radiation and Ni filler) was operating at 40 mA and 40 kV. During scanning process of powdered sample of GCW and sand, the speed of detector was 0.02°/0.5 sec and detector was in a continuous motion in the range from 10.02°-79.98°. Scans of about 5 min duration were performed over powdered specimen of GCW and sand, each of size 10 mm. X'pert High score (with database ICDD 2003) software was used to prepare intensity (counts) vs 2θ graphs for GCW and sand and Origin software was also used for analysis of the these graphs.

Fig. 3.7 and 3.8 shows the X-ray diffraction pattern of the river sand and GCW. Peaks of diffractograms correspond to different compounds present in the specimen. Sharp and narrow peaks indicate the presence of highly crystalline compound whereas flat and broad regions or peaks denote presence of amorphous compound in the sample.

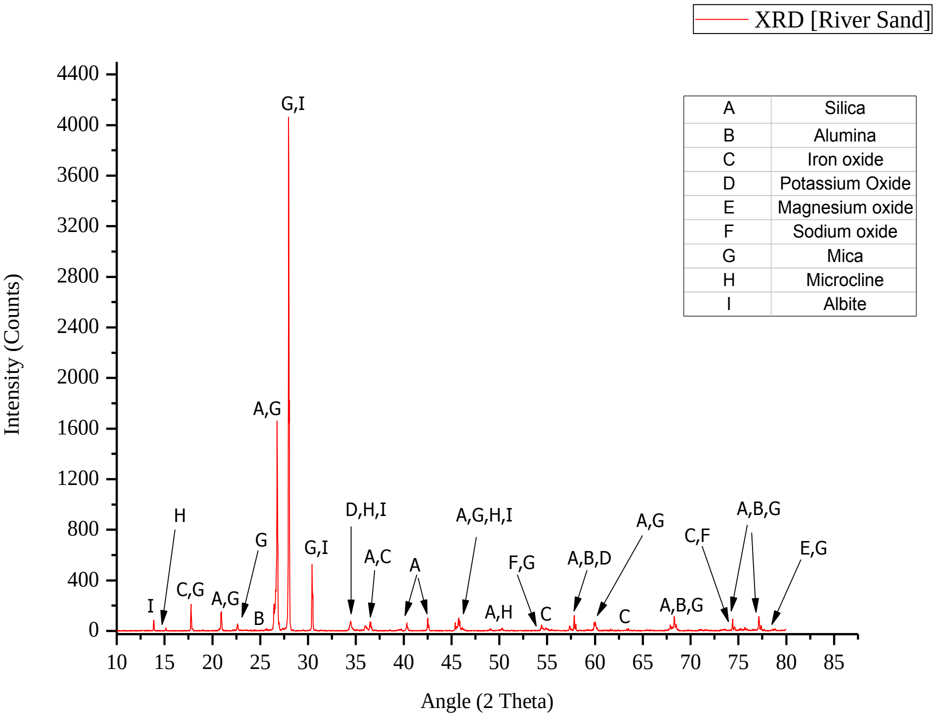


Figure 3.7: X-ray diffractogram of the River Sand

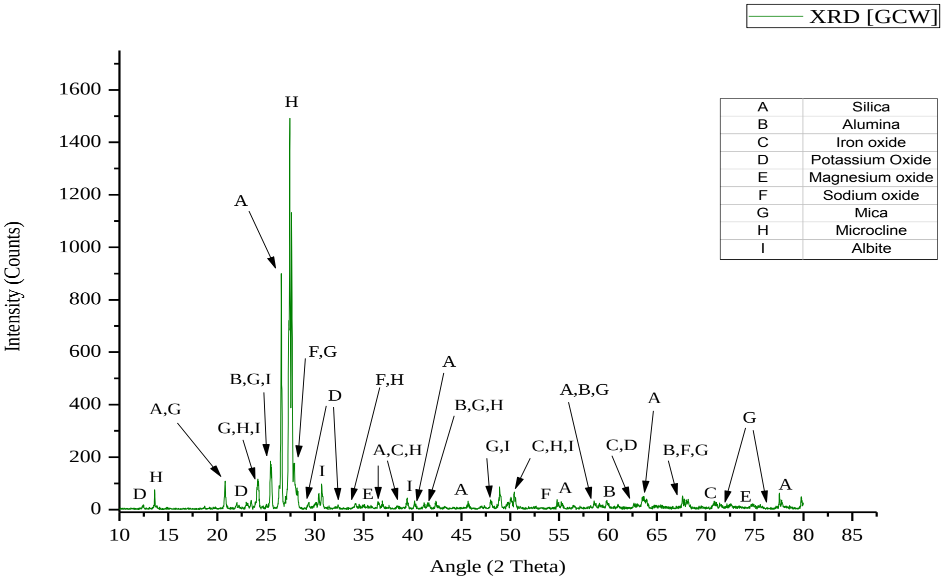


Figure 3.8: X-ray diffractogram of the GCW

XRD analysis of GCW indicates that sharp narrow peaks [High intensity (%) or intensity counts] of silica (at $2\theta = 26.562°$) and alumina (at $2\theta = 25.438°$) clearly denotes that these compounds have high crystallinity whereas flat regions (broad peaks) of diffractograms shows that some amorphous silica is also present in GCW which goes undetected in X-Ray diffraction. Significant peaks of compounds such as MgO, Na_2O and K_2O are also observed in XRD diffractogram of GCW whereas peak of Na_2O was not observed in diffractogram of river sand which means that sodium oxide is absent in river sand. Diffractogram of river sand also indicates the presence of compounds such as silica, alumina, MgO, and K_2O except Na_2O which is absent in river sand (or present in very minute quantity). Diffractograms also helps in comparison of peak intensities corresponding to different compounds present in GCW and river sand which gives clear idea of crystallinity of various compounds. Total number of counts [of different intensities] is directly proportional to quantity of compound present in the sample [Sarkar et al., 2013].

XRD diffraction pattern of GCW and river sand indicates the presence of silica, alumina, etc. Calcium present in cement reacts with silica to produce calcium silicate hydrate (C-S-H) which imparts most of the strength to concrete. Moreover, calcium also reacts with alumina and oxides to produce tri calcium aluminate which helps in initial setting of concrete. Also, peaks corresponding to quartz [SiO_2], iron oxide [Fe_2O_3], Mica, Microcline [$KAlSi_3O_8$], and Albite [$NaAlSi_3O_8$] were observed in diffraction pattern of GCW whereas in river sand, only peaks corresponding to quartz [SiO_2], iron oxide [Fe_2O_3], and Microcline [$KAlSi_3O_8$] were observed. Relative intensities of various compounds were also different in XRD diffraction pattern of sand and GCW which clearly indicates that crystallinity of the compounds present in the aggregates are different. Mica content increases the water requirement in concrete production [Day, 2003] but since it is present in minor quantities in GCW and sand so it does not affect the workability and strength of concrete significantly. Prominent peaks of important compounds present in GCW and River sand are shown in Fig. 3.7 and 3.8.

3.1.2.8 TGA (Thermo-gravimetric analysis)

TGA technique was used to identify the quantity of chemically bound water in GCW and sand. Initially, GCW and sand was grounded into fine powder (less than 75 µm) and 200 mg sample each of GCW and sand was placed in Aluminium oxide crucible separately. Crucible was then placed inside Simultaneous Thermal Analyser (STA 6000). Continuous heating of powdered sample from 30^0C to 900^0C was carried out at a steady rate of 10^0C/min and during the process of heating, furnace of the analyser was purified by introduction of nitrogen at a steady rate of 50ml/min. With variation in temperature, weight lost by the sample was recorded and finally the weight loss is expressed as a percentage of mass of dry sample.

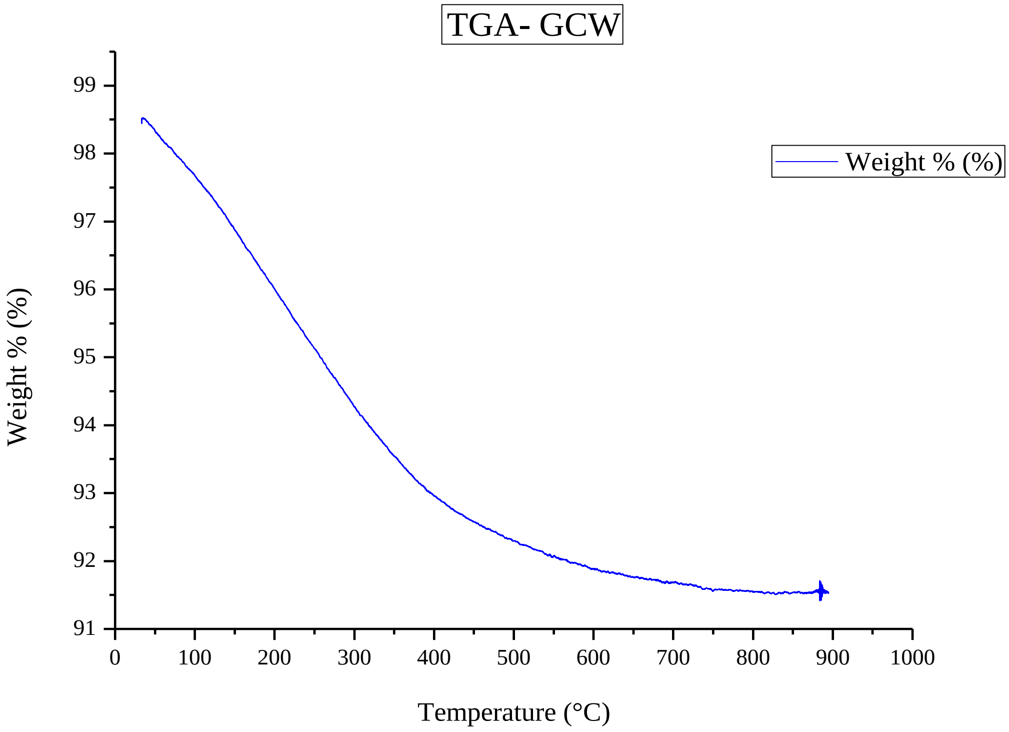


Figure 3.9: TGA Thermal curve of GCW

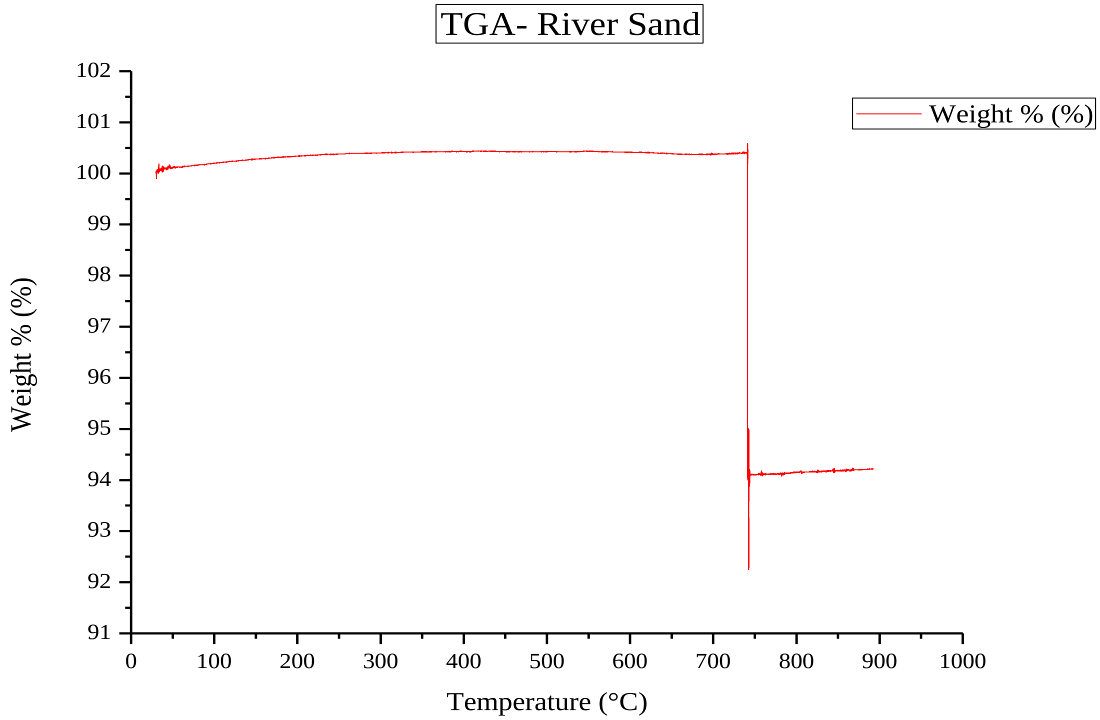


Figure 3.10: TGA Thermal Curve of River sand

Loss in the weight of sample (of GCW and sand) with varying temperature was determined using TGA analysis. Descending trend of TGA thermal curve [(% weight v/s Temperature (^{0}C)], from left to right, indicates that a loss in the weight of the sample has occurred due to rise in temperature. Thermo-gravimetric analysis of dried sample of GCW and sand was performed (separately) to determine the decomposition temperature and loss in the weight of the sample with variation in temperature. Fig. 3.9. shows TGA thermal curve of GCW up to 900 °C. In case of GCW sample, about 6.959 % weight loss has taken place as the temperature increases from 30 °C to 900 °C mainly because of removal of chemisorb (type of absorption involving a chemical reaction between the surface and the adsorbate) water from the dried sample. In case of river sand [Fig. 3.10], % weight loss in same temperature range is about 5.793%.

Main reason of loss of weight of the sample due to rise in the temperature from 30 °C to 900 °C, is the removal of crystalline water resulting from the decomposition of

$Ca(OH)_2$ into CaO. Significant loss in weight of the sample has not occurred beyond this temperature range which clearly indicates that complete decomposition of $Ca(OH)_2$ to CaO has taken place at temperature around 900 °C. Thus, similar behaviour of both sand and GCW with variation in temperature was observed in TGA analysis (as % weight loss values are very close) and hence, GCW is also suitable for concrete production. Moreover, using a mixture of sand and GCW in an optimal proportion is beneficial in terms of performance of concrete without compromising with strength and durability characteristics of concrete.

3.1.3 Coarse Aggregates

Crushed natural stones of nominal size 20 mm and 10 mm in compliance with Indian standards (BIS, 1970) were used in the preparation of experimental concrete specimens.20mm and 10mm aggregates were used in equal proportions to prepare concrete mixes.

3.1.4 Super-Plasticizer

The experimental investigation revealed the fact that a continuous decrement in the workability occurred as the percentage replacement of fine aggregate by Granite cutting waste increased. The loss in workability was made up by using the second generation polycarboxylic ether based superplasticizer (Master Glenium SKY8777) of BSAF company complying with BIS: 9103-1999.

3.2 Mixture Details

3.2.1 Experimental Parameters

The experimental methodology involved detailed analysis based on the following parameters:

- Water/Cement ratio-
    1. Series I-0.30,0.35,0.40
    2. Series II-0.45,0.50,0.55
- Percentage fine aggregate replacement in proportions of 0%, 10%, 25%, 40%, 55% and 70%. The proportions of replacement were decided based on the fact that a clear trend shift or noticeable difference in the properties should be observed for specimens with different w/c ratio to study the effect of w/c ratio on the properties of the concrete.

3.2.2 Methodology for Mix Proportioning

Once the ingredients for the concrete were finalized the next step was to decide the appropriate proportions of ingredients, a process called mix proportioning for the concrete manufacturing. Mix proportioning is an important process of concrete manufacturing that ensures production of high quality concrete meting all the required specifications at an affordable cost by saving wastage of material. To achieve a concrete of required strength it is absolutely essential to have right proportions of all the ingredients which is duly ensured in mix proportioning. The mix design for the experiments was carried out in compliance with IS :10262,2004.The details of the mix design including w/c ratios and corresponding quantities of the ingredients are tabulated as follows in Table 3.4 and Table 3.5 for the two series of w/c ratios chosen.

Table 3.4: Mixture proportions (Kg/m^3) of different concrete mixes Series I

Mix	Water	Cement	w/c	GCW	River Sand	Coarse Aggregate	Superplasticizer
A_0	197	359	0.55	0	670	1114	0
A_{10}	197	359	0.55	67	603	1114	0
A_{25}	197	359	0.55	167.5	502.5	1114	0
A_{40}	197	359	0.55	268	402	1114	0
A_{55}	197	359	0.55	368.5	301.5	1114	0
A_{70}	197	359	0.55	469	201	1114	0
B_0	179.5	359	0.5	0	669	1161	1.615
B_{10}	179.5	359	0.5	66.9	602.1	1161	1.615
B_{25}	179.5	359	0.5	167.25	501.75	1161	1.615
B_{40}	179.5	359	0.5	267.6	401.4	1161	1.615
B_{55}	179.5	359	0.5	367.95	301.05	1161	1.615
B_{70}	179.5	359	0.5	468.3	200.7	1161	1.615
C_0	161.55	359	0.45	0	660	1197	3.590
C_{10}	161.55	359	0.45	66	594	1197	3.590
C_{25}	161.55	359	0.45	165	495	1197	3.590
C_{40}	161.55	359	0.45	264	396	1197	3.590
C_{55}	161.55	359	0.45	363	297	1197	3.590
C_{70}	161.55	359	0.45	462	198	1197	3.590

Table 3.5: Mixture proportions (Kg/m^3) of different concrete mixes series II

Mix	Water	Cement	w/c	GCW	River Sand	Coarse Aggregate	Superplasticizer
D_0	176	440	0.40	0	605	1146	1.980
D_{10}	176	440	0.40	60.5	544.5	1146	1.980
D_{25}	176	440	0.40	151.25	453.75	1146	1.980
D_{40}	176	440	0.40	242	363	1146	1.980
D_{55}	176	440	0.40	332.75	272.25	1146	1.980
D_{70}	176	440	0.40	423.5	181.5	1146	1.980
E_0	154	440	0.35	0	605	1197	4.400
E_{10}	154	440	0.35	60.5	544.5	1197	4.400
E_{25}	154	440	0.35	151.25	453.75	1197	4.400
E_{40}	154	440	0.35	242	363	1197	4.400
E_{55}	154	440	0.35	332.75	272.25	1197	4.400
E_{70}	154	440	0.35	423.5	181.5	1197	4.400
F_0	132	440	0.30	0	602.8	1254	7.040
F_{10}	132	440	0.30	60.28	542.52	1254	7.040
F_{25}	132	440	0.30	150.7	452.1	1254	7.040
F_{40}	132	440	0.30	241.12	361.68	1254	7.040
F_{55}	132	440	0.30	331.54	271.26	1254	7.040
F_{70}	132	440	0.30	421.4	181.4	1254	7.040

All the factors except w/c ratio were kept constant to study the effect of w/c ratio on the concrete attributes clearly. The correction for the absorption and surface moisture were duly made during the process of mix design.

The water content for Series I -w/c ratios of 0.55, 0.5 and 0.45 of were 197,179.5 and 161.55 kg /m^3 respectively. The second series was designed with high cement content coupled with low w/c ratio to study the influence on the properties of concrete. The water content of Series II –w/c ratios of 0.4, 0.35 and 0.3 were 176,154 and 132kg/m^3 respectively.

3.2.3 Preparation of Concrete Mixes

For the purpose of preparing concrete mixes all the ingredients were oven dried and then kept at room temperature. i.e., 27±2°C.The cement was thoroughly mixed before use so as to ensure proper blending and to obtain a homogeneous mass.

Figure 3.11: Pan Type Mixer

The coarse aggregates of size 20 mm and 10 mm were mixed in equal proportions to obtain a mix with proper grading. The mix proportioning was done by weight so as to avoid the problem of bulking. The ingredients were mixed in a Pan type mixer, as shown in Fig. 3.11 to attain a uniform and homogeneous concrete mass. Dry granite powder was mixed with the other ingredients in various proportions already discussed. Once a dry homogeneous mass was obtained a pre-calculated quantity of water was added to obtain the final concrete.

3.2.4 Compaction

After preparing the concrete, it was poured into the oiled moulds in layers of 5cmeach.

Figure 3.12: Casting Beams

Figure 3.13: Casting Cubes

Each layer was then subjected to appropriate vibration facilitating proper compaction while at the same time taking care of the fact that no segregation and bleeding is observed owing to excessive compaction.

The top layer of the concrete specimen was levelled with trowel post compaction.

3.2.5 Curing

The test specimens were kept undisturbed in moist air for 24±2hrs at 27±2°C after the addition of water to the concrete ingredients. The ambient humidity levels were atleast 90%.The specimens were then removed from the moulds and were adequately marked for identification purpose. The specimens were then kept in the curing tank till the date of testing.

3.3 Properties of Concrete

The impact of replacement of fine sand by granite cutting waste in various proportions was assessed in terms of various parameters as mentioned below in compliance with the guidelines issued by the competent authorities in relevant codes concerned.

3.3.1 Rheological Properties

Rheological studies involve assessment of a variety of concrete characteristics including pumpability, placeability, flowability, fluidity, stability and mobility and all of these are to varying extents being affected by the workability of concrete. The workability of fresh concrete is studied using slump cone test in compliance with the codal provisions of BIS 1199-1959.

3.3.1.1 Slump Test

The slump acts as a proxy to monitor the workability and consistency of the concrete. A fairly workable concrete is the one that exhibits ease of mixing, placing and compaction and does not entertain segregation and bleeding .The slump of concrete is defined as the difference between the height of concrete specimen with slump cone and height of unsupported concrete after removing the slump cone from top surface. The slump cone apparatus used for measuring the slump value is demonstrated in the Fig. 3.14.

Figure 3.14: Slump Cone

Workability of concrete was measured using slump loss method as described in BIS 7320:1974. Just after mixing, concrete was placed inside slump cone [BIS-7320, 1974]. The slump cone of height 30 cm, top diameter 10 cm, bottom diameter 20 cm was deployed. The cone was filled completely in four equal layers of fresh concrete, by tamping each layer 25 times. The mould was then raised slowly in vertical direction resulting in subsidence of concrete. The difference between the height of mould and subsided concrete in mm was recorded as slump value.

3.3.2 Mechanical Attributes

The assessment of mechanical properties includes measurement of compressive strength, Flexural strength and pull off strength in compliance with IS516-1959 and ASTM D7234-05 respectively. The age of testing for each test is mentioned below:

- Compressive strength at 7, 28 and 90 days

- Flexural strength at 7, 28 and 90days.
- Pull off strength at 28 days.

3.3.2.1 Compressive Strength

The cube specimens of size 100X100X100 mm^3were cured for 7,28 and 90 days and specimens were dried in the sun before testing the compressive strength of concrete mix using universal testing machine of capacity 2000KN. The test were carried out at 7, 28 and 90 days of curing period. The vertical axis of the concrete specimen was aligned with the center of the loading plate. The setup for assessing compressive strength of the concrete specimen is demonstrated in the figure 3.15 Load was applied at the rate of approx. 140kg/sq cm/min and three specimen of each category of design mix were tested at the required age according to **IS : 516 - 1959**. The test results were obtained by averaging the compressive strength of three specimens.

Figure 3.15: Compressive Strength Testing Machine

The peak load at failure point was recorded and this load divided by the area gave compressive strength of the concrete specimen under study i.e.,

$$C=\frac{P}{A}$$

Where C= Compressive strength of the concrete specimen

P= Peak load at failure

A= Area of the loaded face i.e., 100mmX100mm

3.3.2.2 Flexural test

Preparation of concrete mix was similar to compressive strength test specimens. Beam of size 500X100X100mm were cast and the test was carried out in moist condition using 2 point loading (IS: 516-1959). The setup for the two point loading test for flexural strength is demonstrated by the figure 3.16.

Figure 3.16: Flexure Strength Test

The bed of the testing machine was provided with 2 steel rollers of 38mm diameter and spaced 40cm centre to centre, on which the specimen was supported. Load was applied through two similar rollers placed at the middle third portion of the supporting span spaced at 13.3cm centre to centre. The load was applied without shock and at an increasing loading rate of 400kg/min. The load was increased till the specimen failed and the mean value of modulus of rupture was calculated for each W/C ratio.

Modulus of Rupture = $\frac{Pl}{Bd^2}$

Where P= load at failure

B=width of the beam

d= depth of the beam

3.3.2.3 Pull off Strength Test

Pull off strength of the specimens was measured in compliance with ASTM D7234-05. Pull off strength is a quantification of the surficial tensile strength of the concrete .The experimental methodology involves pulling off a disc bound to the surface of concrete using epoxy adhesive. The pull off strength test apparatus is demonstrated in the Fig. 3.17. The adhesive material possess greater strength than concrete and this ensures that the bond breaks off in such a manner that a small bounded surficial layer of concrete is detached off on application of load. The metal disc was attached to the surface of the concrete using epoxy adhesive and then disc – specimen assembly left undisturbed for 24hours.An increasing load was applied on the assembly and the peak load at which the disc is pulled off the surface gives the value of pull off strength.

Figure 3.17: Pull-off Strength test apparatus

3.3.3 Abrasion Test

Abrasion test was performed in compliance with BIS :1237-2012.The test specimen was prepared of size 100X100X100 mm^3.After curing for 28 days it was dried at 110^o ± 5°C for 24 hours and weighed to the nearest of 0.1 g. The specimen after initial drying and weighing was placed in the thickness-measuring apparatus with its wearing surface upwards and the reading of the measuring instrument was taken. The image of the Abrasion Testing apparatus is shown in the fig 3.18 The specimen was fixed in the holding device with the surface to be grounded facing the disc. Abrasion powder was put evenly throughout the surface of the disc. The specimen was loaded at the centre with 600 N (300N force for each $50cm^2$) load and the disc was rotated at a speed of 30 rev/min. After the abrasion was over the specimen was weighed to the nearest of 0.1 g. Its thickness was also measured at five different points i.e. one at the centre and four at the corners. The thickness lost due to abrasion was calculated in terms of “depth of wear”. The wear path of abrasion disc was evenly laid with 20gm abrasive powder. After the completion of 22 revolutions, the disc was paused and fresh abrasive powder was introduced. The specimen was rotated in clockwise direction about the vertical axis by an angle of 90^0, the sample was then replaced in the holder. The process was repeated nine times by subjecting each specimen to 220 revolutions.

Figure 3.18: Abrasion Testing Machine

Average loss in thickness of concrete specimen was recorded using the formulae mentioned below:

$$\mathrm{t} = \frac{(\mathrm{W1} - \mathrm{W2})\,\mathrm{X}\,\mathrm{V1}}{\mathrm{A}\,\mathrm{X}\,\mathrm{W1}}$$

where,

t= average wear or thickness loss (mm)

W1= initial weight of specimen (gm)

W2=final weight of abraded specimen (gm)

V1= initial volume of specimen (mm^3)

A= surface area of the specimen (mm^2)

3.3.4 Durability Attributes

The durability of concrete is an indicator of its resistance to external disruptive agents like acid, sulphate, carbonates and also dimensional stability of the concrete. The durability is impacted by a number of factors including harshness and severity of the external environment and internal factors including dimensional and concrete matrix stability.

The chapter assesses the durability traits of the concrete with partial replacement for natural sand by Granite Cutting Waste. The permeability of concrete is one important characteristic which reflects the compactness and densification of the concrete matrix and governs the extent of ingress and inclusion of external deteriorating agents like acid, chloride, sulphate and carbonates etc.

Shrinkage of concrete is a strong indicator of degree of dimensional rigidity and stability of concrete .Shrinkage leads to the development of cracks in the concrete specimen thus aggravating the ingress of deteriorating agents mentioned above. Corrosion is a major phenomenon governing the durability of the concrete Corrosion causes damage to the steel reinforcement and characterised by the formation of oxides of iron. The formation of these oxides cause significant increase in the volume and this induces instability and cracks in the concrete matrix.

The durability attributes of the concrete have been assessed in terms of response to water permeability, water absorption, acid attack, sulphate attack, carbonation, chloride penetration and corrosion.

In the past quality of concrete was determined based on the mechanical traits like compressive strength ,flexure strength and modulus of elasticity only but recently it was realized that durability properties of the concrete play an equally important role as does the mechanical attributes in determining the quality of concrete.

The long term serviceability and performance of the concrete is characterized to a larger extent by durability parameters besides mechanical strength attributes. The detailed experimental methodology adapted and their compliance with relevant codal provisions and guidelines are duly mentioned in the subsequent sections:

3.3.4.1 Permeability

Permeability of specimens was calculated using test procedure as specified in DIN 1048:1991.The test apparatus used in the experiment is shown in fig 3.19. Oven dried, 28 days cured specimens of 150 mm dimensions were subjected to a constant water pressure of 0.50 MPa, perpendicular to mould filling direction.

Figure 3.19: Water Permeability Test (DIN)

The pressure was applied for duration of 72 h. The test therefore assesses the permeability response under adverse conditions of sustained water pressure. The specimens were then split from middle and maximum depth of water permeation was noted to the nearest 0.5mm. The mean depth of water permeation obtained from three samples was recorded as final reading.

3.3.4.2 Water Absorption

Quality of concrete can easily be determined by the amount of water it absorbs. The test was conducted as per the guidelines of IS 15658:2006. Three cubical specimens of 100 mm dimensions were immersed in water at room temperature, for 24 h. The specimens were then removed and kept on a 10mm or coarser wire mesh for 1min to facilitate draining of the excess water. After removal, visible water present on specimen was rinsed off by damp cloth. The weight of specimen was then recorded immediately (W_1). Specimens were then dried in an oven at 107±70C for not less than 24 h, until a constant dry weight (W_2) was obtained.

Figure 3.20: Water Absorption

Water absorption of concrete was calculated as percentage of the dried weight. The water absorption is given by the following equation:

$$\text{Water Absorption: } \frac{(W_1 - W_2)*100}{W_2}$$

3.3.4.3 Chloride ion penetration

The penetration of Chloride ion in the concrete and subsequent swelling of concrete along with enhanced susceptibility of the reinforcement to corrosion can be termed as` Chloride-Attack. In order to study resistance to chloride ion penetration standard silver nitrate spraying test was used in accordance with the Ref. Baroghel-Bouny Veronique, (2007). The specimens (100X100X100mm) were tested for the chloride attack at the age of 28 days, 56 days and 90 days respectively being soaked for this duration in 3% NaCl solution. The depth of chloride penetration for these specimens was measured after being soaked in the NaCl solution for 28, 56 and 90 days respectively. The cubes were dissected into halves and the freshly split pieces were sprayed with 0.1N $AgNO_3$ solution .Silver Nitrate on reaction with free chloride ion fetches white precipitate of AgCl. In those regions where free Cl^{-1} ion is not present $AgNO_3$ yields brown colour due to the formation of AgO. Thus the depth of Cl^- penetration can be easily obtained clearly indicated by the transition colour boundary from white to brown. Mean penetration depth was calculated for the three specimens used:

3.3.4.4 Carbonation

The process of deterioration of alkaline environment within concrete specimen domain due to the intrusion and attack of CO_2 and subsequent corrosion of steel reinforcement can be termed as `carbonation`. The depth of penetration was assessed based on the guidelines of CPC RILEM (RILEM 1988). Each of the concrete specimen (100mmX100mmX100mm) was oven dried for a period of 48 hours. Each specimen was dissected into four identical parts of dimensions (50mmX100mm).These parts were then dried in an oven and a dual coating of epoxy paint was applied on the longitudinal surface. The samples were then marked for identification. The dried marked samples were then brought into a standard carbonation chamber. The chamber had the controlled humidity levels of about 55 Rh, CO_2 concentration of 5%, temperature at 27°C.3 pieces were obtained from each specimen after a period of 2, 3, 4, 6, and 12 weeks of exposure in Carbonation Chamber .

Figure 3.21: Carbonation chamber

Figure 3.22: Split and spray samples

These pieces were tested for carbonation depth measurement using Phenolphthalein indicator. Each piece was further dissected along the length such that length of the pieces obtained was same as the parent piece but width of each daughter piece was halved. These pieces were then sprayed with Phenolphthalein Indicator (1% phenolphthalein in 70% ethyl alcohol) The carbonated areas which are characterized by low pH of about 8.3-9.3 do not turn the colourless phenolphthalein into purple colour . However the portion where pH is > 9.2 (non - carbonated area) on contact with phenolphthalein exhibits purple red colour.

The basic analysis model for carbonation originates from Fick`s First Law applied to a simulated diffusion of CO_2 into the porous system of concrete (Anna V. Saetta and Renato V. Vitaliani, 2004). The model states that the diffusion of CO_2 in the concrete matrix is directly proportional to the square root of the duration of exposure under constant hygrometric conditions.

$$C = \frac{X}{T^{0.5}}$$

The carbonation coefficient depends on environmental conditions such as humidity and ambient CO_2 concentration and also on the properties of concrete matrix such as W/C ratio and packing density etc.

Where C is Carbonation coefficient.

X and T is the carbonation depth in mm and period of exposure in days respectively.

3.3.4.5 Acid Attack

The deterioration, break down and leaching away of hydration products of concrete especially calcareous products on exposure to chemical liquids with lower pH values can be termed as acid attack.

The assessment of resistance of concrete specimens towards acid attack was done in accordance with ASTM C 267-01 (ASTM 2012) .The concrete has a high pH value and is strongly alkaline in nature. Concrete is therefore vulnerable to exposure to the acids .These acids may be formed either from SO_3 in the atmosphere or may be synthesized by bacterium present in sewage water. Sulphuric Acid formed by the aforementioned agencies reacts with $Ca(OH)_2$ present in concrete and produces gypsum i.e.$CaSO_4.2H_2O$ which is a water soluble compound. The reaction of Sulphuric Acid with Calcium Silicate Hydrate generates Silicate Oxide in aqueous state.

Two types of observations were taken and analysed for the specimens to study the effect of acid attack. The specimens were observed for the loss in compressive strength at the age of 1, 4,8,12 weeks.

The loss in compressive strength of the concrete is given by:

$$\text{Loss in strength (\%)} \quad = \quad \frac{\text{fc (28 Days)} - \text{fc (t Days)}*100}{\text{fc (28 Days)}}$$

where : $f_{c\,(28\ Days)}$ = Compressive strength of concrete cube specimens at 28 days

$f_{c\quad(t\ Days)}$ = Compressive strength of concrete cube specimens after t days of immersion in H_2SO_4 solution.

The observations for loss in weight were taken after a period of 1, 4, 12 weeks respectively.

The loss in weight of the cube specimens is given by:

$$\text{Loss in weight (\%)} = \frac{\text{W (28Days)} - \text{W (t Days)}*100}{\text{W (28 Days)}}$$

where $W_{(28Days)}$ = Initial weight of the specimen at the age of 28 days

$W_{(t\ Days)}$ = Final weight of the specimen after t days of immersion in H_2SO_4 solution.

3.3.4.6 Sulphate-Attack

The formation of ettringite and other expansive compounds as product of the chemical reaction between Calcium, sodium, magnesium and ammonium sulphates with components of cement hydrates (Calcium Aluminate & $Ca\ (OH)_{2)}$ and subsequent cracking of concrete can be termed as `Sulphate-Attack’. One of the chemical reaction responsible for ettringite is given as follows:

$4CaO.Al_2O_3.Fe_2O_3 + H_2O + SO_4^{-2} \rightarrow Ca_6Al_2(SO4)_3(OH)_{12}.2H_2O + CaSO_4.2H_2O$

Test carried out obeys the methodology prescribed in ASTM C 1012-10 .The sample specimens after having been cured for 28 days were then brought under physical observation in which the length of each of the specimen was noted down .The three sample cube specimens were kept immersed in 10% $MgSO_4$ solution. The readings were then taken after 7, 28, 90,180 and 210 days respectively for the weight of immersed specimens. These readings for the GCW substituted comparator specimens were then compared with that for the control specimen. The loss in weight was noted for all the specimens after 7, 28, 90, 180 and 210 days. Also observations were made for the compressive strength of the specimens after 28, 90 and 180 days respectively.

The loss in compressive strength of the concrete is given by

$$\text{Loss in strength (\%)} = \frac{\text{fc (28 Days)} - \text{fc (t Days)} * 100}{\text{fc (28 Days)}}$$

where: $f_{c\,(28\ Days)}$ = Compressive strength of concrete cube specimens at 28 days

$f_{c\,(t\ Days)}$*= Compressive strength of concrete cube specimens after t days of immersion in $MgSO_4$ solution.

The loss in weight of the cube specimens is given by:

$$\text{Loss in weight (\%)} = \frac{\text{W (28Days)} - \text{W (t Days)} * 100}{\text{W (28 Days)}}$$

where $W_{(28Days)}$ = Initial weight of the specimen at the age of 28 days

$W_{(t\ Days)}$ = Final weight of the specimen after t days of immersion in $MgSO_4$ solution.

3.3.4.7 Shrinkage

The decrement in the initial dimensions of the specimen due to loss of moisture can be termed as shrinkage. Three specimens of dimensions 75X75X300 mm were taken for each of the w/c ratio under consideration. The observations were made over a period of 365 days. Demec studs were installed at a predefined spacing of 212 ±1mm in longitudinal direction after 28 days curing to facilitate quantification of shrinkage of concrete specimen. The specimens were kept at a temperature of 25°C and 55% RH. The numerical observations for quantifying the shrinkage were facilitated by mechanical strain gauge with least count 0.002mm. After recording initial value at 24h observations were made at 7, 15, 30, 45, 60, 90,180, 270, and 365 days respectively. The mean value of shrinkage for the three specimens was recorded as the shrinkage value for a particular w/c ratio.

3.3.4.8 Corrosion

Corrosion in context of concrete can be understood as the electrochemical degradation of steel reinforcement characterized by the formation of oxides of iron. The methodology complied with the guidelines of ASTM G109-99a.Two coats of epoxy based paint were applied on all the vertical faces. A solution of 3% NaCl (by weight) was poured in the ponding well. The specimens were kept at room temperature. The bar at the top was anode and two bars at the bottom were cathode. The 1:2 ratio of anode to cathode facilitates accelerated corrosion rate. The circuit involved anode and the cathodes with a resistance in between. The specimens were subjected to alternate wetting and drying cycles for 14 days respectively. At the end of each wetting cycle the potential difference across the electrodes was measured using a high impedance voltmeter.

- **Macro-cell- Current**

The entire duration of test was confined to a test period of 19 months. ASTM109-99a states that the macro-cell current (I_1) is given as:

$$I_1 = \frac{\text{Voltage(V1)}}{100}$$

Where resistance of the resistor is 100____.

- **Half Cell Potential**

The observations for open cell potential were made for duration of 22 months. The electrical connection for the circuit was deliberately broken 24 hours ahead of making the measurements for the potential difference to facilitate the current stabilization. The electrochemical potential of the top electrode i.e., anode was measured relative to copper-sulphate reference electrode. As per the guidelines of ASTM C 876(ASTM 2009b) copper copper-sulphate reference electrode measurements can be used to project the probability of occurrence of corrosion as per the following guidelines:

i) The value of potential over an area when more positive than -200mV is a clear indicator of less than 10% probability of steel reinforcement being corroded in the particular area under study.

ii) The measured values of potential between -200 and -350mV for the area under study indicates uncertainity in predicting the probability of corrosion in the area.

iii) The measured values of potential more negative than -350mV in the area under study being a strong indicator (> 90% probability) of the steel reinforcement being corroded in that particular area of interest under study.

- **Corrosion Rate**

At the end of the test duration observations were made for assessing the rate of corrosion using gravimetric method. The specimens were disassembled and the anodic steel reinforcement was then weighed. The method used for cleaning the corroded bars was the one stated in ASTM G1-03 which prescribes the use of hydrochloric acid as a cleaning agent. Mean corrosion rate is given as:

Corrosion rate (mm) = (KX W)/AXTXD

Where K= a constant =8.76X10^4
W= mass loss in g
A = cross section area of the specimen
T= time duration of exposure in hours
D= density of steel =78.5g/cc.

3.3.5 Microstructure & Thermographic Analysis

3.3.5.1 SEM (Scanning Electron Microscopy)

Concrete cubes (specimens) were cured in water for 28 days and then the cubes were oven-dried at 105 °C for 24 hours. Sections of 20 mm x 20 mm x 10 mm were obtained from a depth of 50 mm from selected concrete specimens and their microstructure was examined using Field Emission Gun Scanning Electron Microscope (FESEM) as shown in Fig. 3.23. The sections were polished with diamond paste and coated with platinum layer to avoid cutting& grinding damages and improve the conductivity of electrons respectively.

Figure 3.23:Field Emission Gun SEM

FESEM focussed a beam of incident electrons and developed a topographical image of specimen by collecting reflected and scattered electron beams.

3.3.5.2 XRD Analysis

XRD Analysis was carried out using PANalytical X pert PRO Powder diffractometer (Type-11141934) as shown in Fig. 3.24.

Figure 3.24: X-ray Powder Diffractometer

Copper electrode, acting as a radiation source (Cu kα radiation and Ni filler) was operated at 40 kV and 40 mA. There was a continuous movement of detector in range from 10.02°-79.9800° during the measurements and its speed was set to 0.02°/0.5sec (during scanning of powdered sample) where 0.02 is the step size [°2Th.] and 0.5 is scan step time in seconds. Scans of specific time (about 5min) were performed over each of the powdered specimen size of 10mm for different concrete mixes. Diffractograms of each sample were prepared using X'pert High score with database ICDD 2003. Origin Software was also used for data analysis (peak analysis) and for making Intensity (counts) vs 2θ graphs for different concrete mixes. The intensities of peaks for different minerals is directly proportional to the quantity of the mineral present in the sample.

Procedural Deduction of Minerals from XRD Diffractogram:

i) For a given sample, XRD graphs are plotted in a way such that intensities and 2_ values are plotted on Yaxis and X axis respectively.

ii) The d values and intensities of peaks of various minerals are compared with the standard information available in the library resource files of the software.

3.3.5.3 TGA (Thermo-gravimetric Analysis)

TGA test aims to study the trend in the variations of weight loss of concrete as a function of temperature when exposed to progressively elevated temperatures at a predefined rate.

Figure 3.25: TGA-DTA

Few experiments for studying effect of elevated temperature on compressive strength of Ordinary Portland Cement, concrete containing fly ash or slag cement have been attempted in the past. G.G. Carette et.al (1982) observed in their experimental study on a set of cylinders that the compressive and split tensile strengths of cylinders showed a steady decline relative to that prior to the exposure to elevated temperatures. R Sarshar and G.A. Khoury, (1993) observed that lightweight aggregate concrete exhibits a much lower loss of strength than the normal weight concrete. C.Castillo & A.J Durrani, (1990) found in their study of TGA test given in section 3.1.2.8. High strength concrete that there occurred a relatively higher loss of strength in the case of high strength concrete relative to the normal strength concrete. The amount of chemically bound water, present in different concrete mixes were found by TGA. Three small pieces of mortar paste were taken out at depths of 30, 75 and 130 mm from 150 mm x 150 mm x 150 mm concrete specimen. The mortar pieces so obtained, were grounded together to a fine powder (<75µm).Sample is prepared for The powdered sample was continuously heated from 30^{0}C to 900^{0}C at a steady rate of 10^{0}C/min. While heating, furnace of analyser was purified with nitrogen at a constant rate of 50ml /min. The weight lost by the sample against varying temperature was recorded. The weight loss was expressed as % of dry sample mass taken.

Chapter 4

RESULTS AND DISCUSSION

- **Rheological Properties**
- **Mechanical Attributes**
- **Abrasion**
- **Durability Attributes**
- **SEM & XRD ANALYSIS**
- **TGA (Thermo-gravimetric Analysis)**

The present experimental methodology involves testing of thirty six different mixes at six different w/c ratios with partial replacement for natural sand by Granite Cutting Waste in proportions of 0%, 10%, 25%, 40%, 55% and 70%. All the concrete mixes were provided with adequate dosage of superplasticizers on trial basis except w/c ratio of 0.55 (no super-plasticizer required). Rheological attributes (workability), mechanical attributes (compressive strength, tensile strength and pull off strength), durability attributes (permeability, water absorption, acid attack, sulphate attack ,carbonation, chloride diffusion, chloride penetration and corrosion) and microstructural attributes (SEM and XRD studies) and thermographic analysis have been studied and the results are presented in the chapter for the two series of w/c ratios chosen.

4.1 Rheological Properties

4.1.1 Slump Test

The increased substitution of river sand by GCW resulted in a gradual loss of workability at all w/c. The slump values for control and maximum replacement level were 120, 110,105, 100, 95, 90 mm and 69, 63, 54, 50, 46, 41 mm at 0.55(A), 0.50 (B), 0.45 (C) 0.40 (D), 0.35 (E) and 0.30 (F) w/c respectively. (Fig: 4.1).The workability loss of mixes containing GCW can be due to increased internal friction due to incorporation of angular and rough textured GCW particles in concrete. Rounded aggregates of sand particles have lesser surface area and in turn lesser demand of cement paste for lubrication. The rounded aggregates of natural sand also have lesser voids than the rough, angular and flaky GCW particles. This enables availability of lesser amounts of cement paste for lubrication in case of GCW substituted concrete mixes.

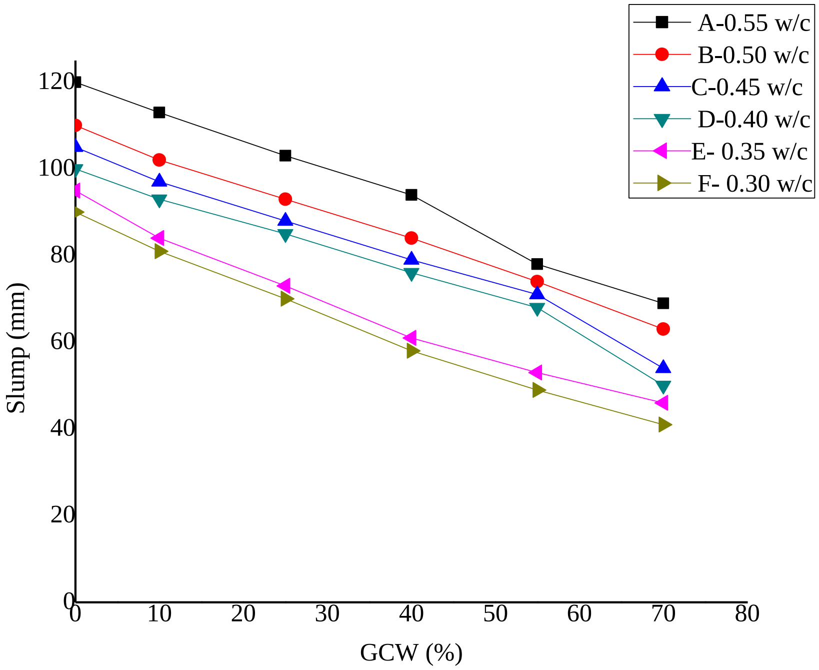


Figure 4.1: Slump values v/s GCW content

Vijaylakshmi et al. (2013) also documented that concrete containing granite dust is less workable than reference concrete. On the contrary, Adigun (2013) reported increased workability of concrete containing granite fines.

4.2 Mechanical Attributes

4.2.1 Compressive Strength

Fig 4.2-4.4 displays the compressive strength of control and GCW substituted concrete. The concrete mixes were divided in the following series i.e. , A, B, C, D, E and F series with w/c ratio of 0.55.0.5,0.45,0.4,0.35 and 0.3 respectively. Similar pattern was followed for the other series as well.

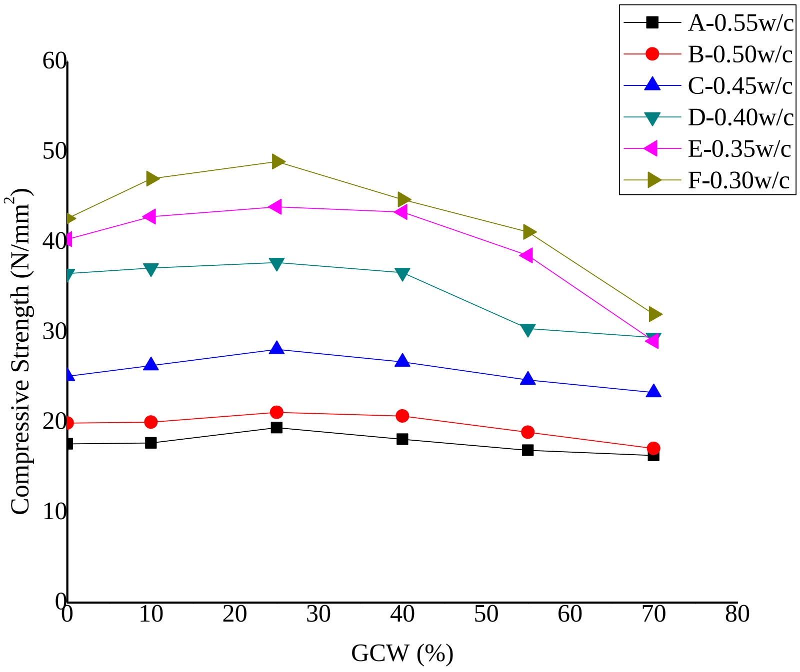


Figure 4.2:7days Compressive Strength v/s GCW content

It was observed that the 7d compressive strength showed a continuous increment over control concrete for all the series upto 40% replacement. The maximum value of compressive strength was observed for the mix with 25% GCW replacement in all the series. This may be attributed to the fact that initial addition of GCW led to the densification of the concrete mix due to the addition of fine Granite waste. However beyond a particular optimum replacement level (25%), further addition of

Granite Cutting Waste led to increase in the specific surface area thus demanding more cement paste to facilitate proper blending and bonding of aggregate and cement. Since the quantity of cement was kept constant the increased specific surface area led to the poor strength of aggregate cement paste and transition zone between cement paste and aggregate in turn leading to the poor strength at higher than optimum substitution levels.

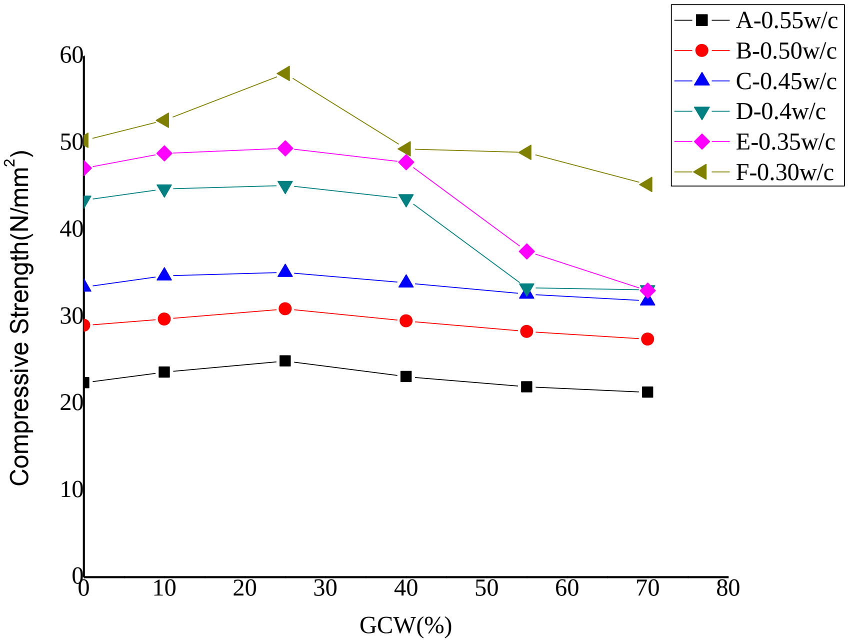


Figure 4.3:28 days Compressive Strength v/s GCW content

It was observed that the 28d compressive strength showed an increment for all the series of mixes upto 40% replacement except 0.3 w/c ratio mix for which increment in strength over the control concrete was observed till 25% replacement only. The maximum value of compressive strength was observed for the replacement level of 25% for all the series of mixes. The reason for increase in the 28 days compressive strength for all the mixes upto 25% granite replacement could be attributed to the less availability of effective water content available for hydration due to the greater surface area of the Granite Cutting Waste Particles. The Granite substituted concrete mix would therefore behave as the concrete mix with lower w/c ratio.

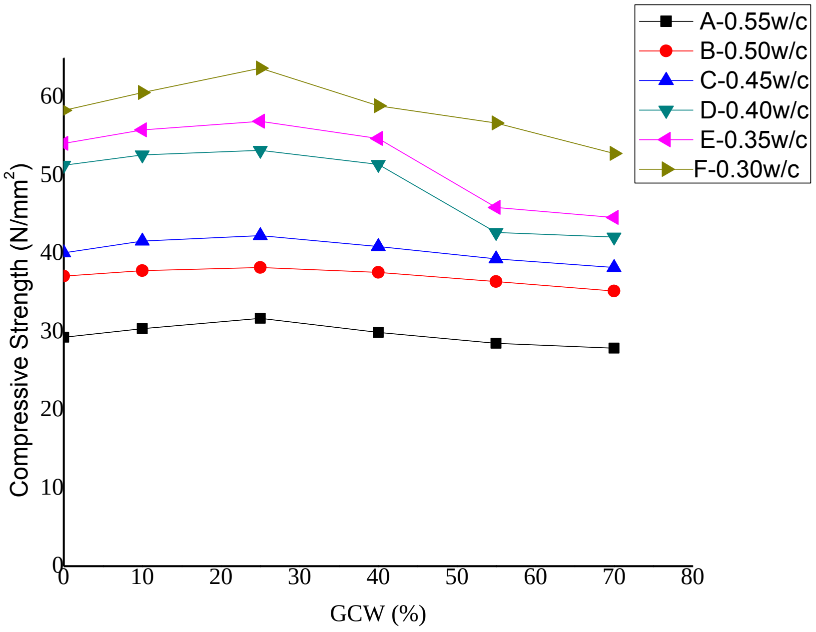


Figure 4.4:90 days Compressive Strength v/s GCW content

The 90 days compressive strength was observed to be exhibiting almost similar behaviour as that of 28 days behaviour for all the series of concrete. The 90 days compressive strength was observed to be exhibiting a sustained increment over the control concrete for all percentages of Granite Cutting Waste upto 40% replacement. The maximum Compressive strength was obtained at the percentage replacement level of 25%. This may be attributed to the better densification of the concrete matrix formed by filling up of large number of voids with micro-filler material i.e. GCW, which is fine enough. with fine GCW particles and also to the enhanced hydration due to availability of more surface area for gel formation. Increase in strength can also be accredited to better adhesion between cement mortar paste and rough GCW particles. However beyond a particular optimum percentage replacement the increased GCW content increases the specific surface area of concrete which in turn increases the demand for cement paste. However the cement content remaining the same leads to poor aggregate binder bonding. The strength of the interfacial transition zone also decreases which could be one of the reason for the decrement observed in the value of 90 days compressive strength at higher percentage replacement levels beyond 40%. In a similar study, conducted by Vijaylakshmi et al. satisfactory strength performance of concrete containing 15% granite dust was reported. Adigun (2013) found that the maximum compressive strength for Crushed Granite Fine substituted concrete was found at a replacement percentage between 25% and 50% for different concrete mixes. Similarly Flexikala and Partheban (2010) found that the maximum compressive strength was obtained for a percentage replacement of 25%.

4.2.2 Flexural Strength

The trend observed for the 7th day flexure strength is depicted in the Fig. 4.5. It is evident from Fig. 4.5 that the flexural strength showed a slight increment till the percentage replacement of 55% and the maximum flexural strength was obtained at the percentage replacement of 40%.

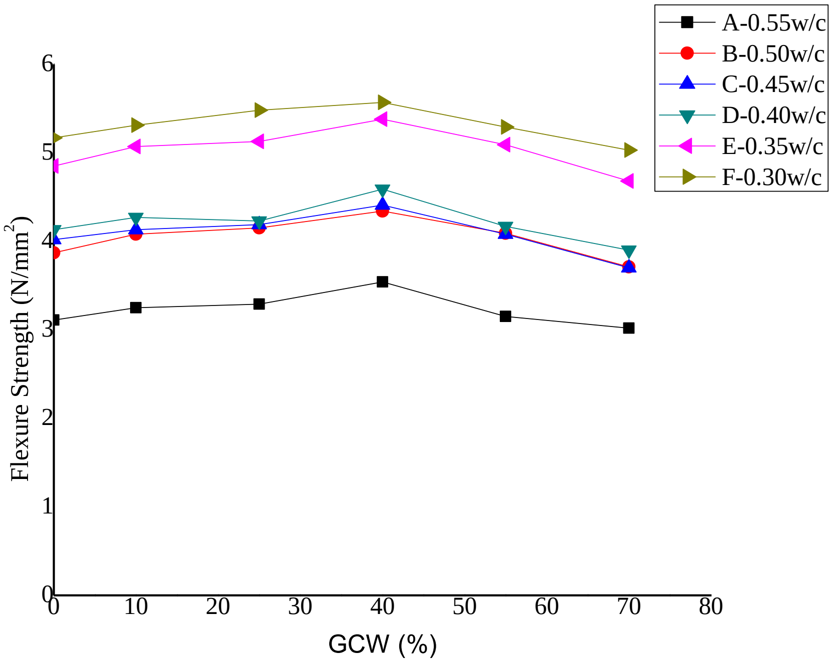


Figure 4.5:7 days Flexure Strength v/s GCW content

The maximum increment in the values of flexural strength at 40% over the control concrete were found to be 7.74%, 10.93%, 11.13%, 9.7%, 12.14% and 13.82% for the series F, E, D, C, B and A respectively. This clearly reflects the fact that as the w/c ratio increased the corresponding increment in the 7th day flexural strength also increased except for the C series.

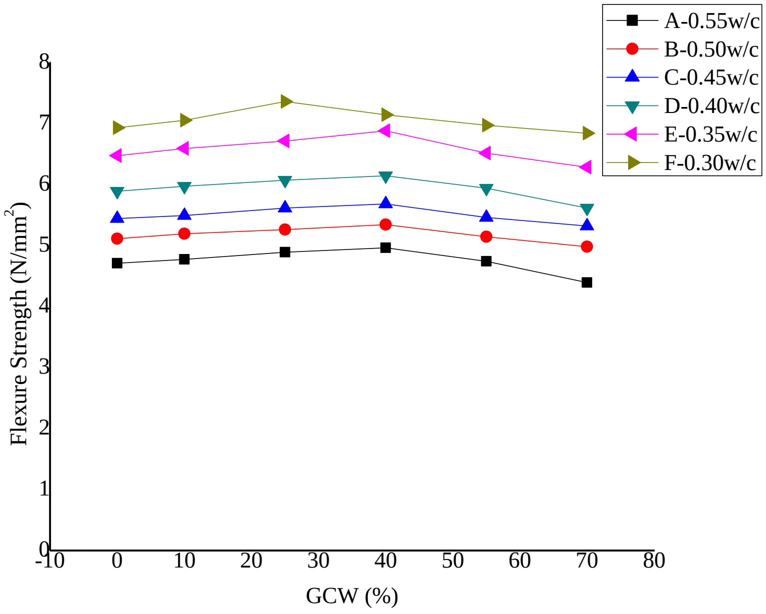


Figure 4.6: 28 days Flexure Strength v/s GCW content

It was observed that 28th day flexural strength showed increment over the control concrete for all percentage of replacement .The increment is strength was marginal with maximum increment observed for all series 40% replacement. Similarly the maximum increment observed in the flexural strength over the control concrete was observed to be even lesser at 90th day flexural strength measurement

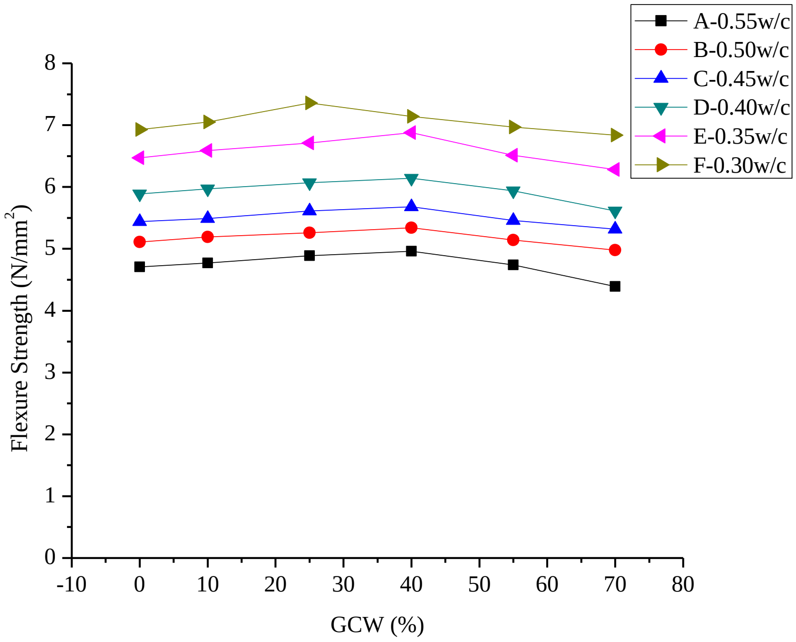


Figure 4.7: 90 days Flexure Strength v/s GCW content

This reflects the fact that the influence of substitution on early age flexural strength is more. This may be attributed to the better initial hydration with the use of angular and rough textured Granite Cutting Waste particles. The GCW particles provide better densification and compact concrete matrix thus might be leading to increase in the flexural strength. Diwakar et al. (2012) and Kala (2013) also reported increase in the flexural strength on replacement with Granite Cutting Waste and respectively concluded the optimum percentage replacement as 5% and 25%.

4.2.3 Pull off Strength

The values obtained for the pull off strength showed a close correlation with the compressive strength. The peak values for all the water/cement ratios were obtained for specimens at 25% replacement as shown in Fig. 4.8.

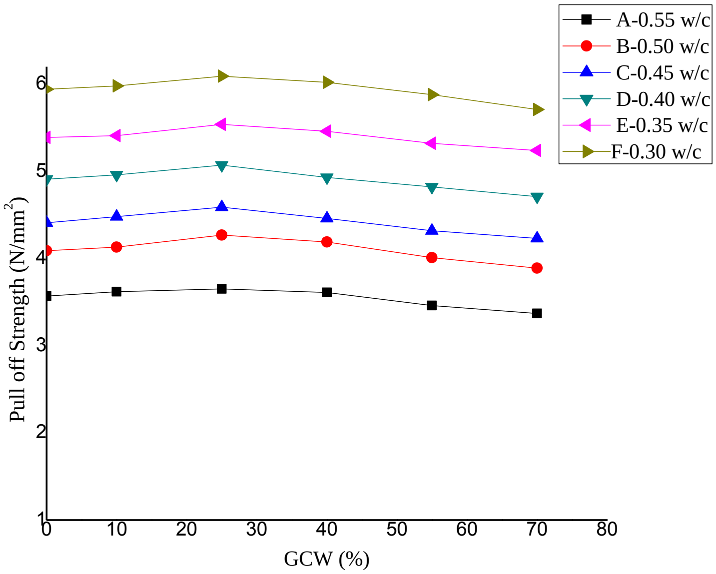


Figure 4.8: Pull-off Strength v/s GCW content

The maximum values of the pull off strength for specimens with water/cement ratios of 0.55, 0.5, 0.4, 0.35 ad 0.3 were found out to be 3.65, 4.27, 4.59, 5.07 ,5.54 and 6.09 N/mm^2 respectively. The pull of strength of the control specimens for the above specimens were observed to be 3.57, 4.09, 4.41, 4.91, 5.39, and 5.94 N/mm^2 respectively. Pull strength of the concrete is a function of surface adhesion between the concrete and the steel reinforcement. Particles of granite being rougher in texture than the corresponding grains of sand exhibit enhanced friction at surface upto an optimum percentage replacement. Also pull off strength of the concrete is a function of its compressive strength at for mixes of lower compressive strength. Since the compressive strength of the concrete mixes was found to be maximum at 25% replacement, this could be a major factor responsible for the enhanced pull off strength of the concrete mixes. The bond strength of concrete might also be dependent indirectly to some extent on the densification of the concrete matrix as the flaws or cracks present might cause stress concentration for certain portions of the concrete and result in premature failure of the concrete specimen. Since Fig. 4.2-

4.4 showed that maximum densified and compact concrete was observed to be the one with 25% replacement the results obtained for the pull strength test were found to be in alignment with those observed for the compressive strength.

4.3 Abrasion

The abrasion resistance of concrete containing up to 40% GCW was comparable or better than control for the series A, B, C and D. The abrasion resistance of concrete generally depends upon its compressive strength and hardness at surface zone .A, B, C and D series exhibited the minimum depth of wear at 40% replacement. The depth of wear for these series was observed to be 1.77mm, 1.74mm, 1.68mm and 1.62mm respectively. For these series the depth of wear for the control mix were found to be 1.92mm, 1.84mm, 1.76mm and 1.70mm respectively. For the series E and F the minimum depth of wear was observed at 25% GCW replacement. The depth of wear for series E and F were observed to be 1.43mm and 1.39mm respectively. The depths of wear for the control mixes of these series were observed to be 1.52mm and 1.45mm respectively.

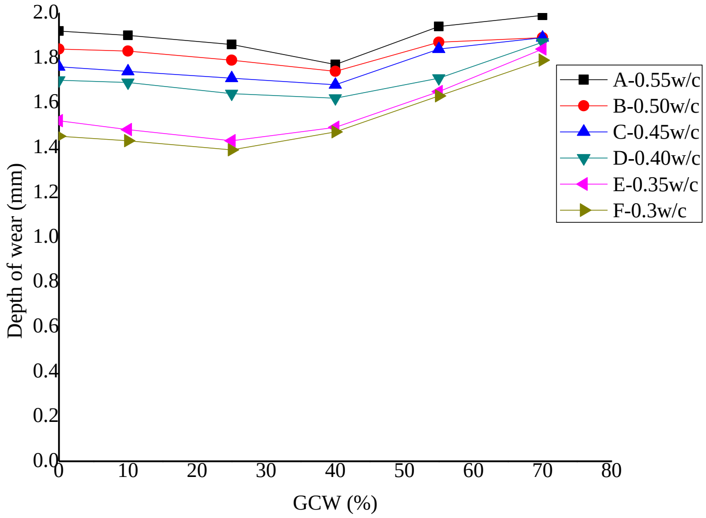


Figure 4.9: Depth of wear v/s GCW content

The depth of wear or the abrasion resistance can be thought of as the trade-off between the compressive strength and the intrinsic hardness of the Granite cutting waste. Upto a certain percentage replacement both the compressive strength and aggregate hardness of the concrete matrix increases as the percentage replacement increases. However beyond a certain optimum percentage replacement the compressive strength of the concrete decreases courtesy to the increment in the specific surface area and poor aggregate –binder bonding. However intrinsic aggregate hardness goes on increasing as the percentage replacement increases owing to the fact that the GCW particle exhibits more intrinsic hardness than the sand particle. The decrement in the compressive strength is steep beyond 40% and 25% replacement for the series A, B, C, D and series E and F respectively. This steep fall in compressive strength gets exhibited in the form of decreased abrasion resistance beyond optimum replacement.

4.4 Durability Attributes

4.4.1Permeability

The durability of a concrete structure is much dependent upon its permeation characteristics. An impermeable concrete will result in increased life of structure.The increasing replacements of GCW in place of river sand resulted in increased impermeability of concrete upto 70% replacement level for series for all series of mix. The control mixes prepared at all w/c ratios were more permeable than GCW concrete. Concrete mixes formulated with 55% substitution ratio were least permeable at all w/c ratio for series D, E and F.The reduced water penetration for GCW concrete can be attributed to reduced number of capillaries and voids due to the fine GCW addition. However for series A, B and C the minimum permeability was observed at 70% replacement.

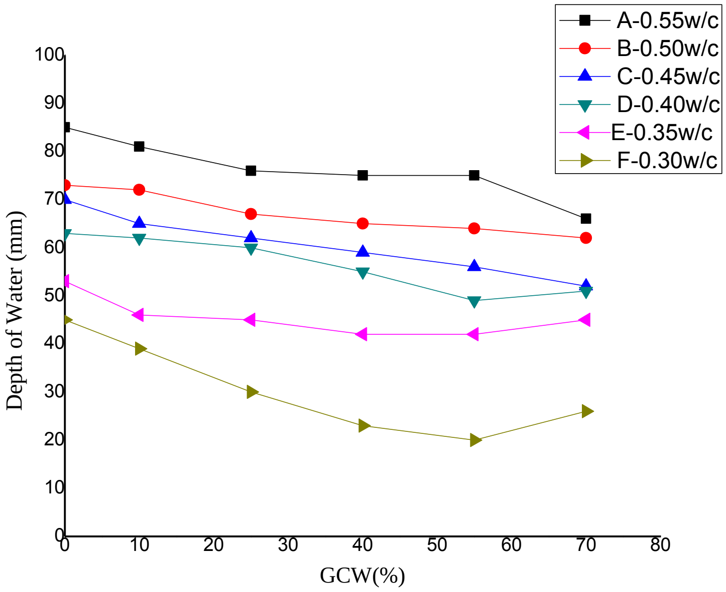


Figure 4.10: Depth of water v/s GCW content

The differences in the behaviour of permeation characteristics of these series may be attributed to the fact that for high w/c ratio concrete mixes the behaviour of GCW particles predominantly remains that of a micro filler since these highly porous concrete mixes exhibit the capacity to absorb the fine GCW particles as a densifying agent within the voids present in the concrete matrix .For low w/c ratio mixes only an optimum percentage (55% GCW) could be accommodated within the concrete matrix. Further addition of the GCW would invariably increase the cement paste demand and specific surface area thus making the compaction of the concrete mix difficult and in turn increasing the porosity and voids within the concrete matrix. Increment beyond 55% leads to development of micro cracks because of binding action being adversely affected by the extra amount of GCW which can also be envisaged from SEM image of G70 mix [Fig 11 (a)]. Fig.4.10 depicts the variation of penetration depths of various concrete mix with GCW (%). Water permeation of 70% GCW concrete was slightly higher than 55% GCW concrete. Still, 70% GCW concrete displayed less permeability than control. On the contrary, Vijaylakshmi et al. (2013) reported increased permeation in concrete mixes prepared with granite dust.

4.4.2 Water- Absorption

The water absorbed by a concrete is a good indicator of its quality and durability. The results of water absorption test were very similar to those of water permeability.

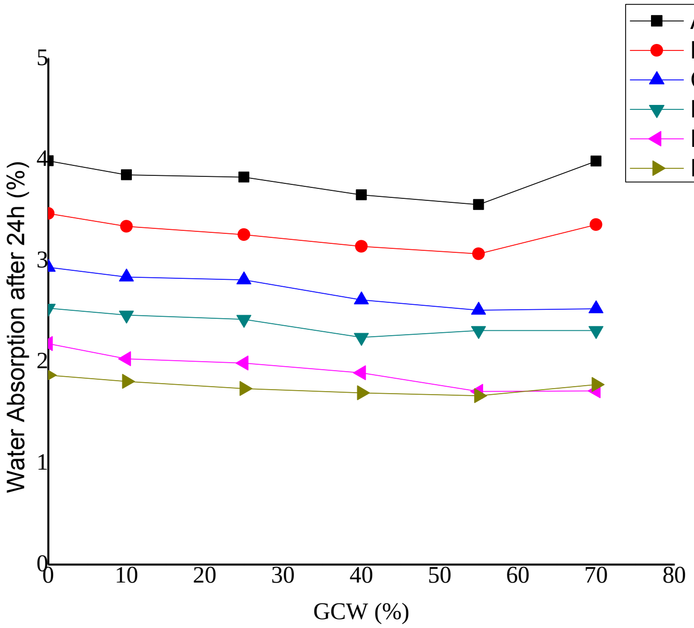


Figure 4.11: Water Absorption v/s GCW content

The concrete containing 55% and 0% GCW showed minimum and maximum water absorption at all substitution levels (Fig. 4.11) for all the series of concrete mixes. The water absorption of concrete containing GCW progressively reduced upto 55% substitution level. The water absorption of 70% GCW concrete was slightly more than 55% GCW concrete. The concrete containing GCW absorbed relatively less water than control mix. This may be attributed to the fact that the introduction of fine GCW particles might have densified the concrete matrix by reducing the volume and connectivity of capillary pores. The dense microstructure of GCW concrete reduced the volume of water absorbed by it.

4.4.3 Chloride Penetration

Fig 4.12-4.17 shows the graphs for the chloride penetration depth v/s percentage GCW replacement for these W/C ratios the maximum depth of chloride penetration observed was at 90 days with a GCW percentage replacement of 70% and the corresponding values were found out to be 27.1, 22.5, 19.4, 18.4, 16.8 and 15.2 mm respectively for the w/c ratio series A,B,C,D,E and F respectively. The corresponding values for the control concrete were found out to be 24.9, 20.8, 17.6, 16.6, 15.9 and 14.3mm respectively. The minimum depth of penetration was observed at 28 days for a GCW percentage replacement of 25%.It was observed that initially as the percentage GCW replacement increases from 0% to 25% depth of chloride penetration decreases at all durations of exposure. This is in agreement with the results obtained for the carbonation. The minimum values of the chloride penetration depth were reported to be 13.8, 10.6, 8.7, 7.8, 5.9 and 4.7 mm for the series A, B, C, D, E and F respectively.

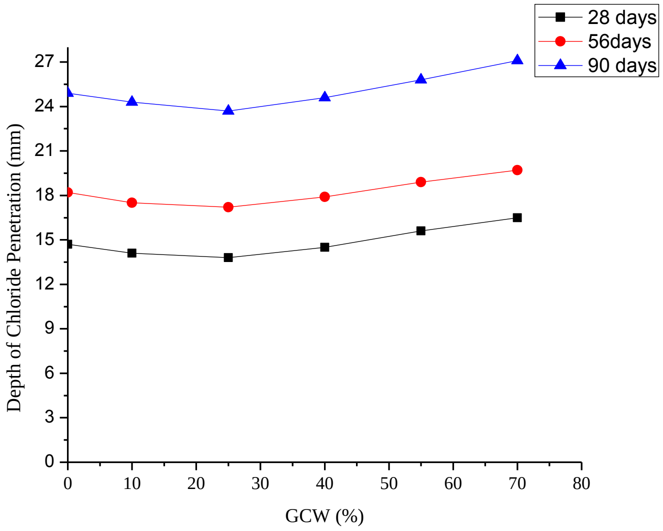


Figure 4.12: Depth of chloride penetration v/s GCW Content at w/c=0.55 (A Series)

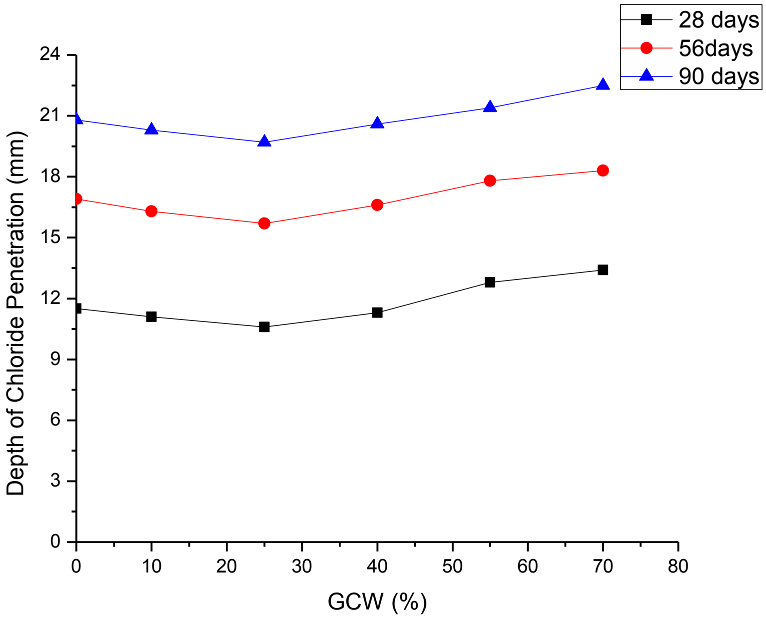


Figure 4.13: Depth of chloride penetration v/s GCW Content at w/c=0.50 (B Series)

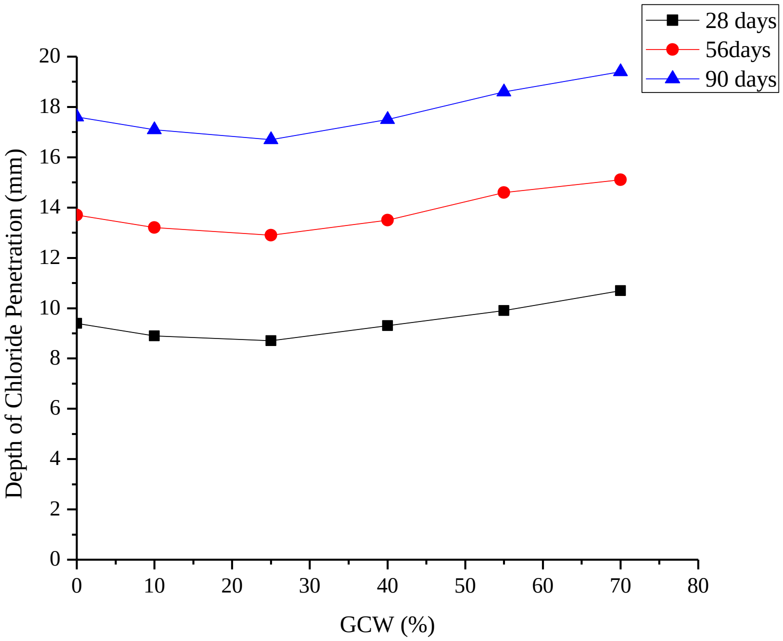


Figure 4.14: Depth of chloride penetration v/s GCW Content at w/c=0.45 (C Series)

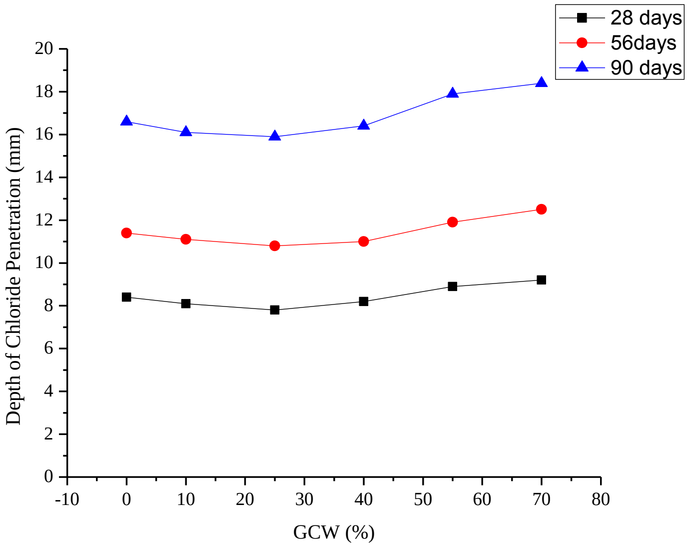


Figure 4.15: Depth of chloride penetration v/s GCW Content at w/c=0.40 (D Series)

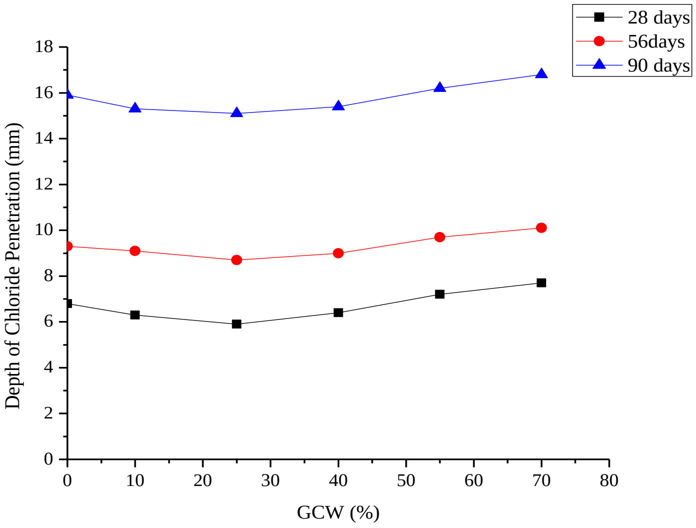


Figure 4.16: Depth of chloride penetration v/s GCW Content at w/c=0.35 (E Series)

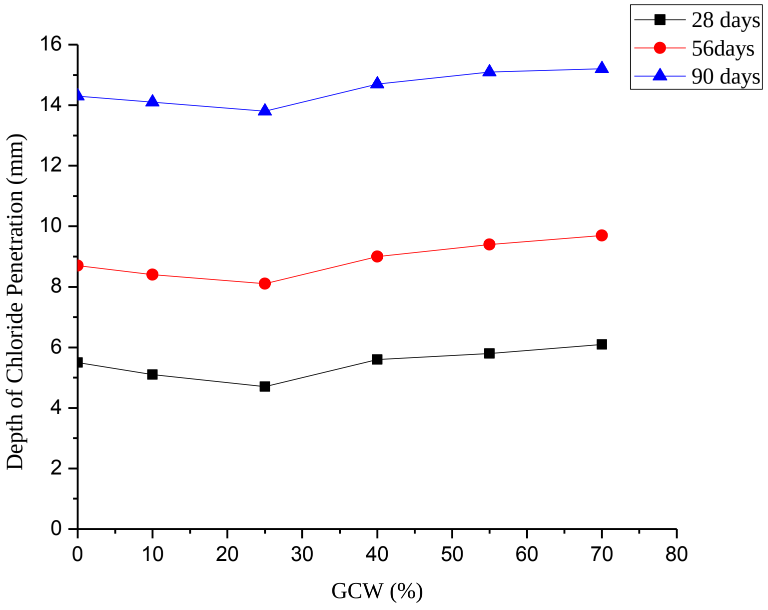


Figure 4.17: Depth of chloride penetration v/s GCW Content at w/c=0.30 (F Series)

The decrease in the depth of chloride penetration can be attributed to the improved microstructure of concrete matrix. The GCW initially act as a filler material (being even finer than sand) and improves the denseness of the concrete matrix. The enhanced denseness of the matrix results in the decreased permeability which inhibits to some extent ingress of chloride in the concrete matrix. However with the increase in the GCW content gradation of fine aggregate begins to get affected. This leads to the poor pore structure of concrete matrix and seriously affects the resistance to chloride penetration. The other parameters remaining the same, depth of penetration observed for W/c ratio of 0.3 were remarkably lesser than those observed for W/c ratio of 0.4 and other w/c ratios reassuring the fact that with increase in W/c ratio the flaws, micro cracks and porosity of the concrete matrix increase noticeably thus leading to increased permeability and subsequently enhanced chloride penetration depth.

4.4.4 Carbonation: The graphs for the depth of carbonation for the two series of W/C ratiowith various percentage of GCW have been shown in figure 4.18 to 4.23.

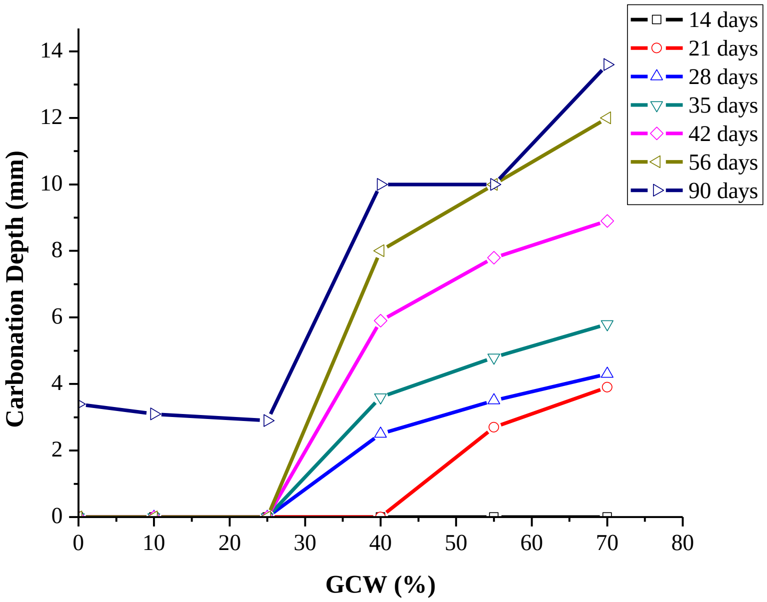


Figure 4.18: Carbonation depth v/s % GCW content (for 0.30 w/c ratio F Series)

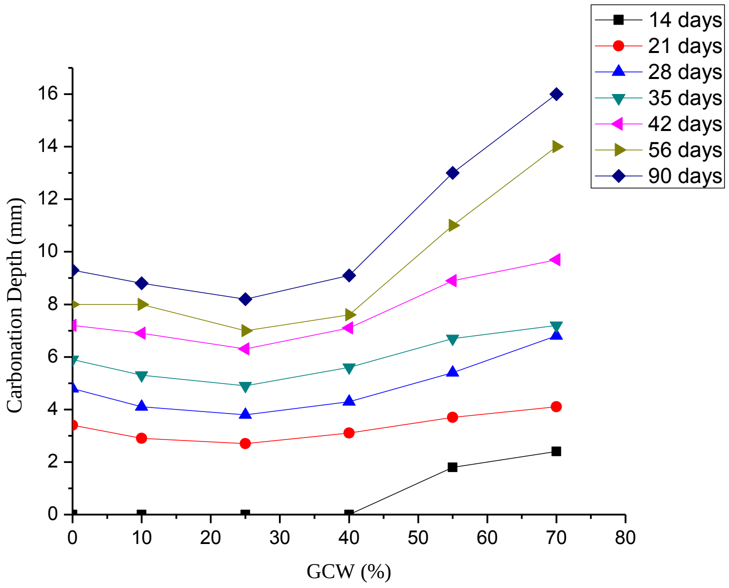


Figure 4.19: Carbonation depth v/s % GCW content (for 0.35 w/c ratio E series)

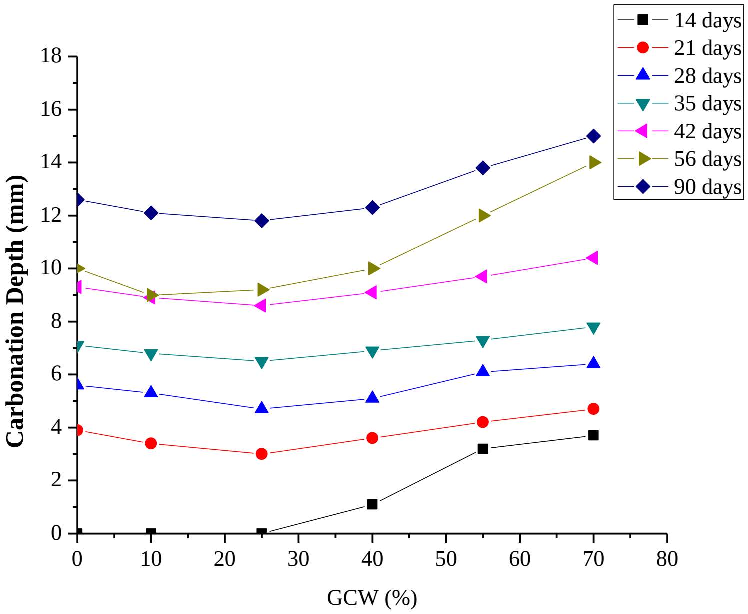


Figure 4.20: Carbonation depth v/s % GCW content (for 0.40 w/c ratio D Series)

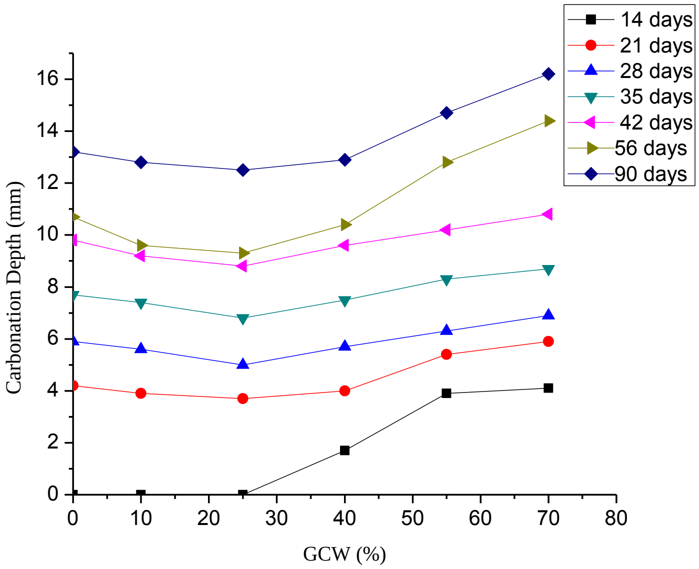


Figure 4.21: Carbonation depth v/s % GCW content (for 0.45 w/c ratio C Series)

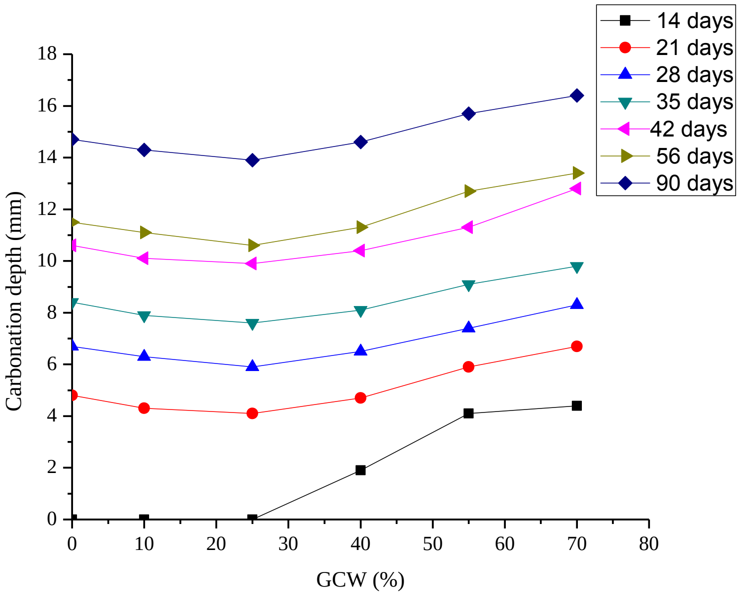


Figure 4.22: Carbonation depth v/s % GCW content (for 0.50 w/c ratio B Series)

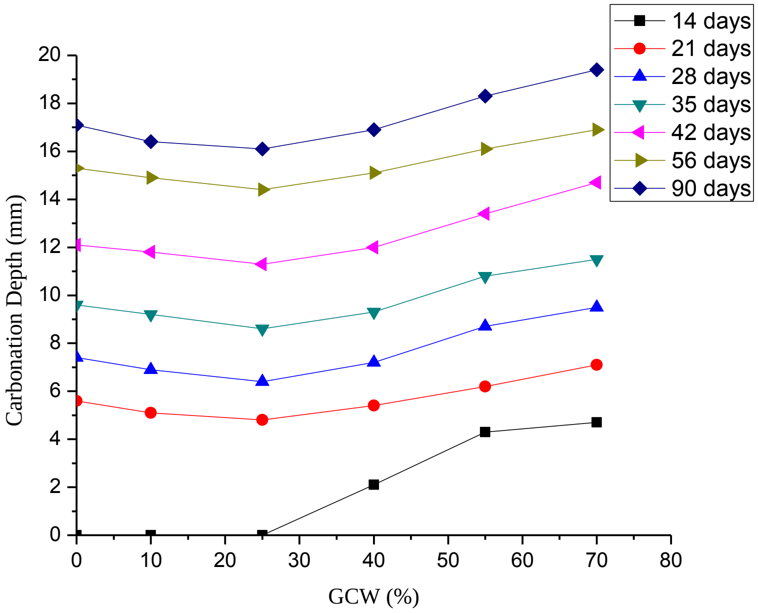


Figure 4.23: Carbonation depth v/s % GCW content (for 0.55 w/c ratio A Series)

It can be seen that a noticeable CO_2 penetration was observed for all the specimens after 90 days of exposure. However for 0.3 w/c ratio control concrete specimen showed nil carbonation depth till exposure period of 90 days. This is due to lower W/C ratio. The lower W/C ratio do not facilitate significant dissolution of CO_2 in the pore water thereby preventing Carbonation for exposure periods of less than 90 days. This indicates that as the strength of concrete increases (in case of lower W/C ratio) depth of carbonation decreases. Carbonation Depth at 90 days showed a declining trend as the percentage of GCW replacement increased from 0% to 25% indicating improved pore structure. GCW being a fine material serves as an effective filler material in the concrete matrix thus improves the denseness of the matrix. Beyond 25% replacement CO_2 penetration was observed at all periods of exposure indicating poor matrix behaviour.

For W/C ratio of 0.35,0.4,0.45,0.5 and 0.55 carbonation phenomenon was observed at all duration of exposure which can be attributed to the enhanced pore moisture content of the concrete thereby facilitating easy dissolution of CO_2 and subsequent carbonation. For these W/C ratio as the GCW replacement increased from 0% to 25% carbonation depth showed a declining trend. The depth of carbonation increased continuously as the percentage of replacement was increased from 25% to 70%. This may be attributed to the fact that once the optimum replacement is done the increased GCW content affects the gradation of fine aggregate in concrete matrix and thus results in poor mix which increases the probability of CO_2 ingress in the concrete matrix which further enhances depth of carbonation. The minimum depths of carbonation at 90 days were found to be 16.1, 13.9, 12.5, 11.8, 8.2 and 2.9 mm for the series A, B, C, D, E and F respectively and at 25% respectively. The corresponding values for the control concrete were found to be 3.4, 9.3, 12.6,13.2 , 14.7 and 17.1 mm respectively. However Vijaylakshmi et.al. (2013) reported slightly contradictory results as they found that with increase in the percentage replacement by Granite waste the carbonation depth continuously increased. This may be attributed to the different particle size used in their experimental study v/s this study.

Carbonation Coefficient

Fig. 4.24 shows the variation of carbonation coefficient with varying percentage replacement with GCW for all the series of w/c ratios. The values of carbonation coefficient have been taken for 90 days in order to assess the impact of substitution on long term durability.

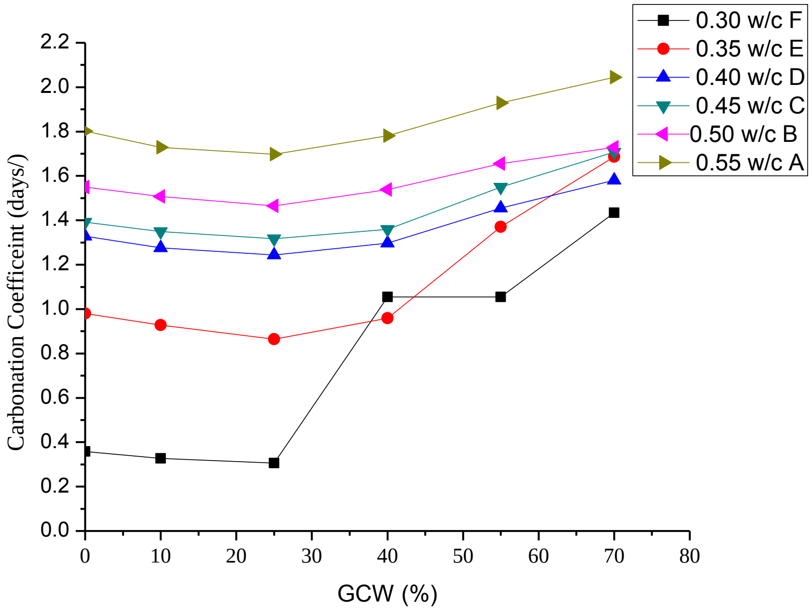


Figure 4.24: Carbonation coefficient vs GCW Content

It can be readily inferred from the figure that the values of carbonation coefficient were observed to be minimum at 25% replacement .All the mixes with percentage replacement upto 25% exhibited values of carbonation coefficient lesser than the control concrete for all the water/cement ratios. This may be attributed to the enhanced denseness of the concrete matrix due to the inclusion of the finer GCW particles The minimum values of carbonation coefficient were found to be 1.697,1.466,1.318,1.244,0.864,0.306 mm/day$^{0.5}$ for the series A,B,C,D,E and F respectively .The corresponding values of carbonation coefficient for the control concrete specimens were observed to be 1.803,1.549,1.391,1.328,0.980and 0.358 mm/day$^{0.5}$ for the series A,B,C,D,E and F respectively .The graph shows that the rise in the value of carbonation coefficient for the water/cement ratio 0.3 was strikingly high as compared to other w/c ratios indicating the adverse impact of replacement beyond 25%. Beyond a certain optimum replacement (25% in this case) the specimens exhibited enhanced values of carbonation coefficient indicating poorer carbonation resistance due to poorer concrete matrix at higher percentage replacement.

4.4.5 Acid Attack

Weight loss

Figs 4.25-4.26 displays the deterioration of concrete specimens in terms of percentage weight loss v/s Immersion period in days. With gradual increase in the percentage GCW replacement from 0% to 40% a decrease in the percentage weight loss was observed for all the w/c ratios except 0.3 w/c for which the declining trend in the values of percentage weight loss was observed till 25% replacement. The minimum percentage weight loss was observed for the percentage GCW replacement of 25% for all the w/c ratios. The weight loss can be attributed to the leaching out of the products of the reaction b/w hydration products and sulphuric acid. This leaching out of these by-products results in protruding irregular surface projections which serve as a means of visual inspection of deterioration of concrete by acid attack. These protrusions reinforce the fact that by and large acid attack is a surface phenomenon. The result is in agreement with those obtained for the (Fig. 4.5.3) carbonation and chloride penetration. The improved microstructure of the concrete matrix might be a possible reason behind this behavior. However once the optimum percentage replacement was attained the additional GCW fines replacement resulted in the poor gradation of the fine aggregates, poor packing density of the concrete matrix and increased demand for cement (as the surface area increases with increase in the percentage GCW replacement). This leads to inefficient matrix behaviour and provides a conducive atmosphere for acid attack to occur.% age weight loss observed in case of A,B and C series specimens was greater than that observed for D,E and F series specimens confirming the fact that greater is the porosity of the concrete matrix greater is the probability of deterioration due to acid attack.

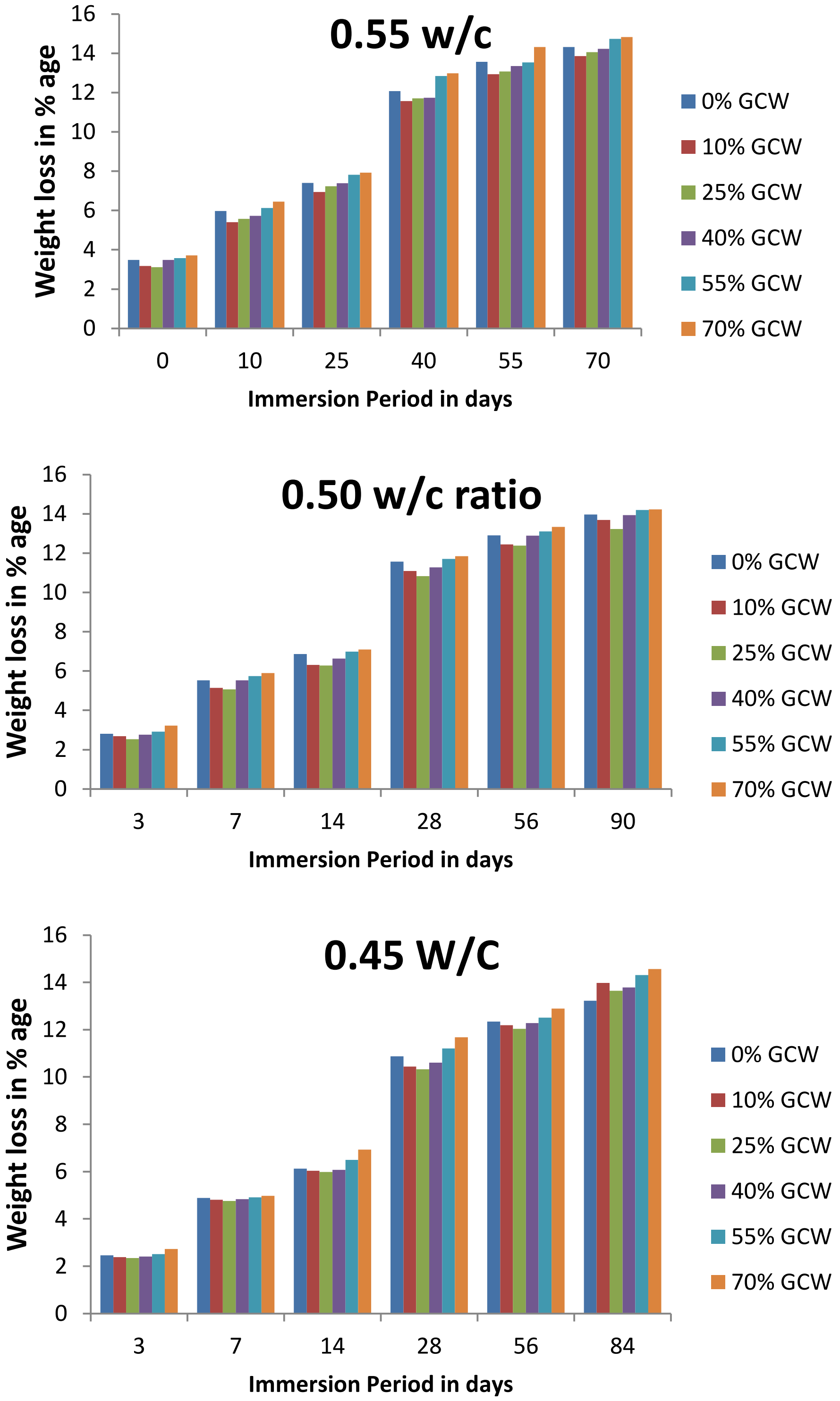


Figure 4.25: % Weight loss v/s immersion Period for the concrete specimen at 0.55, 0.50,0.45 w/c ratio

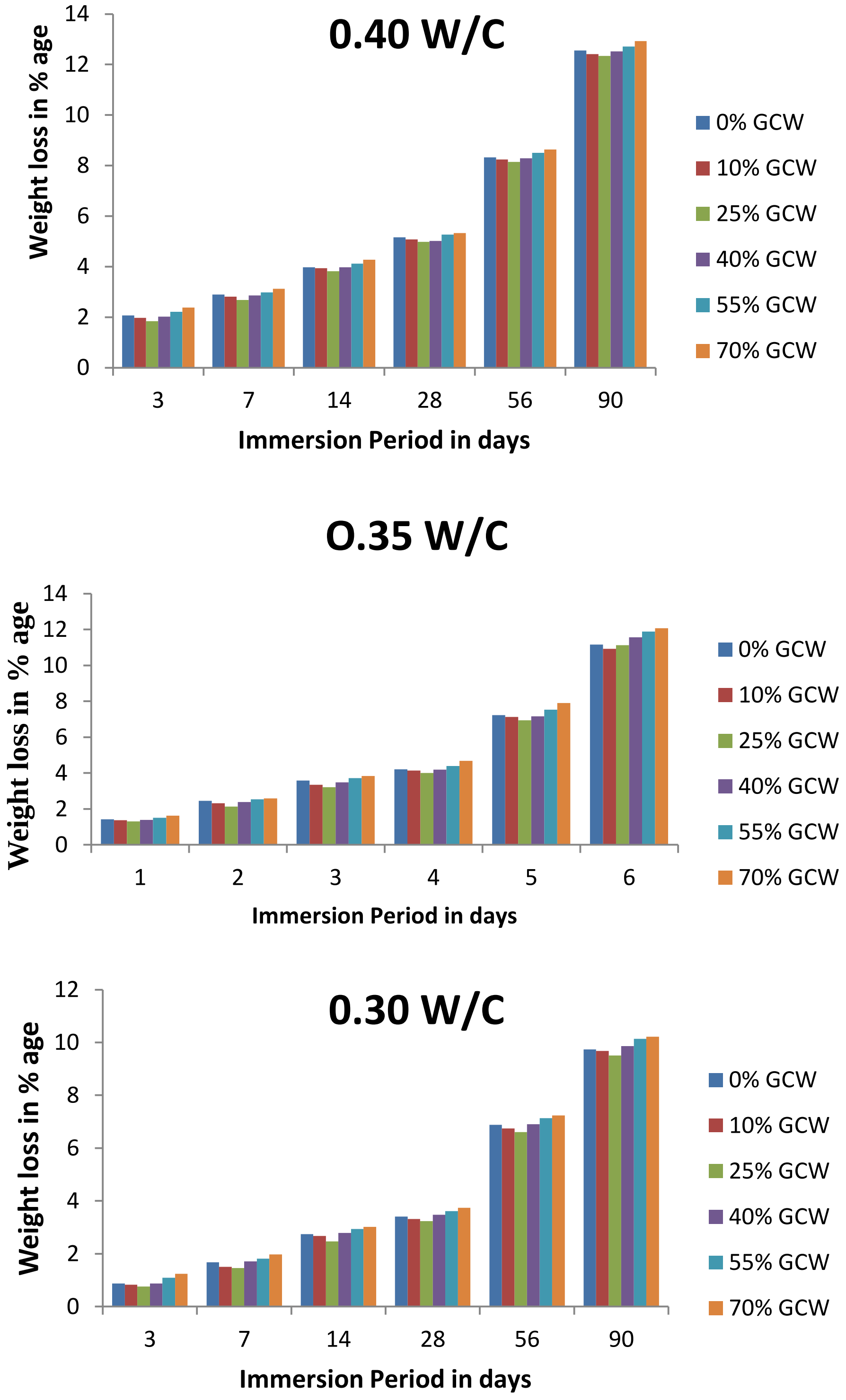


Figure 4.26: % Weight loss v/s immersion Period for the concrete specimen at 0.40, 0.35,and 0.30 w/c ratio

Sulfuric acid attack is more dangerous than sulfate attack reason being that attack of sulphate ion is also there besides dissolution by hydrogen.

Bassuoni and Nehdi (2007) gave the following equations to explain the impact of H_2SO_4 on the hydration products of concrete(Bassuoni MT and Nehdi ML, 2007)

$Ca(OH)_2 + H_2SO_4 \rightarrow CaSO_4.2H_2O$

$CaSiO_2.2H_2O + H_2SO_4 \rightarrow CaSO_4 + Si(OH)_4 + H_2O$

$3CaO.Al_2O_3.12H_2O + 3(CaSO_4.2H_2O) + 14H_2O \rightarrow 3CaO.Al_2O_3.3CaSO_4.32H_2O$

Singh and Siddiqui (2014) in their study found that weight loss of concrete specimens at all durations was lesser for bottom ash concrete than the control concrete upto 100% replacement of sand by bottom ash. They attributed it to the reduced permeability of the bottom ash concrete due to bottom ash inclusion.

Strength loss

The losses in compressive strength for the concrete specimens at various durations of exposure are shown in fig 4.27-4.28 for all the series of concrete mix. It can be readily inferred that at the optimum percentage GCW replacement of 25% the loss in compressive strength was observed to be minimum for all the water cement ratios. This may be attributed to the enhanced denseness of the concrete due to the filler effect of the GCW. The value of percentage loss in compressive strength was comparable to control concrete at 40% replacement for all the w/c ratios. Beyond 40% replacement, loss in compressive strength begins to increase surpassing loss in compressive strength of the control concrete specimen at the percentage replacement of 55% and beyond. The loss in compressive strength for the series A, B and C were observed to be greater than the values obtained for the series D,E and F respectively at corresponding durations of exposure.

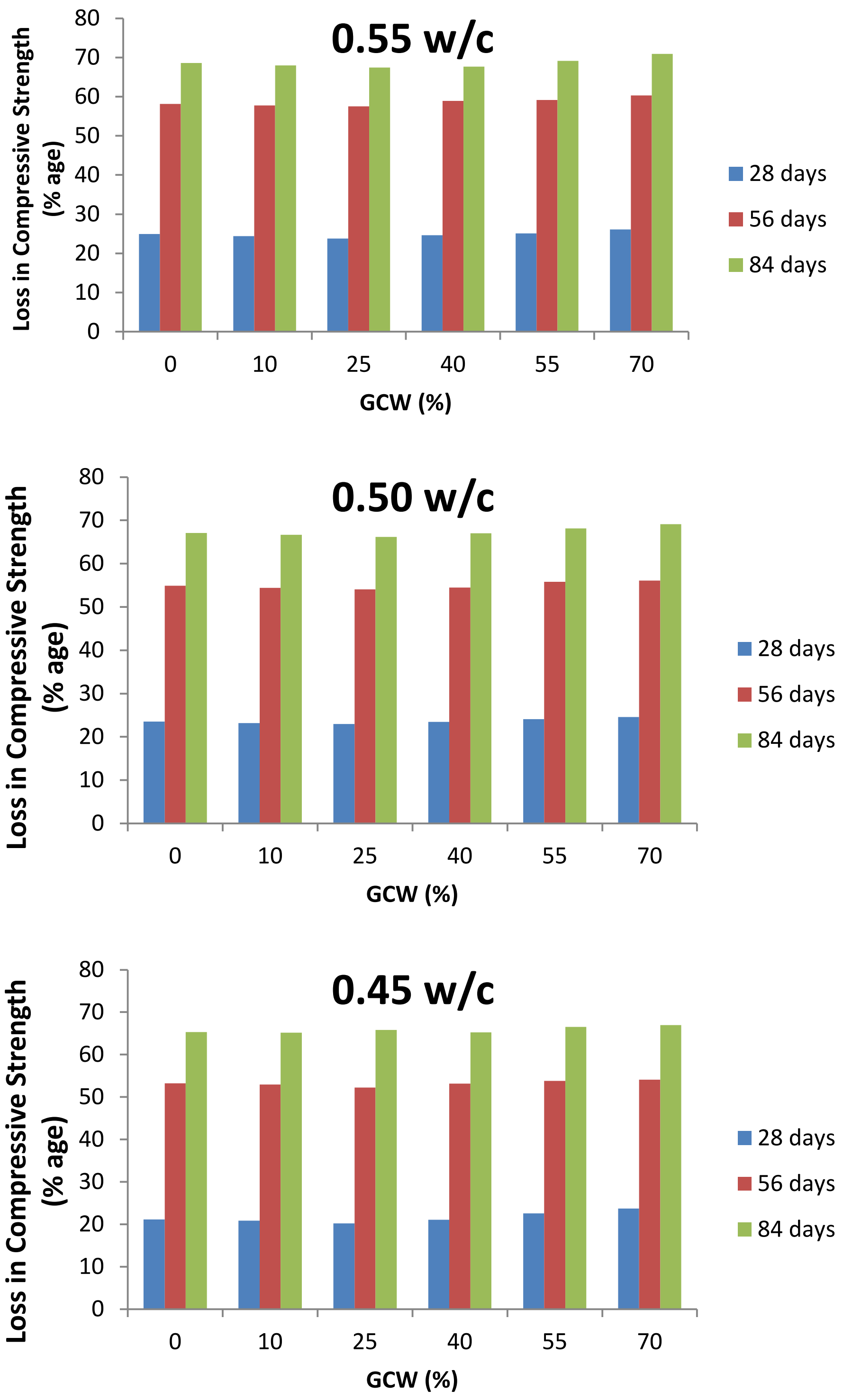


Figure 4.27: Loss in Compressive Strength v/s % GCW content for 0.55, 0.50, 0.45 w/c ratio

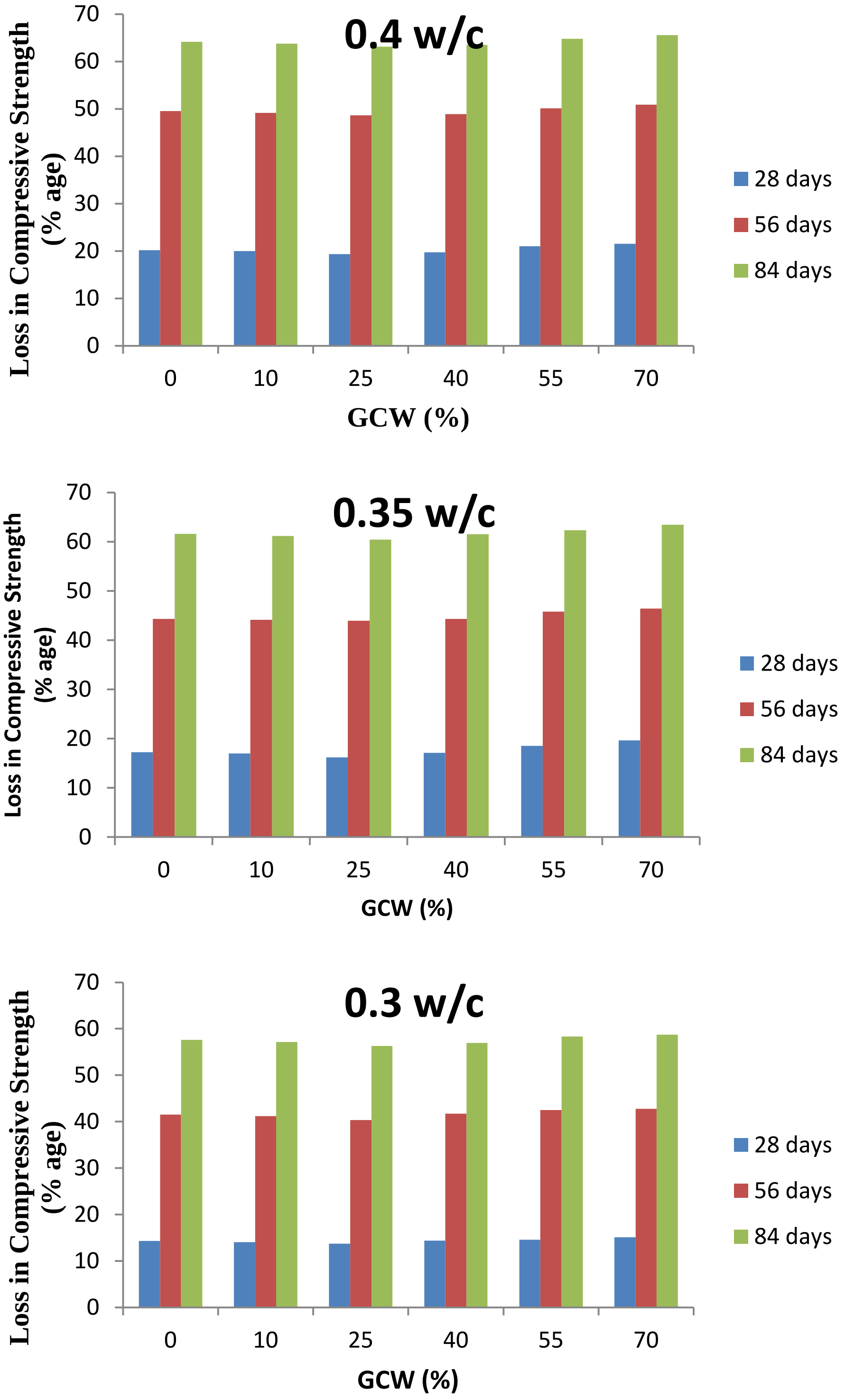


Figure 4.28: Loss in Compressive Strength v/s % GCW content for 0.40, 0.35, 0.30 w/c ratio

This may be attributed to the fact that with the increase in the w/c ratio the porosity of the concrete specimen increases resulting in a state of concrete matrix including more voids, flaws and internal micro-cracks. As the porosity of the concrete matrix increases the probability of intrusion of acid increases and this makes the concrete specimen vulnerable to the acid attack which in turn leads to the increased leaching out of the products of chemical reaction between hydrated products and the acid. This also leads to the increased loss in compressive strength in response to acid attack. Singh and Siddiqui (2014) found in their study that the percentage loss in compressive strength decreased with increase in the percentage replacement by bottom ash. They also attributed the reduced permeability of the bottom ash concrete as one of the reason behind the decreased loss in compressive strength as compared to the control concrete.

4.4.6 Sulphate attack

Weight Loss

For the specimens immersed in 10% $MgSO_4$ solution no noticeable loss in weight was reported at 28d, 90d, 180d or 210d respectively . The specimens displayed no signs of spalling or cracking throughout the duration of the test. The specimens however displayed noticeable white deposits at the end of 210d immersion. Even no deformation in shape was reported at the immersion period of 210d.Similar observations were reported by Malkit Singh and Rafat Siddique, 2014 for sand replacement by coal bottom ash in concrete.

Compressive Strength

The compressive strength of all the specimens was found to be increasing with the increase in the duration of immersion period. The percentage change in compressive strength values for series A, B, C, and series D, E F specimen are presented in Figure 4.29 and 4.30 respectively. The percentage increment in the control concrete at 180d was found to be 27.17%, 37.59%, 43.17%, 52.4%, 57.1%and 59.2% for the series A, B, C, D, E and F respectively.

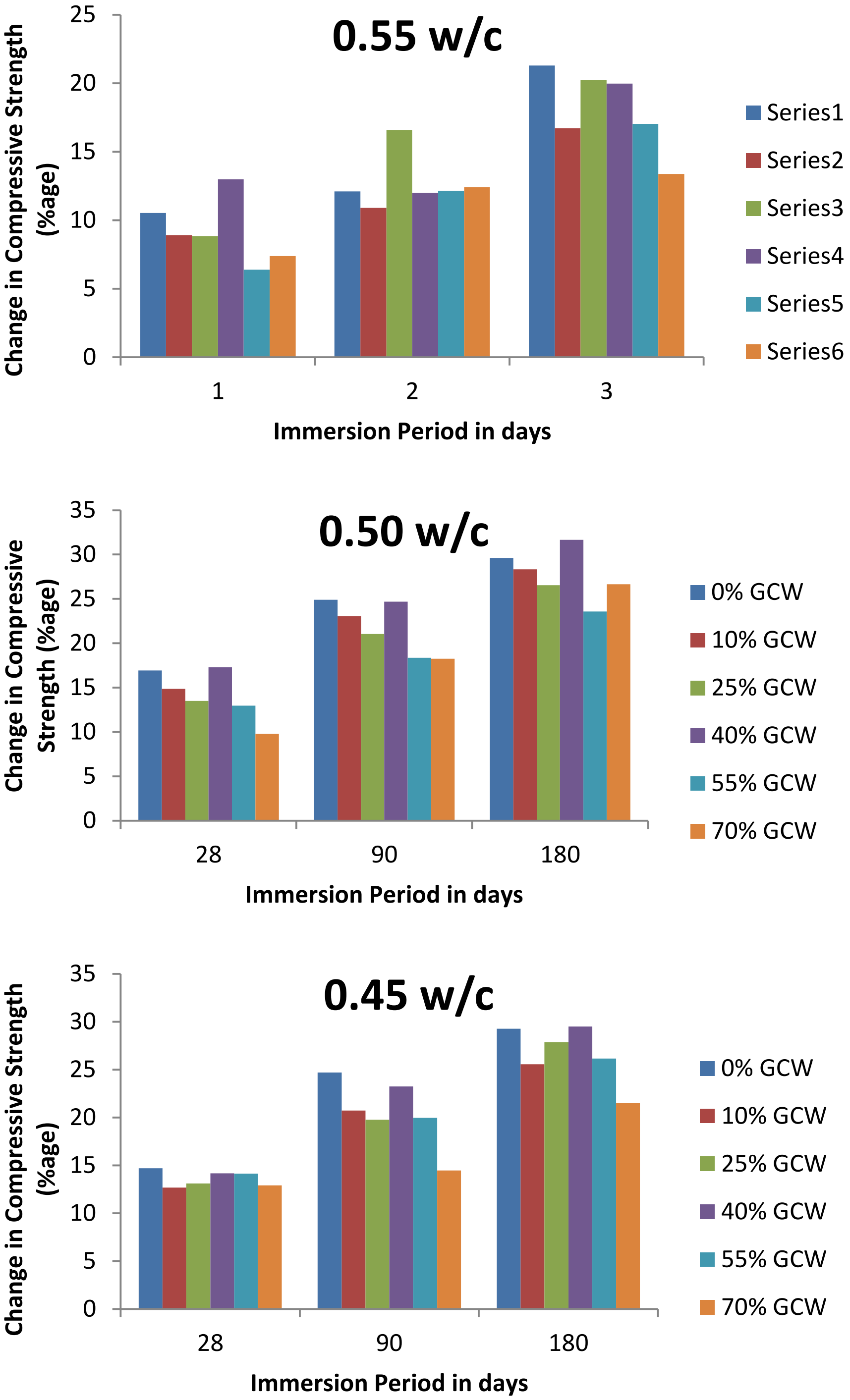


Figure 4.29: Change in compressive strength v/s immersion Period 0.55, 0.50, 0.45 w/c ratio

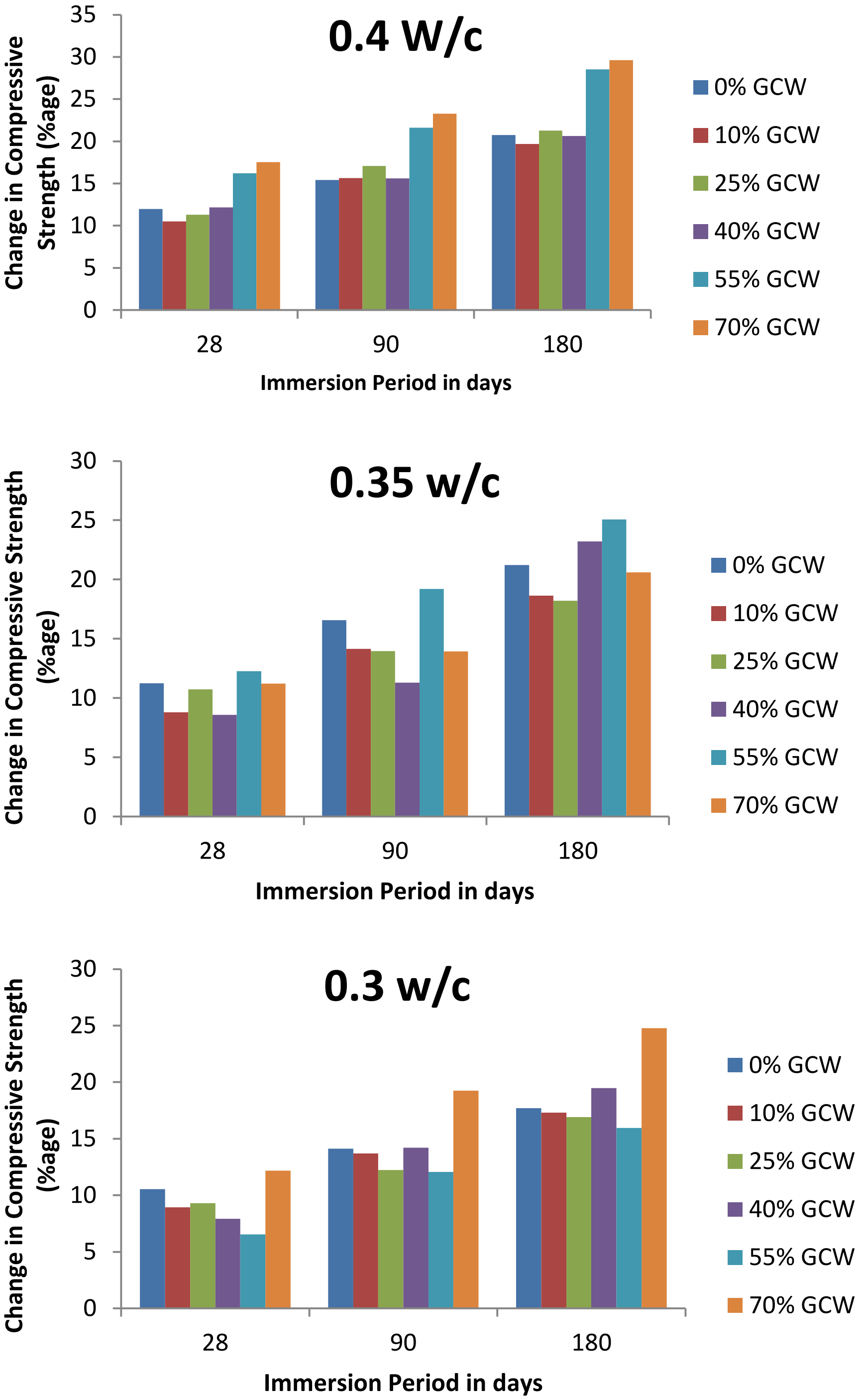


Figure 4.30: Change in compressive strength v/s immersion Period 0.40, 0.35, 0.30 w/c ratio

It was found that the peak value of compressive strength was higher for lower w/c ratios at any given percentage replacement. The higher incremental change in the compressive strength in case of lower w/c ratios may be attributed to the less porous and denser concrete matrix at lower w/c ratios. The compressive strength of the specimen with 25% GCW content was found to be maximum at all durations of exposure. It was found that the absolute value of compressive strength was slightly higher than the control concrete at a percentage replacement of 40% for all the w/c ratios. The increase in the compressive strength of all the specimens may be attributed to the continued hydration. The reason for the fact that that no spalling or cracking of concrete specimens may be attributed to the improved permeability of the concrete specimens due to the ingress of the finer particles of GCW. This improved permeability might be responsible for the less porosity and in turn decreased inclusion of the sulphate in the concrete matrix. The ettringites formed might have remained confined to the internal void spaces and thus accounting for the fact that no weight loss was observed for the specimens. The better performance of GCW specimen with 25% replacement may be attributed to the high Alumina content in GCW besides the densification of matrix due to GCW inclusion. Here Alumina might have formed a protective layer inhibiting entry of Sulphate in the concrete matrix similar to what is believed to occur in case of High Alumina Cement. This improved permeability might be a reason for the superior performance of the GCW concrete. Singh and Siddiqui (2014) found that increment in the compressive strength was higher for bottom ash concrete than the control concrete upto 100% replacement of natural sand by bottom ash. They attributed it to the continued hydration, pozzolonic action of bottom ash and the reduced permeability of the bottom ash concrete.

4.4.7 Shrinkage

The values of shrinkage strain vs time period are shown in fig 4.31-4.36. The figures show that the initial shrinkage values upto 60d were lesser for the GCW concrete than the control concrete at all percentage replacements for all the w/c ratios. After 60days, the shrinkage strain in the GCW concrete became comparable to the control concrete.

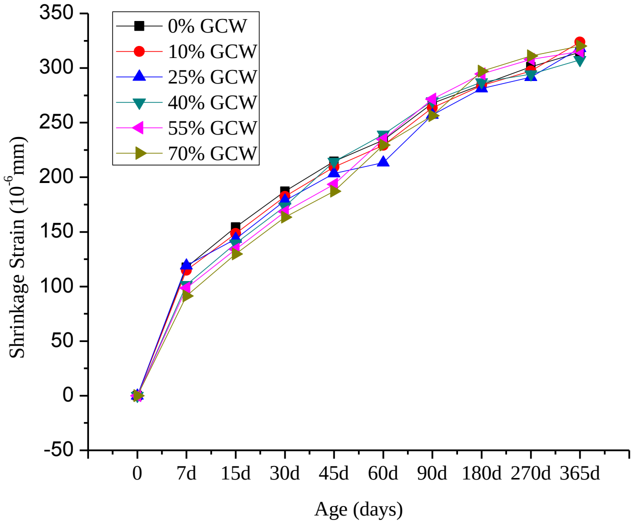


Figure 4.31: Shrinkage strains in w/c 0.55 concrete mixes.

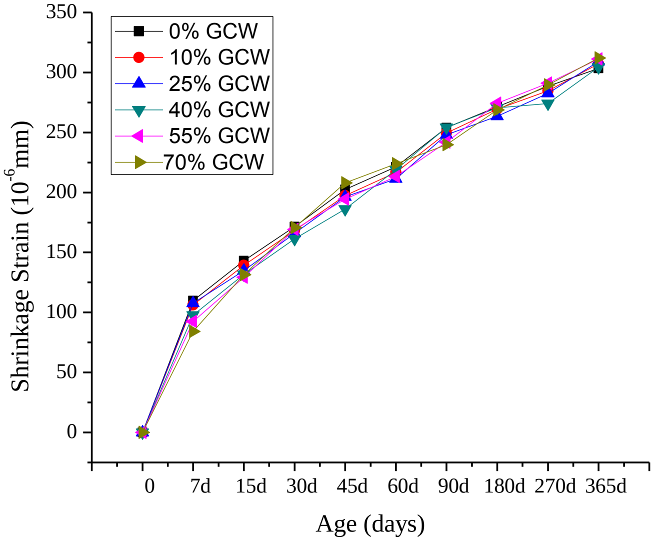


Figure 4.32: Shrinkage strains in w/c 0.50 concrete mixes

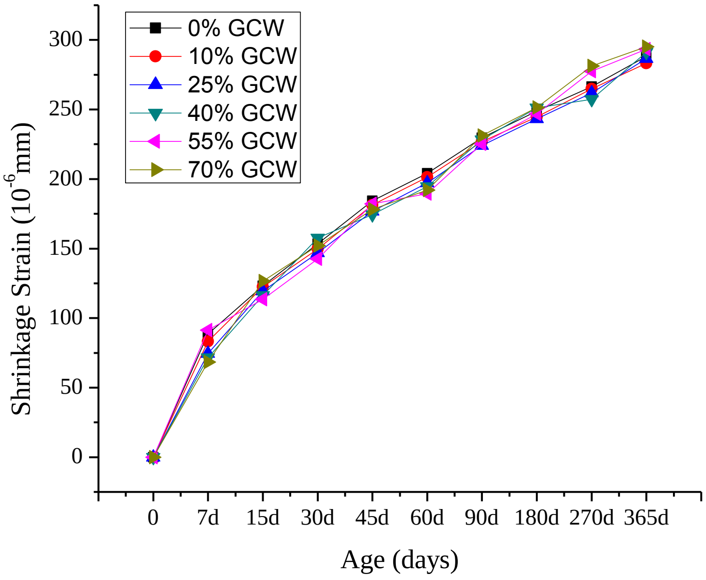


Figure 4.33: Shrinkage strains in w/c 0.45 concrete mixes

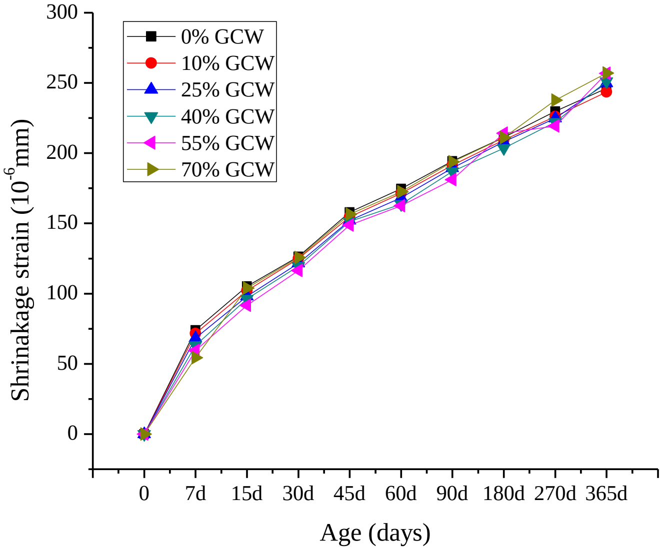


Figure 4.34: Shrinkage strains in w/c 0.40 concrete mixes

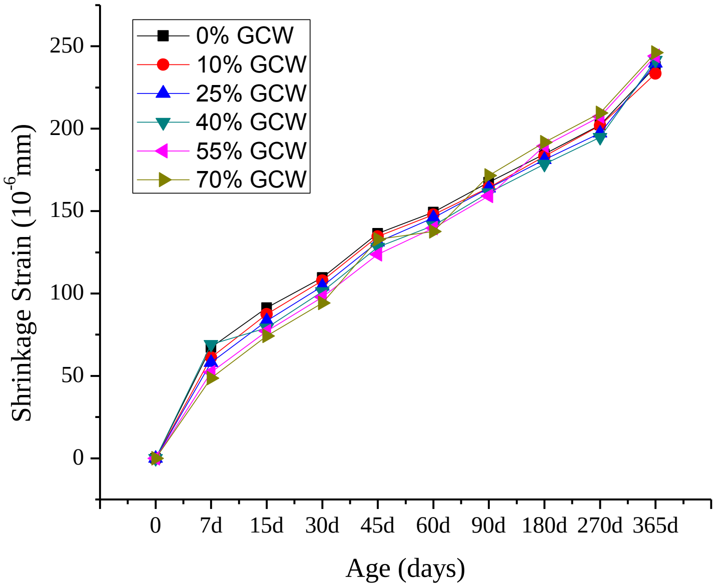


Figure 4.35: Shrinkage strains in w/c 0.35 concrete mixes

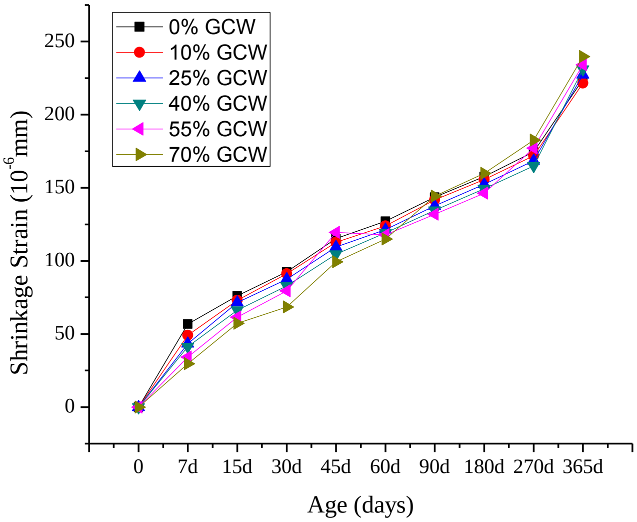


Figure 4.36: Shrinkage strains in w/c 0.30 concrete mixes

The slowdown in the initial shrinkage value for all the w/c ratios can be attributed to the fineness and irregular shape of the GCW particles. The fine and irregular GCW particles might have absorbed significant amount of pore water from the concrete matrix thereby leaving lesser amount of free water. This water would have then been released gradually as the time progressed thereby leading to lesser shrinkage strain than the control concrete. However as the time progressed almost all the absorbed water might have been released by the fine GCW particles thereby leading to comparable shrinkage strain values to that of the control concrete at the duration of 1 year. The variation in the final values of shrinkage strain for GCW concrete at the duration of 365 days was within 5% to that of the control concrete for all the w/c ratios at all percentage replacements indicating the similar behaviour of control concrete and the GCW concrete from shrinkage point of view.

4.4.8 Corrosion

Macrocell Current Values

The macrocell current v/s time for the series A,B,C,D,E and F respectively are shown in fig 4.37-4.42. The analysis is consistent with the guideline of ASTM G109-99a which states that macrocell current value greater than +10µA is an indication of corrosion process in progress. This can be readily inferred from the figures that initially all the bars in concrete mixes with different w/c ratios and at different percentage replacements showed a value of macrocell current lesser than +10µ indicating negligible corrosion activity in the beginning. It was found that for all the mixes the time taken (in no of months) was comparable for the control concrete and the GCW concrete upto 40% replacement .However the corresponding time taken was lesser in case of 55% and 70% replacements. .It was found that the GCW concrete with 55% and 70% replacement reached a macrocell current value greater than +10µA at about 6 months for all the series of w/c ratio. The corresponding time taken in case of other percentage replacements was about 7-8 months in all the series.

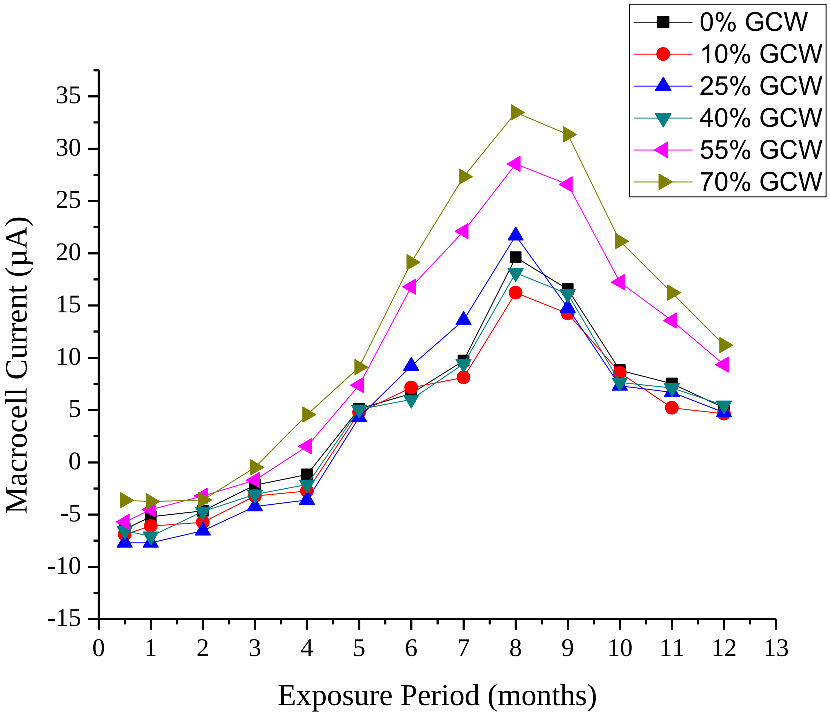


Figure 4.37: Macrocell Current v/s Exposure period for w/c 0.55 concrete mixes (ASTM Limit <10µA No corrosion)

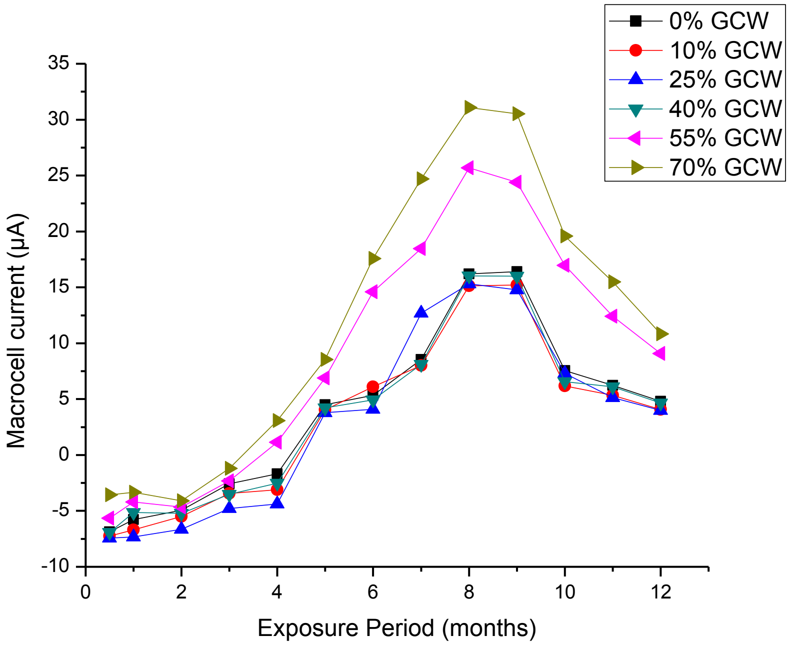


Figure 4.38: Macrocell Current v/s Exposure period for w/c 0.50 concrete mixes

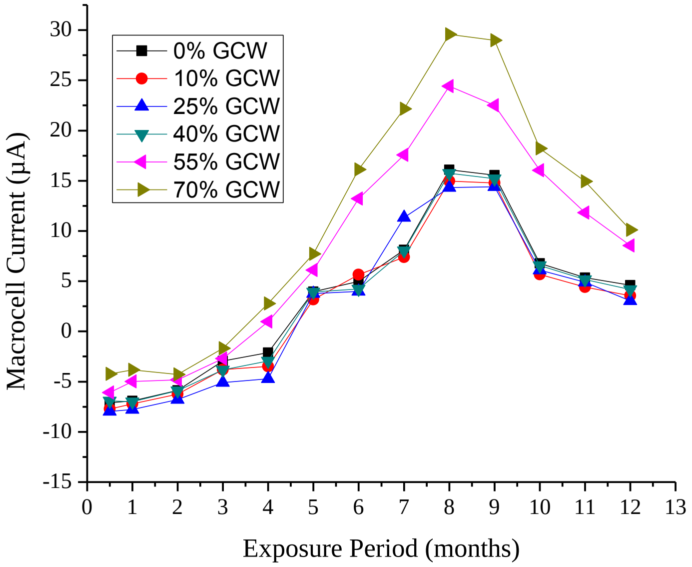


Figure 4.39: Macrocell Current v/s Exposure period for w/c 0.45 concrete mixes

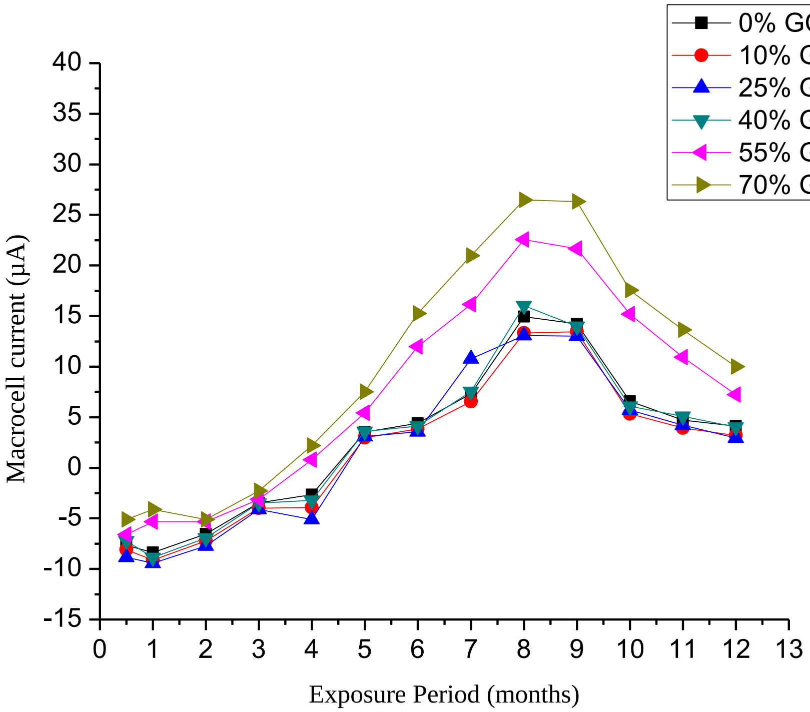


Figure 4.40: Macrocell Current v/s Exposure period for w/c 0.40 concrete mixes

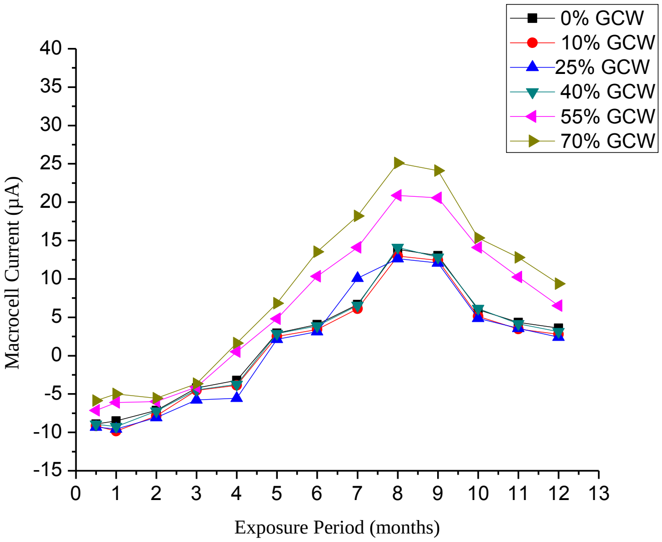


Figure 4.41: Macrocell Current v/s Exposure period for w/c 0.35 concrete mixes

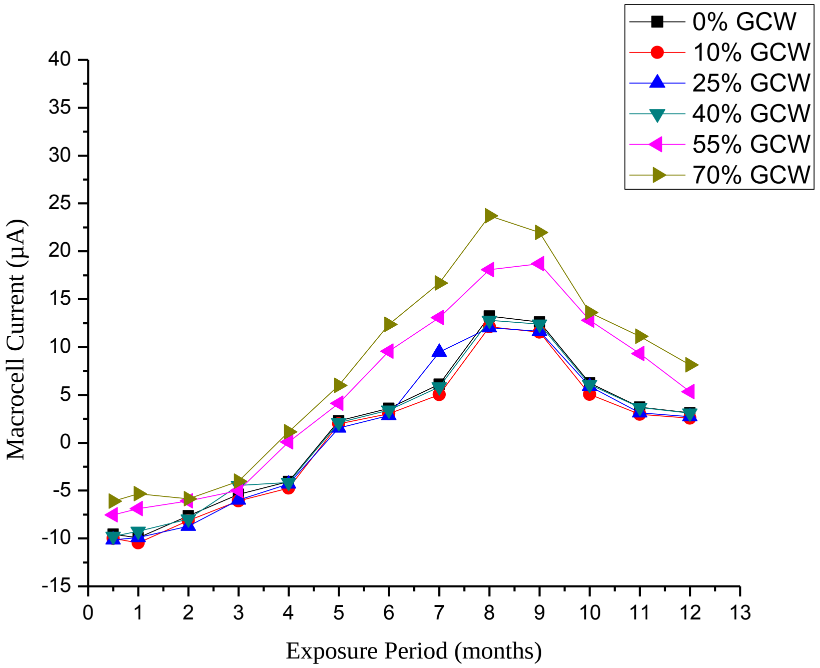


Figure 4.42: Macrocell Current v/s Exposure period for w/c 0.30concrete mixes

As the percentage replacement was increased beyond 40% the values of macrocell current showed a steep rise in magnitude over the values of control concrete at any given point of time. This may be attributed to the poor gradation and mix properties at higher replacements in GCW substituted concrete. The peak value of macrocell current was found to be lesser in case of lower w/c ratios than that observed for higher w/c ratios of series A, B and C. This may be due to the decreased porosity and inturn decreased chances of corrosion with decrease in the w/c ratio

Half-Cell Potential

The graph between the half-cell potential & exposure period for all the series of w/c ratios are shown in fig 4.43-4.48 respectively. The analysis done is in compliance with the guidelines issued by ASTM G 109-99a which states that a half cell potential value more negative than -350mV measured using copper-copper sulphate half-cell indicates greater than 90% probability for corrosion being in progress. It is clear from the graphs that initially for all the concrete mixes with different w/c ratios, the values of half-cell potential were between -100 -200mV.It can be readily inferred that the values of half-cell potential more negative than -350mV were observed to be after 6-7 months for the percentage replacements of 0%,10%,25% and 40% for all the series of w/c ratios. For 55% & 70% replacements the corresponding time taken to attain half-cell potential values more negative than -350mV were observed to be lesser than or equal to 6 months indicating poorer gradation, compaction and enhanced porosity at higher percentage replacements.

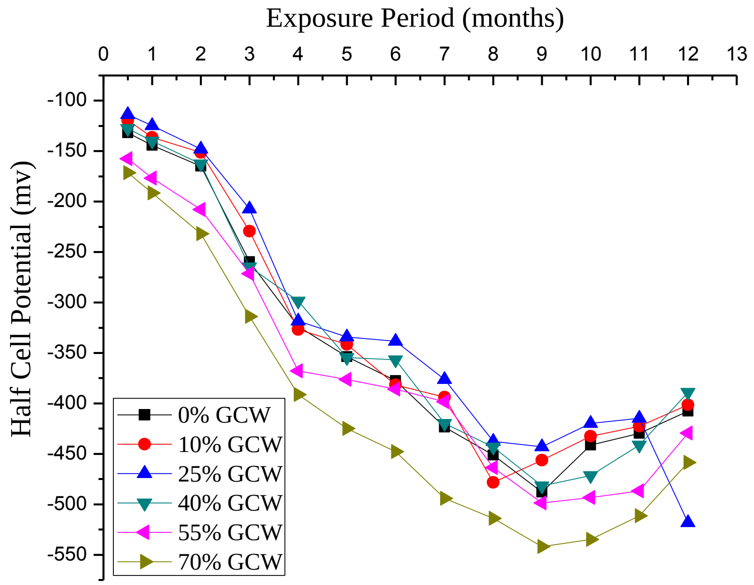


Figure 4.43: Half-cell Potential v/s Exposure period for w/c 0.55 concrete mixes (ASTM limit <350 mV No corrosion)

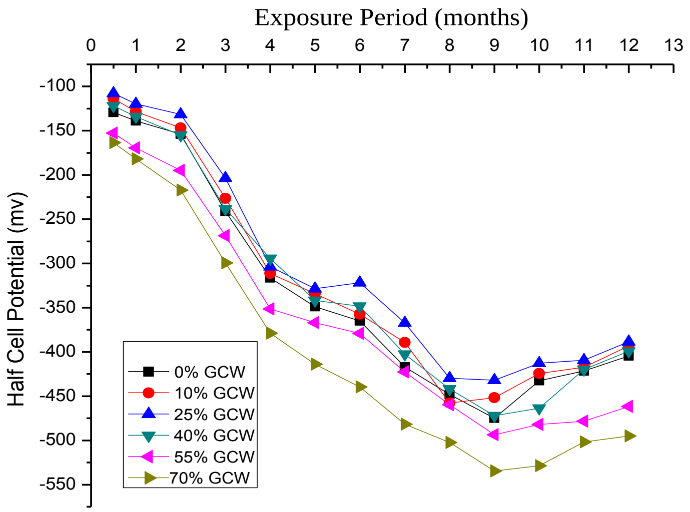


Figure 4.44: Half-cell Potential v/s Exposure period for w/c 0.50 concrete mixes

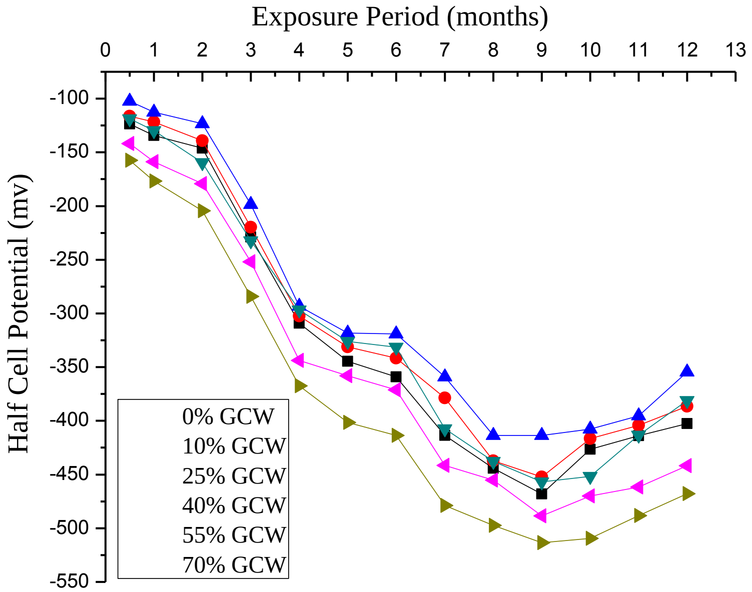


Figure 4.45: Half cell Potential v/s Exposure period for w/c 0.45 concrete mixes

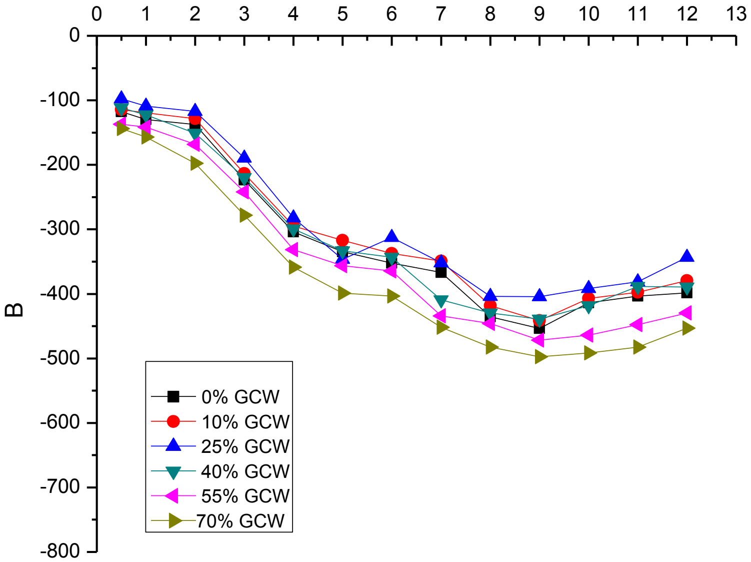


Figure 4.46: Half cell Potential v/s Exposure period for w/c 0.40 concrete mixes

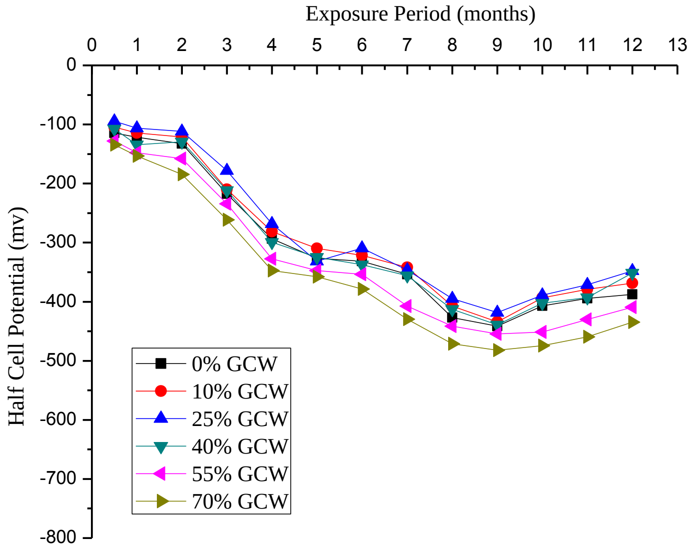


Figure 4.47: Half cell Potential v/s Exposure period for w/c 0.35 concrete mixes

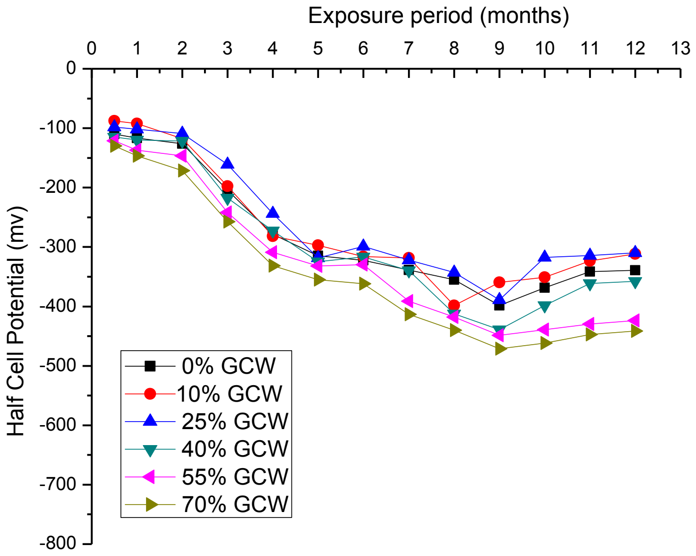


Figure 4.48: Half cell Potential v/s Exposure period for w/c 0.30 concrete mixes

It was observed that the time taken to attain a potential value more negative than -350mV was equal to or slightly higher for low w/c ratios as compared to the higher w/c ratios. The slight increase in the initiation of more negative potential than -350mV reassures the fact that with increase in w/c ratio there was a slight decrease in the porosity of the concrete matrix thus inevitably increasing the susceptibility to the corrosion. The time taken was maximum in case of 25% replacement in all the series indicating the significant enhancements in the properties of the concrete matrix at this replacement.

An important observation can be made from the results of micro-cell current and half-cell potential measurement. After attaining a maximum value a decrement in the values of both of these parameters was observed. Similar trend was observed by Bhavna Tripathi & Sandeep Chaudhary (2015). This was attributed to two reasons. First one being the retardation offered in the flow of current by the corrosion products. Second being interruption in the flow of electrons due to non-availability of electrons caused by the saturation of pores with water.

4.4.1.3 Corrosion-Rate

Figure 4.49: Broken corrosion specimen for visual examination

The end of electrochemical monitoring was followed by the visual inspection of the anode bars that were embedded in the concrete. All the anode bars were chemically cleansed before the visual inspection for corrosion activity. Reddish Brown corrosion product ,$Fe_2O_3 . H_2O$ was taken as the prime indicator of corrosion in the anode bars. However few bars also showed the presence of black coloured corrosion products as distinct separate patches at different locations of the bars. Similar products have been reported by the Shalon and Raphael (1959) & Broomfield (2007). This may be due to the lack of availability of oxygen despite alternate wetting and drying cycles.

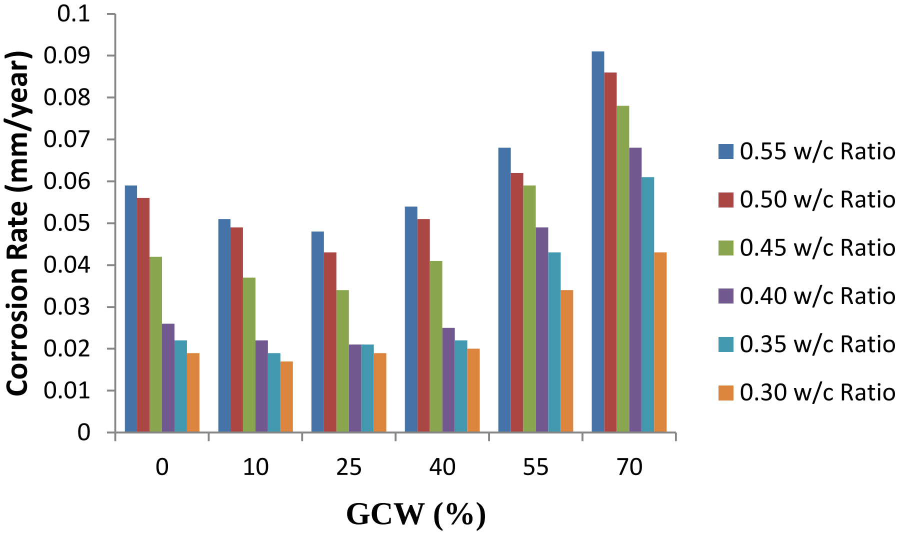


Figure 4.50: Corrosion Rate of steel bars

The visual examination revealed the presence of different amounts of corrosion products in different bars. Fig30 represent the corrosion rate in mm/year Vs percentage GCW content for the different w/c ratios. It can be readily observed from the figure that at any given percentage replacement the corrosion rate was invariably higher at higher w/c ratio. The corrosion rate was found to be lesser than or almost similar to the control concrete upto 40% replacement. As soon as the percentage replacement increased beyond 40% a steep rise in the value of corrosion rate can be observed from the graph for all the w/c ratios.

Overall from the results of micro-cell current, half-cell current and corrosion rate it can be unilaterally established that any increase in the w/c ratio led to increase in the corrosion rate. Also the concrete mixes with replacement upto 40% GCW content exhibited similar or better resistance than the control concrete for all the w/c ratios.

4.5 Microstructure of concrete

The microstructural analysis of concrete was carried out in conjunction to the strength and durability assessment tests in order to develop a deeper understanding of the various parameters affecting the properties of GCW concrete. The SEM and XRD analysis were carried out in order to study the nature and type of hydration products and chemical constituents of GCW concrete respectively. The SEM and XRD analysis of all the w/c ratios involved similar reasoning and trends and therefore for the sake of simplicity and clarity the results of 0.4w/c ratios have been included in the results and discussion as follows:

SEM & XRD ANALYSIS

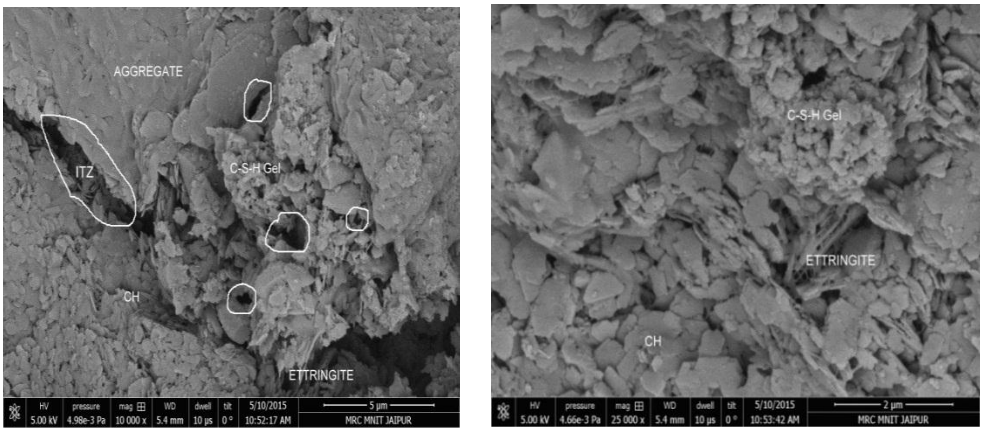
XRD and SEM analysis of control mix (CM) and mixes with different percentages of Granite Cutting Waste (GCW) was carried out to investigate the microstructure of concrete which helps in determining the reasons for variation in strength and durability of concrete.

4.5.1 SEM Analysis

Scanning Electron Microscopy (SEM) plays an important role in examining concrete samples at micro-structural level. At macro-level, two phases are observed in concrete namely aggregate phase and cement paste phase whereas in microstructure examination a new zone, called Inter-facial Transition Zone or ITZ is also observed (Mehta and Monteiro, 2006). ITZ is the weakest zone and hence it becomes extremely important to closely examine this zone so as to explain mechanical properties of concrete which would otherwise be very difficult to explain (for example, compressive strength of concrete). Microstructure of concrete is heterogeneous and very complex to understand. C-S-H (calcium–silica–hydrate) is most important phase of the cement-aggregate matrix and there are various factors which influences the mechanical behaviour of C-S-H phases such as size, shape, distribution and concentration of particles, composition of phases, orientation of particles in the matrix etc.

After 28 days, tests analysis of concrete specimens under Scanning Electron Microscopy(SEM)was carried out so as to obtain the SEM images (micrographs) of all G mixes from (G0-G55). Analysis of SEM images is done by assuming the dark portion to be voids and long continuous black portion to be ITZ. Also, CH or $Ca(OH)_2$ crystals (calcium hydroxide or portlandite) are assumed to be large crystals with a hexagonal-prism morphology whereas aggregation of small fibrous crystals in the images stands for C–S–H gel/ paste (Mehta and Monteiro, 2006). Moreover, bright particles are inert aggregates, long whisker like particles are ettringite crystals (present in relatively small amounts in all the mixes) and lastly the medium bright small particles over coarse aggregate and at ITZ stands for GCW fines. These assumptions are made based on the fact that the basic structure of the concrete in all the samples is the same i.e. only CM is kept constant whereas in all the G mixes different percentages of GCW fines is added as partial replacement of FA.

G0 Mix



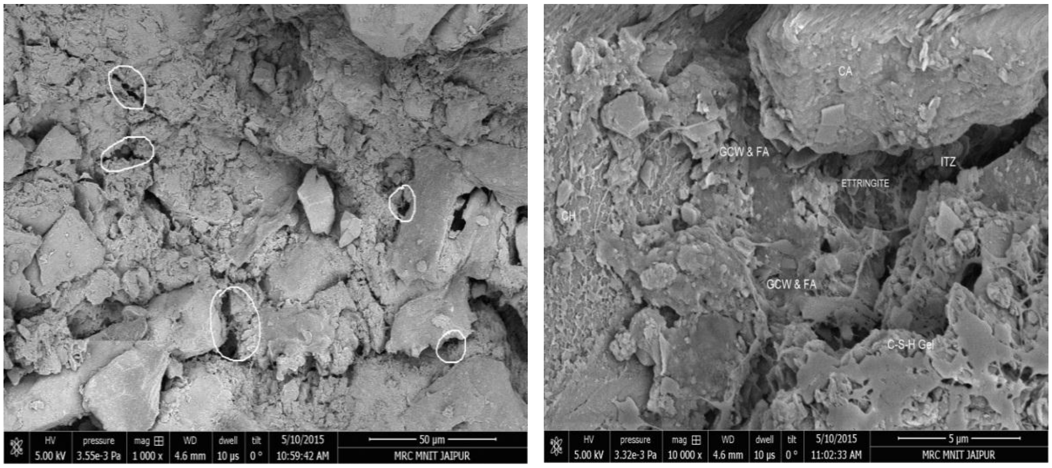
(a) **(b)**

Figure 4.51(a),(b). Micrograph of Control Mix [CM or G0 mix] at 10K X and 25KX

Fig. 4.51(a) shows the SEM image or micrograph of control mix (G0) at 10 KX magnification. The gel formation is visible in the micrograph. The encircled dark portions represents the voids and ITZ, fibrous portion of the SEM image indicates C–S–H gel and hexagonal plate-like particles are CH crystals (well crystallized $Ca(OH)_2$ crystals) which are present in large amounts (Poon et al., 2004) and finally, inert aggregates (both fine and coarse) are also spotted in the image (clearly marked on the image). Large pores are also observed at the interfacial transition zone of cement and aggregate. C–S–H gel & CH crystals are distributed over the aggregates and ITZ (Poon et al., 2004). C-S-H gel acts as a binder for aggregate-cement matrix. SEM image also shows lesser amount of C-S-H gel and whisker-like ettringite, at and near the ITZ. SEM image at 25 KX magnification [Fig. 4.51 (b)] clearly demonstrates well- crystallized CH crystals (in large amount) along with fibrous C-S-H gel and elongated ettringite in relatively smaller concentration.

Above explanation of SEM images can be clearly understood from the fact that, after 28 days, as the hydration progresses, poorly crystalline C-S-H and smaller crystals of ettringite and calcium hydroxide (CH crystals) start filling the empty voids that exists between the framework created by the large ettringite and calcium hydroxide crystals, which were formed in earlier stages of hydration reactions. This helps in enhancing the density and hence the strength of the Interfacial transition zone (Mehta and Monteiro, 2006).

G10 Mix



(a) **(b)**

Figure 4.52(a),(b). Micrograph of G10 mix at 1 KX and 10 KX

SEM images of G10 mix at 1KX and 10KX magnification [Fig.4.52 (a), (b)] clearly depicts some major features such as the reduction of number of bigger voids compared to CM and distribution of C-S-H gel (at few places) such that it leads to an increase in strength of concrete (by relatively small amount). This clearly indicates that GCW fines are showing a positive response in terms of enhancement of strength of concrete. But, increase in concrete strength is not very significant as the optimum amount of GCW content is not present in this mix which means optimum compaction and density of matrix is not achieved. SEM image of 10KX magnification also shows deposition of CH crystals and C-S-H gel over aggregates in concrete mix with a larger concentration of C-S-H gel near ITZ. Lesser proportion of ettringite is also observed in the image. Also, growth of CH is not much affected by addition of GCW as the replacement percentage in this mix is less compared to other G-mixes.

G25 Mix

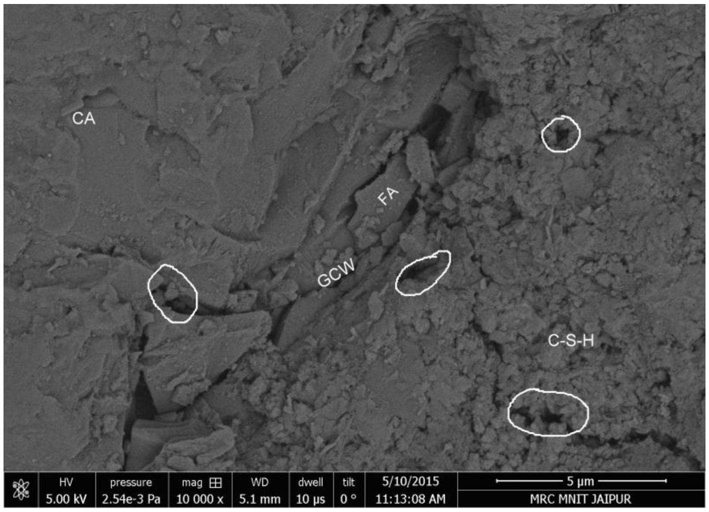
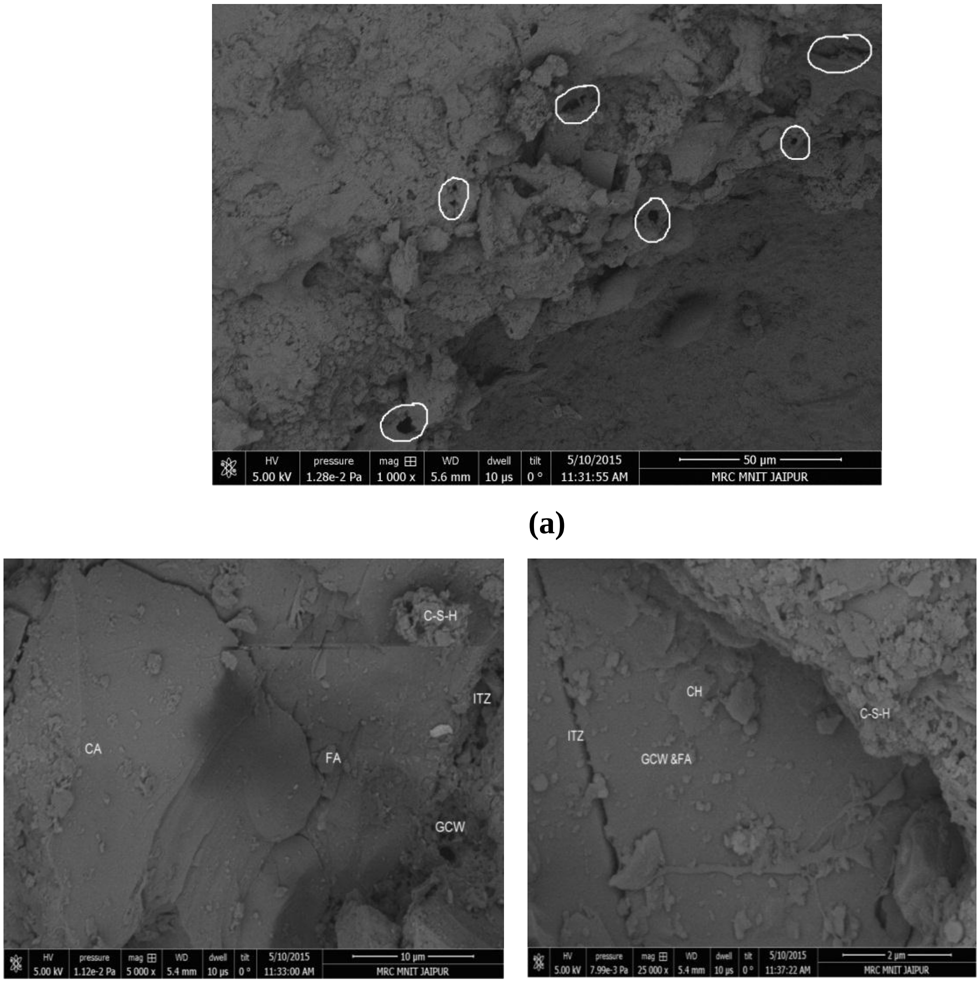


Figure 4.53: Micrograph of G25 mix at 10 KX

Micrograph of G25 mix at 10 KX magnifications [Fig. 4.53] clearly shows a much more reduction in voids and thickness of ITZ mainly because of the occurrence of greater amount of GCW particles (distributed throughout the image) as GCW content is increased to 25%. Thus, matrix of G25 mix is relatively more compact and denser compared to previous mixes. Moreover, C-S-H gel is observed near the ITZ in addition to relatively higher amount of CH crystals. GCW fines and FA (Fine Aggregate) are clearly visible at ITZ and are also distributed on CA (Coarse Aggregate) as well as in the other portions of the image. Lesser amount of ettringite is visible in SEM images. In this mix, distribution and amount of C-S-H gel is much better than previous mixes and this might have increased the strength of G25 concrete mix compared to G0 and G10 mixes.

G40 Mix



(a)

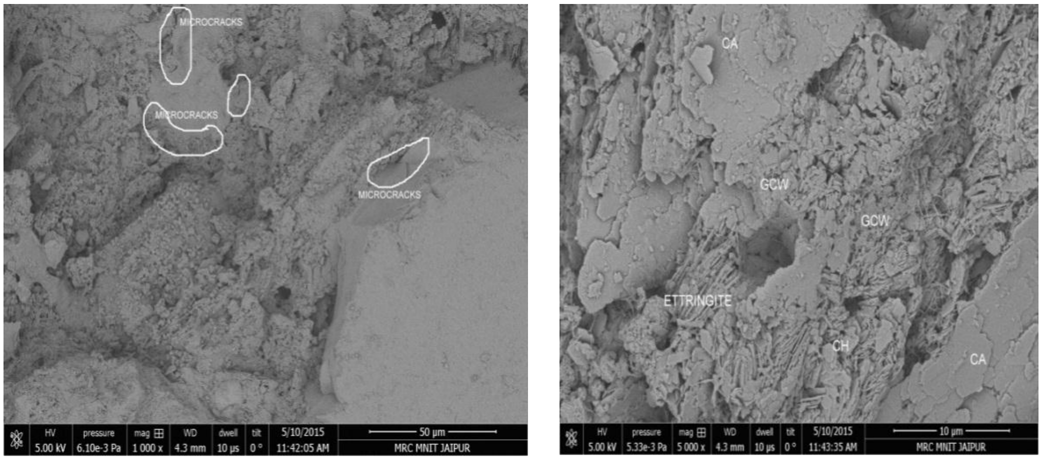
(b) **(c)**

Figure 4.54 (a),(b),(c). Micrograph of G40 mix at 1 KX, 5 KX and 25 KX

Fig. 4.54 shows the SEM images of G40 concrete at different magnifications. Fig. 4.54(a) shows micrograph of G40 mix at 1 KX magnification. This micrograph shows that throughout the sample the paste has spread finely and also the paste firmly binds the matrix. Moreover, matrix has become denser and more compact as the voids are less. Proper distribution of C-S-H gel and GCW, in addition to their larger concentration has led to a high strength concrete with strength even higher than all the G-mixes and control mix. Thus, G40 mix has the highest strength because of the optimum GCW content as well as better distribution and formation of C-S-H gel in the matrix. This indicates that there is a perfect blend of all components in the mix and perfect reactions must have taken place during the production of this concrete mix.

SEM images of G40 mix at 5 KX and 25 KX magnification [Fig. 4.54 (b), (c)] depicts the presence of CH crystals and C-S-H gel near ITZ as well as on the aggregates. Also, the thickness of ITZ is very less because of the fact that matrix has become denser, compact and less porous due to an optimal amount of GCW fines.

G55 Mix



(a) **(b)**

Figure 4.55 (a),(b). Micrograph of G55 mix at 1 KX and 5 KX

SEM images of G70 mix closely resembled those of G55 mix and therefore have been omitted here for facilitating clear and simple presentation of the results.

SEM images of G55 mix at 1 KX magnification [Fig. 4.55 (a)] clearly shows a large amount of loose and bigger GCW particles which are distributed throughout the matrix and are distinctly visible. Moreover, increased percentage of GCW particles has disrupted the binding action of the gel/paste and thus, resulted into a weak and porous microstructure of concrete. All this has led to a significant reduction in strength of concrete mix, which is even lesser than CM.SEM image at 5KX magnification [Fig. 4.55 (b)] shows the presence of GCW particles in ITZ, voids, around ettringite and CH crystals and hence these particles cause hindrance in the functioning of C-S-H gel which is of prime importance in increasing strength of concrete mix. Also with higher GCW content, the distance between these particles decreases, so the $Ca(OH)_2$ crystal cannot grow large enough because of limited space and this leads to a relative decrease in the quantity of CH crystals. Thus, CH crystal to gel ratio becomes small and the matrix becomes relatively looser. Some micro-cracks and pores are also visible (marked on image) in the matrix because of higher density of GCW particles. Although C-S-H gel is in good amount but GCW particles hamper the growth of C-S-H gel because of the congestion and less availability of space in the matrix (Siddique et al., 2011). Whisker like ettringite is also visible in the image and is densely surrounded by GCW. Thus, G55 mix has minimum strength out of all the G-mixes.

Therefore, a close examination of SEM images of G10, G25, and G40 at different magnifications shows that ITZ becomes denser as we move from G0 to G40 mix and a decrease in porosity of aggregate-cement matrix is also observed, which can be understood from the fact that the percentage of granite fine content (GCW) is increasing relatively. Number of irregular shaped small sized pores decreases by larger amount as the content of granite fines increases from 10 to 40%. Moreover, SEM images of G55, shows that apart from large amount of CH and ettringite crystals, there is an excessive amount of free granite fine content which hinders the binding action in cement-aggregate matrix and hence increase of GCW content beyond 40% adversely affects the strength of concrete mix.

SEM analysis of G-mixes also implies that replacement of FA (sand) by GCW beyond 40% leads to flaws in concrete. Thus, best mix out of the all concrete mixes is G40 mix. G40 mix has highest strength, dense microstructure, and formation of large amount of fibrous C-S-H gel which apart from strength development, also decreases the permeability of the cement-aggregate matrix and thus making the concrete mix more water resistant which is also observed in water permeability test. Moreover, optimum Ca/Si ratio is obtained in this mix which clearly means better reaction between CaO and SiO_2. This means that C-S-H gel formation is optimal in this mix.

4.5.2 XRD Analysis

X-ray diffraction tests helps in determining the relative intensities of the peaks in XRD patterns. The diffraction patterns are used to compare the mineralogical nature (Bacarji et al., 2013) and compositions of the test samples (concrete mixes). Compositional analysis of concrete mixes was carried out using XRD technique. Powdered samples were used for the study of microstructure of matrix using XRD.

The X-ray diffraction pattern and analysis of the concrete mixes i.e. control mix (CM), and GCW concrete mixes (G mixes- G0,G10,G25,G40& G55) at 28 days are shown in Fig. 4.56 (a)-(e). XRD images of G70 mix closely resembled those of G55 mix and therefore have been omitted here for facilitating clear and simple presentation of the results.

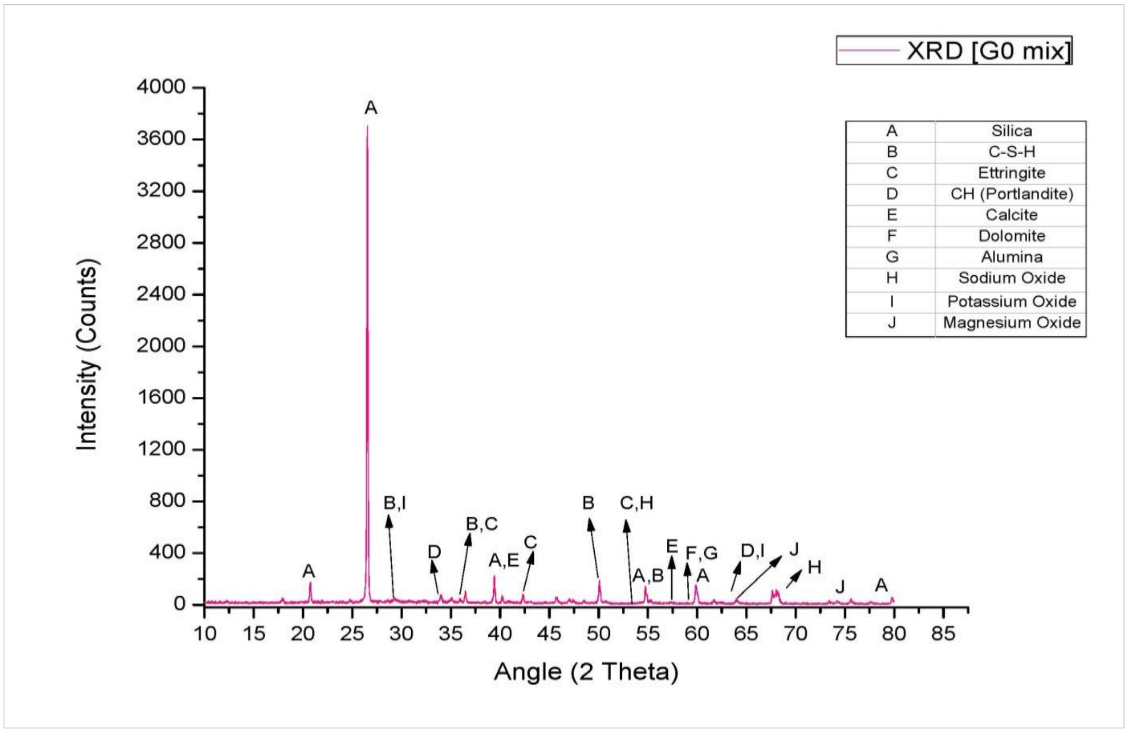


Figure 4.56 (a).

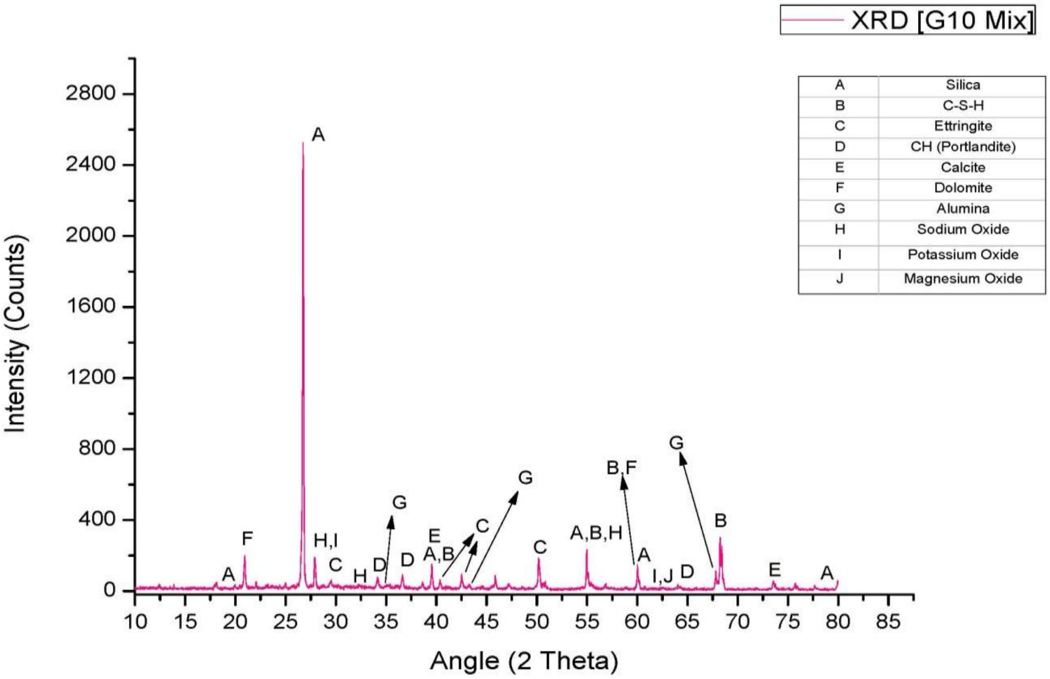


Figure 4.56 (b).

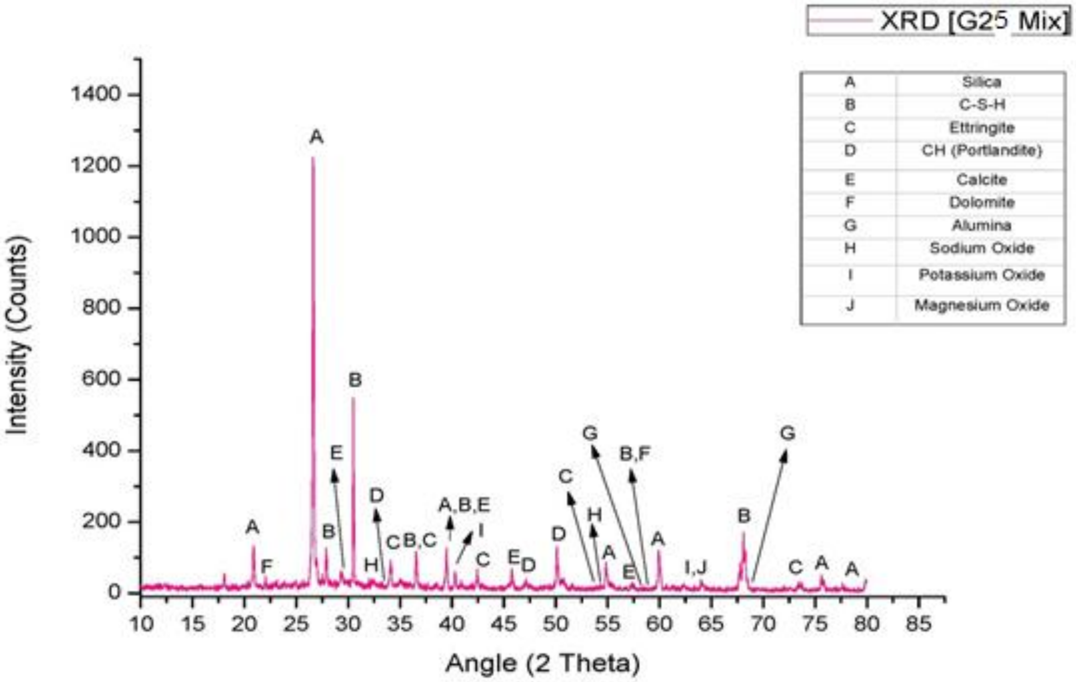


Figure 4.56 (c).

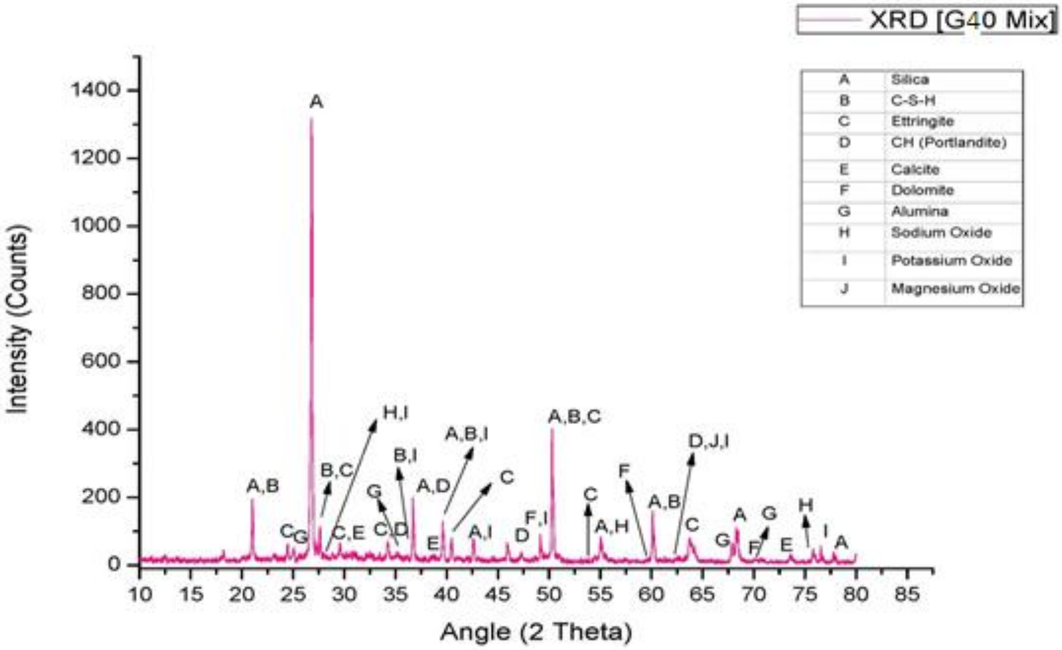


Figure 4.56 (d).

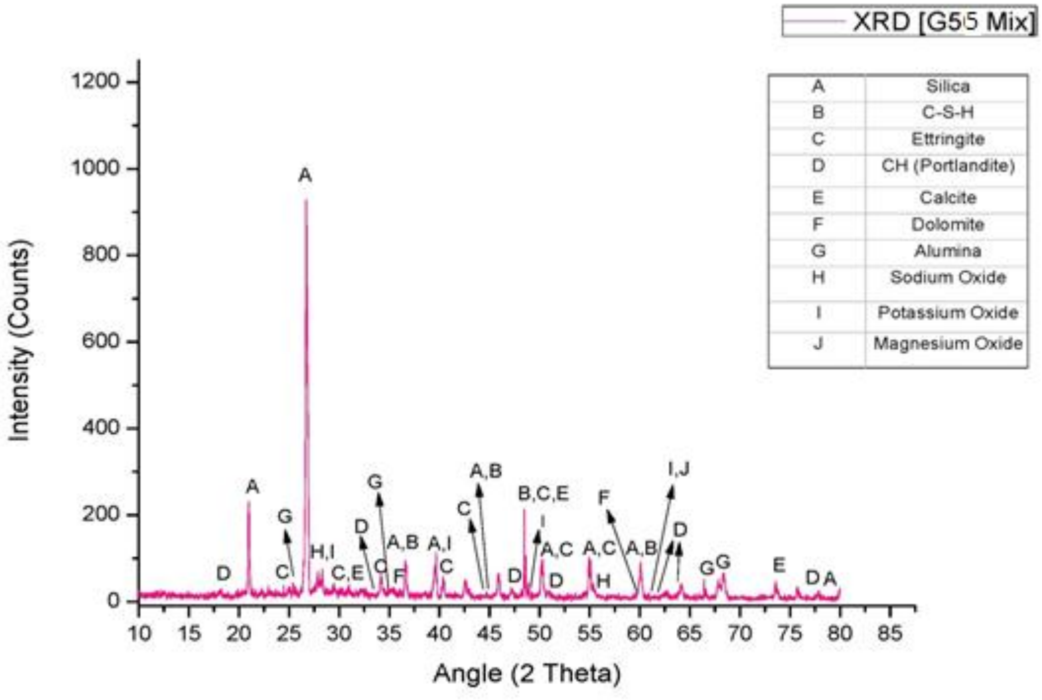


Figure 4.56 (e).

Figure 4.56: XRD diffraction patterns of various concrete mixes

Intensity vs angle diffractogram of all the G mixes in Fig. 4.56 (a)-(e), shows that the peaks of C_2S, C_3S, and C_4AF are not visible which clearly indicates that these compounds are fully consumed after 28 days.

Effect of Silica

XRD analysis of G0 shows that the peak of free silica (SiO_2) was obtained at 3676.89 (at 2θ= 26.53°) and the peak value or intensity (counts or cts) value of free silica for the G10 mix is 2503.95, obtained at 26.7321° which is relatively closer to peak value of G0 mix i.e. 3676.89 at 2θ =26.53°. This is because of addition of a nominal amount of GCW in G10 mix compared to CM and other G mixes. Also, a significant variation in peak values for G10, G25, G40 and G55 mixes was observed because of increased amount of GCW content in these mixes. In case of G25 mix, intensity or peak value decreases to 1203.80 (at 2θ=26.636°) whereas for G30 mix the peak value was 1315.59 (at 2θ= 26.813°). Finally, the peak value for G50 mix was 889.12 (at 2θ= 26.706°). Moreover, experimental results of compressive strength of G25 mix comes out to be maximum out of all G mixes which clearly means that optimum utilisation of silica has taken place for maximum C-S-H gel formation that resulted into enhanced binding action of the cement- aggregate matrix.

Silica has a positive impact over strength generation of concrete because it reacts with most of the calcium hydroxide which is formed (during hydration reaction) within 28 days. This improves the compressive strength of concrete. Reaction of silica with CH formed around sand particles and also with the CH dispersed throughout the paste, affects the pore size distribution of the matrix. Also, Ca/Si ratio of C-S-H decreases as the content of micro silica increases which ultimately affects the compressive strength of concrete (Nazari and Riahi, 2011). In addition to this, presence of small particles of SiO_2 helps in improving the porous structure of concrete as these particles gets uniformly distributed in cement-aggregate matrix. Thus, presence of SiO_2 affects compact packing and density of cement- aggregate matrix in concrete and hence their relative amounts in concrete mixes (from G0-G55) affect the compressive strength of the mixes. Optimum amount of SiO_2(having a positive influence) is obtained at 30% replacement of FA by GCW with compressive strength being maximum of all the mixes whereas 50% replacement leads to adverse effect on the compressive strength as it comes out to be even less than that of CM. This can be explained by the fact that the increase in GCW percentage beyond 30% leads to a reduction in binding action of cement and aggregate as contact area of GCW becomes higher than the desired level. Also, with higher GCW content (beyond 30%), the distance between SiO_2 particles decreases, so the $Ca(OH)_2$ crystal cannot grow large enough because of limited space and this leads to decrease in the quantity of CH crystals. Thus, CH crystal to C-S-H gel ratio becomes small and the porous structure of the matrix becomes relatively looser (as some micro cracks are also visible in SEM images [Fig. 4.55 (a)]). Moreover, an optimum amount of GCW indicates optimum amount of SiO_2 particles which not only helps in making dense and compact matrix but also enhances cement hydration (in early stages of concrete production) because of high activity of these particles.

Effect of C-S-H (Calcium Silicate Hydrate)

Calcium silicate hydrate is the most important product of hydration reaction. It governs the overall strength of concrete as it binds the cement and aggregates into a compact matrix. Higher concentration of C-S-H gel leads to higher compressive strength of concrete (The Science of Concrete, 2015). XRD analysis of G mixes shows the diffraction peaks of C-S-H gel at different 2θ positions. Also, the mixes with varying percentage of granite cutting waste (Fig. 4.56), contains different amounts of C-S-H gel indicated by the number of peaks of C-S-H gel in the diffractograms. G40 mix has a large number of C-S-H peaks, but the relative intensities of these peaks are lower compared to CM (control mix) as well as other G mixes. This can be easily observed in the diffractograms. Some important high intensity peaks of C-S-H in G30 mix (beyond 26° 2θ), with intensities equal to 52.473, 111.225, 393.122 and 146.98 are observed at 2θ equal to 29.588°, 39.619°, 50.301°, and 60.124° respectively. For CM, some prominent peaks with intensity equal to 31.502, 208.539, 18.698 and 136.891 cts, are observed at 29.294°, 39.409°, 48.478°, and 59.846° 2θ positions.

As compared to $Ca(OH)_2$, the concentration of C-S-H gel is higher in all the G-mixes. Higher concentration of C-S-H is preferable as $Ca(OH)_2$ doesn’t contributes much in strength development of concrete (The Science of Concrete, 2015). Moreover, optimal concentration of C-S-H gel is present in G40 mix compared to G10, G25 and G55 mix and this is the main reason behind higher compressive strength of G30 mix. This is also observed in SEM analysis of G mixes with G40 having a dense and compact matrix and with a proper distribution of C-S-H gel at various portions of the image. In addition to C-S-H crystals, compressive strength of concrete mix is also dependent on relative concentration of whisker-like ettringite and well crystallized $Ca(OH)_2$ crystalscommonly called as portlandite. Diffractograms of all concrete mixes are closely examined and it clearly shows the diffraction peaks at different positions which indicates the presence of the compounds such as ettringite, and portlandite [$Ca(OH)_2$].

Effect of Ettringite

In fresh and plastic concrete, most of the sulphates present in cement is converted into primary ettringite crystals and this mechanism mainly controls the stiffening of matrix. After 28 days, dissolution and recrystallization of bigger ettringite into large number of small and whisker-like crystals, called secondary ettringite crystals, takes place in the cracks and spaces in cement-aggregate matrix (Portland Cement Association, 2015). This helps in reduction of voids in the concrete, resulting into a compact matrix which ultimately helps in increasing durability of the concrete (Portland Cement Association, 2015).

In SEM analysis, relatively higher amount of needle-shaped ettringite crystals are observed in G mixes compared to CM. This is because of better dispersion of cement particles around granite fines which may have increased the reaction rate and thus, accelerated the occurrence of ettringite in concrete mixes after 28 days. XRD analysis of G mixes (in Fig. 12) clearly shows the relative diffraction peaks of ettringite. For G0 to G50 mix intensity in counts per second are 164.82, 79.918, 75.292, 393.12 and 203.756 respectively. 2θ position of these peaks are 50.076°, 42.529°, 34.114°, 50.301°, and 48.48° respectively. Also, in case of G40 mix, more number of peaks are observed around 26° 2θ (in addition to peaks at other angles), as compared to other mixes. Moreover, G30 mix has a highest peak (393.12 cts) as well as large number of diffraction peaks of ettringite which means that concentration of ettringite crystals is highest in G30 mix (among all G mixes). This implies that the number of voids / empty spaces is very less in this mix, thus resulting into dense and compact matrix which leads to a high compressive strength of G30 mix. This is also observed in SEM image of G40 mix at different magnifications.

Effect of CH crystals (Portlandite)

In case of G0 concrete mix, XRD patterns of 28 day old samples shows that well crystallized CH layer is in high concentration at the interface of cement-aggregate, and higher peak intensity of 90.88 cts (counts per second) at 36.499° 2θ. Moreover, intensity (counts) vs 2θ diffractograms shows a higher proportion of C-S-H gel at 26.526° and 40.244° 2θ positions. For G10 mix, peak value of CH i.e. [$Ca(OH)_2$] was observed to be 81.85 at 36.639° 2θ which is slightly lower than that of G0 mix. Moreover, peaks of G20, G30 and G50 were observed to be 104.84, 187.16, and 77.04 respectively. All these peaks were observed around 36° 2θ. For G40 mix another prominent peak of 17.46 cts was observed at 28.889° 2θ which was neither observed in CM nor in any other G mix.

In general, contribution of CH in strength and non-permeability of concrete is less as it fills up the voids or reduces the pore volume by converting the liquid water into solid form i.e. crystal form (The Science of Concrete, 2015). Hence, G40 mix (with high CH peak value) has more strength as well as least permeability out of all mixes. The only drawback of higher CH content is that it decreases the durability of concrete (The Science of Concrete, 2015). XRD analysis of G40 mix shows that the number of peaks and hence, the concentration of CH crystals are less in G40 mix compared to the other mixes. But, above all, amount of C-S-H content is most important criteria for determining strength of concrete i.e. higher amount of C-S-H clearly indicated higher compressive strength of concrete. Also, the concrete mix with highest C-S-H/CH ratio has highest compressive strength.

Effect of Calcite, Dolomite and Alumina

XRD analysis of G mixes also shows the predominance of calcite [$CaCO_3$] and dolomite [$CaMg(CO_3)_2$] peaks with G40 having most number of peaks corresponding to $CaCO_3$ and dolomite, as compared to all the other concrete mixes. For $CaCO_{3,}$ observed highest peak values are 208.54, 142.32, 115.119, 111.23 and 203.756 cts (around 39° 2θ) corresponding to CM, G10, G20, G30, and G50 mixes respectively. Whereas for Dolomite, highest peaks are 136.891, 119.034, 109.433, 393.12, and 71.97 cts (around 59° 2θ) corresponding to CM, G10, G20, G30, and G50 mixes respectively. Also, minimum peak of calcite as well as maximum peak of dolomite is observed in case of G40 mix. Since, number of peaks of calcite and dolomite are less hence these compounds are present in small amount compared to silica, and C-S-H crystals. Therefore, calcite and dolomite does not have significant influence on performance of concrete.

In general, higher alumina content has a positive influence on initial compressive strength but it weakens the long term strength of concrete (Ramachandranand Beaudoin, 2008). GCW consist of only 15.63% alumina which does not play any predominant role in strength development of concrete. XRD analysis of all G mixes shows that peaks of alumina varies insignificantly with changes in GCW content. Moreover, alumina content is also very less in comparison to silica (as number of peaks are less). So, alumina does not affect 28 day compressive strength of concrete. Also, amount of alumina (peak value= 97.89 cts at 2θ=68.266°) detected in G40 mix is less in comparison to all other G-mixes.

Effect of Alkali oxides (Na_2O and K_2O) and Magnesium oxide [MgO]

XRD analysis shows that in case of Na_2O compound, highest peak for G0 to G55 mix are 130.42, 211.149, 109.625, 101.729 and 94.722 cts respectively. Highest peaks for G0, G10, and G55 occur around 54° 2θ whereas for G25 and G40 mix highest peaks are observed around 26° 2θ. In case of K_2O, similar trend is observed. Also, more number of peaks is located near 26° 2θ in case of G40 and G55 mix as GCW content is increasing. But these trends cannot clearly depict the effect of alkali oxides on concrete strength as alkali oxides are present in very less amounts in GCW as compared to silica. In general, larger amount of alkali oxides i.e. Na_2O and K_2O, diminishes the rate or degree of hydration reaction during concrete production which in turn affects the 28 day compressive strength of concrete (Ghosh, 2003).

A large quantity of free magnesia (MgO) leads to unsoundness in Portland cement (Ghosh, 2003), so lesser proportion of free MgO is preferable in cements so as to avoid unsoundness to a larger extent. Moreover, free magnesia has no significant contribution towards development of compressive strength of concrete (Ghosh, 2003). XRD analysis shows that in all the mixes, peaks of magnesia or Magnesium Oxide are very less and quantity of magnesia is insignificant and hence, magnesia does not have any significant role in strength development of concrete mix.

4.6 TGA (Thermo-gravimetric Analysis)

Thermogravimetric Analysis involves exposing the sample concrete (powdered form) to elevated temperatures and the corresponding loss in mass reflects the amount of hydration products present. The strength and other durability parameters depend significantly on the extent of hydration of the concrete and therefore results of thermogravimetric analysis can be taken as a crucial indicator for the quality& performance of the GCW concrete.

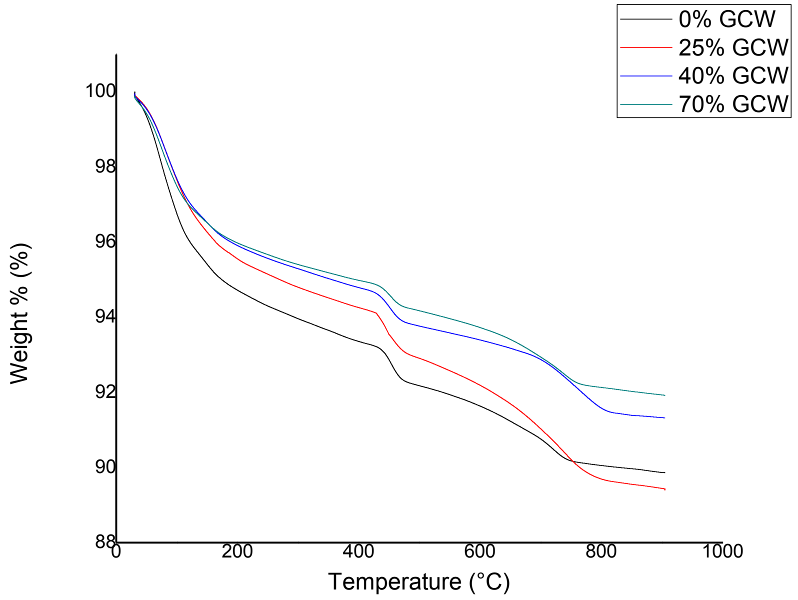


Figure 4.57: TGA curves for concrete specimen v/s temperature

Fig displays the percentage weight loss observed v/s increments in temperature for the specimens with varying percentages of percentage GCW content for 0.4w/c ratio. It was observed that as the percentage GCW replacement increases the corresponding weight loss for the specimen decreases .This can be attributed to the fact that with l increase in the percentage replacement of GCW beyond optimum percentage, the extent of hydration decreases which in turn may be associated with the higher value of CaO: SiO_2 ratio.The CaO: SiO_2 ratio increases as the percentage GCW replacement increases (Watcharapong Wongkeo and Arnon Chaipanich, 2010). This explains the gradually poor hydration trend observed as the percentage GCW replacement increases .The decreasing peak areas of the TGA curves for the C-S-H ,ettringite peak (peak at about 105°C) at higher replacement reassures the fact of gradually decreasing hydration extent with increasing percentage GCW content. Fig 16 depicts the DTG curves obtained for control concrete specimen and concrete specimens with varying GCW percentage content. Each curve displays three major endothermic peaks signifying corresponding major weight losses at these temperatures. The first major endothermic peak was obtained at about 105°C corresponding to the calcium silicate hydrates, mainly C-S-H(I) and minor amounts of ettringite.

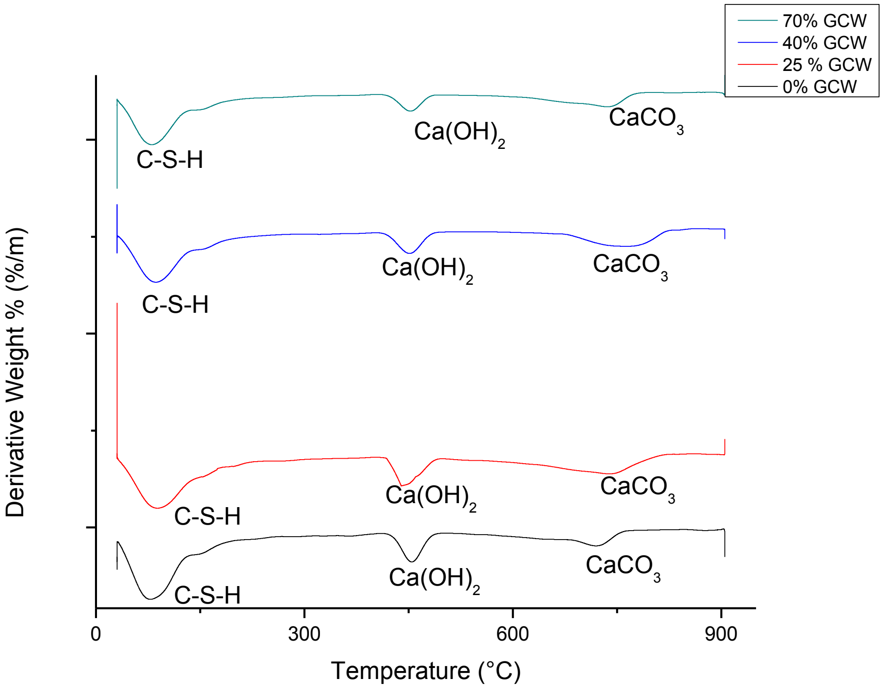


Figure 4.58: DTG curves for Concrete Specimens v/s Temperature

The second endothermic peak observed at about 450°C signifies the dehydroxylation of portlandite ($Ca(OH)_2$).The third endothermic peak was observed for the specimens in the range 700°C to 800°C corresponding to the breakdown of $CaCO_3$ and its amorphous form. The TGA and DTG curves for the specimens with all other w/c ratios exhibited similar trend.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

- **Rheological Properties**
- **Strength Properties**
- **Abrasion**
- **Durability Properties**
- **Microstructure (SEM and XRD)**
- **TGA (Thermo-gravimetric Analysis)**
- **Recommendation**

The use of industrial waste in concrete offers the possibility of the addressing the seemingly mind-boggling problem of eco- friendly disposal. Over the past few years, use of stone waste in concrete has been a hot topic of research. There have been ample studies conducted across the globe on assessing the feasibility of marble as a potential substitute for fine aggregate in concrete. However, the research on examining the potential of Granite Cutting waste in concrete has been limited in terms of in depth discussion about the effect of Granite on Durability and Microstructural aspects besides Strength properties. The present study aims at assessing the aforementioned attributes of Granite Substituted Concrete comprehensively. The entire experimental setup has been kept quite exhaustive in terms of a wide range of w/c and percentage replacements of fine aggregate by Granite Cutting Waste. The specimens were prepared for the two series of w/c. The first series comprised 0.55, 0.50 and 0.45w/c while the second series included 0.40, 0.35 and 0.30w/c. The percentage replacements made for each of the w/c were 0%, 10%, 25%, 40%, 55% and 70%. The effect of Granite Cutting Waste on the setting time and workability was studied. The impact on strength properties was assessed in terms of compressive strength, split tensile strength and flexure strength. The study included detailed study of long term durability parameters including carbonation, acid-attack, sulphate attack, chloride penetration and corrosion. In order to assess the changes in microstructure of granite substituted concrete, discussion of SEM and XRD analysis has been included.

Following are the conclusions of the study conducted:

5.1 Rheological Property

5.1.1Workability:

The workability of the Granite Substituted concrete was lesser than the control concrete and it was observed that the workability decreased with increase in the percentage replacement for all the w/c ratio. The loss of workability can be easily recovered with the application of new generation super-plasticizers.

5.2 Strength Properties

5.2.1 Compressive –Strength

1) Upto a certain optimum percentage replacement the use of Granite substituted concrete enhanced the compressive strength of the concrete as compared to the control concrete. The compressive strength started decreasing for substitution beyond this optimum replacement attaining even lesser value than the control concrete at very high percentage replacements.
2) For 0.3w/c the optimum percentage replacement was found to be 25% . The optimum percentage replacement for all other w/c was found out to be 40%.A significant decrement was observed in the value of compressive strength beyond 40% for all the w/c.
3) The same trend was observed for the compressive strength measurements at 7d, 28d and 90d.

5.2.2 Flexure-Strength and Pull-Off Strength:

1) The flexure strength and Pull –Off strength results followed the same trend as the compressive strength. The flexure strength was found to be either same or slightly higher than the control concrete at 7d, 28d and 90d for all the w/c ratios upto 40% replacement. Similar trend was observed for the Pull-Off strength at 28d.
2) Therefore Optimum substitution of Granite Cutting Waste in concrete leads to the enhanced strength properties.

5.3 Abrasion

The abrasive resistance of the Granite Substituted concrete was found to be enhanced upto optimum percentage replacement. For 0.3w/c ratio and all other w/c ratios the optimum percentage replacement was found to be 25% and 40% respectively. It was found that at a particular replacement percentage the abrasive resistance improved with the decrease in the w/c ratio. The mean value of wear was found to be within the permissible limits as specified by the Indian Standards for concrete tiles to be used in General purpose buildings. The results suggest the feasibility of using GCW concrete in applications of high abrasive resistance such as tiles, paving blocks, rigid pavements etc.

5.4 Durability Properties

5.4.1 Permeability and Water Absorption:

- It was observed that the permeability and water absorption of the Granite substituted concrete was less than the control concrete for all w/c ratios and at all percentage replacements. The minimum permeability was observed at 70% and 55% replacements for series first and series second respectively.IS:15658-2006 specifies the permissible limit for water absorption for concrete paving blocks as 6%.It was found that water absorption for all the concrete mixes was less than 6% at all percentage replacements. Most of the deleterious chemicals such as chlorides, sulphates, alkalis use water as a transport medium to get into concrete. The use of less permeable GCW concrete might enhance the service life and durability of concrete significantly.

5.4.2 Carbonation

For all the w/c ratios except 0.3 w/c, the carbonation depth was found to be lesser than the control concrete upto 40 % replacement. The minimum carbonation depth was found to be at 25% replacement for all the w/c ratios. For a given percentage replacement, it was observed that the carbonation depth decreased with decrease in the w/c ratio. The carbonation depth at 55% and 70% replacement was found to be greater than the control concrete at all the w/c ratios.

5.4.3 Chloride- Penetration

The depth of chloride penetration was lesser than the control concrete upto a percentage replacement of 40% for all w/c ratios except 0.3 for which, optimum percentage was 25%. The depth of chloride penetration increased with the exposure period and for a given percentage replacement the depth of chloride penetration was found to be increasing with the increasing w/c ratio.

5.4.4 Acid-Attack

Weight loss for the GCW substituted concrete on exposure to 3% H_2SO_4 solution was lesser than the control concrete upto a percentage replacement of 40% for all the w/c ratios except 0.3w/c for which the optimum percentage replacement was found to be 25%. The lowered values of weight loss with GCW substitution suggest the feasibility of utilizing GCW concrete in acidic environments.

The loss of compressive strength on exposure to acidic environment was found to be lesser than the control concrete upto a percentage replacement of 40% for all the w/c ratios except 0.3w/c for which the optimum percentage replacement was found to be 25%.For all other w/c ratios the loss of compressive strength was found to be minimum for the optimum percentage replacement of 40%.

5.4.5 Sulphate –Attack

Compressive strength continued to increase with time during the entire duration of exposure to $MgSO_4$ solution and there occurred a negligible mass loss even at 210th day of exposure period. This may be attributed to the continued hydration of the concrete and the negligible formation of expansive compound i.e., gypsum. Also it suggests that whatever amount of ettringite was formed, it remained well confined within the volume of voids since visible signs of expansion were not seen.

5.4.6 Corrosion

1) Values of macrocell current were comparable for the GCW concrete and the control concrete upto 40% replacement for all the w/c ratios except 0.3w/c for which the optimum replacement was found to be 25%.The GCW concrete with 55% and 70% replacement showed slightly higher susceptibility to corrosion as indicated by the reduced duration to attain a macrocell current value greater than +10 A in these specimens. The time taken to attain the +10A value was 7 months and 6 months for the 0.3w/c and all other w/c respectively. Also for a given percentage replacement it was observed that the values of peak macrocell current increased with the increase in the w/c.
2) Similarly it was found that the GCW concrete showed comparable values of the half –cell potential to that of the control concrete upto a percentage replacement of 40%except 0.3w/c for which the optimum replacement was found to be 25%.55% and 70% replacement GCW concrete attained the value of half-cell potential slightly earlier than the control concrete.
3) GCW concrete showed slightly lesser value of corrosion rate than the control concrete upto a percentage replacement of 40% except 0.3w/c for which the optimum replacement was found to be 25%.Also, visual inspection of the specimens revealed that the visible corrosion activity was slightly lesser than the control concrete upto a percentage replacement of 40% for all the w/c except 0.3.

5.4.7 Shrinkage:

Incorporation of GCW in concrete led to the decreased shrinkage strain in the beginning. However the final values of shrinkage strain were comparable to the control concrete indicating the similarity between GCW concrete and control concrete. It also establishes the feasibility of using GCW concrete from shrinkage point of view.

5.5 Microstructure (SEM and XRD)

- SEM analysis confirms that the cement-aggregate matrix has maximum density as well as compactness at 40% replacement level. Therefore, strength of G40 mix is maximum among all mixes. Moreover, porosity of overall system has also decreased with use of GCW. Also, presence of micro-cracks in G55 mix proves that the porosity of concrete increases and thereby decreasing the durability of concrete. So, replacement level must be well below 55% and roughly about 40%.
- XRD analysis proves that optimal concentration of C-S-H gel is found in G40 mix without any adverse effect on binding action of cement and aggregate (due to GCW addition).This indirectly supports the experimental finding of increased compressive strength of GCW concrete with 40% replacement..
- XRD and SEM analysis clearly demonstrates that the presence of GCW, decreases the content of $Ca(OH)_2$ crystals in the ITZ (observed in SEM images) and less peaks of CH crystals are observed in diffractograms of concrete mixes. Moreover, size of $Ca(OH)_2$ crystal also reduces because of GCW, which in turns make the microstructure of ITZ more dense and compact . Thus compressive strength of G mixes increases with optimum amount of GCW replacing fine aggregate in concrete.
- XRD analysis of all G mixes indicates a small quantity of compounds such as ettringite, $CaCO_3$, Dolomite, alkali oxides (Na_2O, K_2O), alumina, MgO and portlandite in comparison to silica and C-S-H which are present in relatively larger concentration in concrete mixes.
- Above all, optimum concentration of C-S-H gel and the formation of dense and compact cement-aggregate matrix (as observed in SEM images) are two important reasons behind generation of high compressive strength of G40 concrete mix. Thus, concrete with optimal GCW is suitable in adverse environments.

5.6 TGA

It was observed that as the percentage GCW replacement increases beyond the optimum percentage replacement, the corresponding weight loss for the specimen decreases. The decreasing peak areas of the TGA curves for the C-S-H, ettringite peak (peak at about 105°C)were reflected the phenomenon of gradually decreasing hydration extent with increasing percentage GCW content in the concrete specimens.

The results of mechanical, durability and microstructural studies suggest that upto 40 % GCW can be effectively used as a substitute for the fine aggregate in concrete for both the series of w/c ratios with improved characteristics and without any adverse impact. It was found that the morphology and fineness of the GCW played a significant role in determining the strength and durability traits of the manufactured concrete. The enhanced properties of the G25 and G40 mixes as reflected by the microstructural studies establish the feasibility of utilizing GCW in concrete as substitute for natural sand upto 25%-40% replacement. While GCW concrete exhibited better performance than the control concrete on grounds of compressive strength, Carbonation, permeability, chloride penetration, the trend in values of other strength and durability parameters was comparable to the control concrete.

Overall, it can be safely concluded that the GCW acts can be utilized as a feasible substitute for natural sand in concrete upto a percentage volumetric replacement of 25%-40%.

5.7 Recommendation

Although the present study establishes the feasibility of utilizing GCW as a potential substitute for fine aggregate in concrete the following may be considered as a recommendation for further research:

1) The use of GCW in combination with other industrial wastes can be considered for the study of strength, durability and microstructure parameters.
2) The possibility and feasibility of utilizing GCW in the manufacturing of new construction materials like hollow blocks, paver-blocks and bricks can be worked out.
3) The feasibility of simultaneous replacement of sand by GCW and use of Granite aggregates may be worked out.

REFERENCES

Abukersh SA, Fairfield CA. Recycled aggregate concrete produced with red granite dust as a partial cement replacement. Construction and Building Materials.2011;25(10):P4088–4094

Adigun EMA. Cost Effectiveness of Replacing Sand with Crushed Granite Fine (CGF) In the Mixed Design of Concrete. *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)* .2013;10(1): *P 01-06*

Agarwal, D., Hinge, P., Waghe, U.P., Raut, S.P.,” Utilization of waste material in construction industry – a review”, International Journal of Innovative Research in Science, Engineering and Technology, Vol. 3, Issue 1, January 2014, ISSN: 2319-8753.

Aggarwal Y., Siddique R., Microstructure and properties of concrete using bottom ash and waste foundry sand as partial replacement of fine aggregates, Construction and Building Materials, Volume 54, 15 March 2014, Pages 210-223, ISSN 0950-0618.

Al Hamaiedeh HD, Khushefati WH. Granite Sludge Reuse in Mortar and Concrete. Journal of Applied Sciences.2013;13: 444-450

Aliabdo, A.A., Abd Elmoaty, A.E.M., Auda, E.M., 2014. Re-use of waste marble dust in the production of cement and concrete. Constr. Build. Mater. 50, 28-41.

Al-Jabri KS., Hisada M., Al-Oraimi SK., Al-Saidy A.H, Copper slag as sand replacement for high performance concrete. Cement and Concrete Composites 2009;31(VII): 483-488

Allam ME, Bakhoum ES, and Garas GL . Re-Use Of Granite Sludge In Producing Green Concrete. ARPN Journal of Engineering and Applied Sciences. 2014;9(12): 2731-2737

Alnuaimi AS.,”Effects of Copper Slag as a Replacement for Fine Aggregate on the Behavior and Ultimate Strength of Reinforced Concrete Slender Columns”

American Concrete Institute. State of the Art Report on High Strength Concrete, 363R-92, ACI Committee 363 Report. Detroit, 1992

André,A.,DeBrito,J.,Rosa,A.,Pedro,D., Durability performance of concrete incorporating coarse aggregates from marble industry waste. Journal of CleanerProduction.2014

Anna V. Saetta, Renato V. Vitaliani, Experimental investigation and numerical modeling of carbonation process in reinforced concrete structures: Part I: Theoretical formulation, Cement and Concrete Research, Volume 34, Issue 4, April 2004, Pages 571-579

Arivumangai A, Felixkala T. Strength and Durability Properties of Granite Powder Concrete. Journal of Civil Engineering Research 2014; 4(2A): 1-6

Arulraj GP , Adin A, Kannan TS. Granite Powder Concrete. IRACST – Engineering Science and Technology: An International Journal (ESTIJ) 2013; 3 : 193-198

Arumugam B. Effect of specific gravity on aggregate varies the weight of concrete cube. SSRG International Journal of Civil Engineering 2014; 1(3).

Arumugam K., Ilangovan R. and James MD.,"A study on characterization and use of Pond Ash as fine aggregate in Concrete", INTERNATIONAL JOURNAL OF CIVIL AND STRUCTURAL ENGINEERING, Volume 2, No 2, 2011, ISSN 0976 – 4399.

ASTM C 267-01. Standard Test Methods for chemical resistance of mortars, grouts and monolithic surfacing and polymer concretes. West Conshohocken, USA: ASTM International.

ASTM C 78-10. Standard Test Method for Flexural Strength of Concrete Using Simple Beam with Third-Point Loading.

ASTM C1012-10. Standard test methods for length change of hydraulic-cement mortars exposed to a sulphate solution. West Conshohocken, USA: ASTM International.

Bacarji, E., Filho, R.D.T., Koenders, E.A.B., Figueiredo, E.P., Lopes, J.L.M.P., 2013. Sustainability perspective of marble and granite residues as concrete fillers. Constr. Build. Mater. 45, 1-10.

Balaha MM., Badawy AM.and Hashish M.,"Effect of using ground waste tire rubber as fine aggregate on the behavior of concrete mixes", Indian Journal of Engineering & Materials Sciences, Vol. 14, December 2007, pp. 427-435.

Balaji Rao, K. ; Bhaskar Desai, V. ; Jagan Mohan, D. Probabilistic analysis of Mode II fracture of concrete with crushed granite stone fine aggregate replacing sand . Construction and Building Materials, February 2012, Vol.27(1), pp.319-330

Balasubramaniam, T., Thirugnanam, G.S. An experimental investigation on the mechanical properties of granite powder concrete, 2015,InternationalJournalof AppliedEngineeringResearch10(3), pp.7623-7630)

Baroghel-Bouny Veronique, Belin Patrick, Maultzsch Matthias, Henry Dominique. AgNO3 spray tests: advantages, weaknesses, and various applications to quantify chloride ingress into concrete. Part 1: Non-steadystate diffusion tests and exposure to natural conditions. Mater Struct, Springer 2007;40:759–81

Baroghel-Bouny Veronique, Belin Patrick, Maultzsch Matthias, Henry Dominique. AgNO3 spray tests: advantages, weaknesses, and various applications to quantify chloride ingress into concrete. Part 2: Non-steady state diffusion tests and exposure to natural conditions. Mater Struct, Springer 2007;40:783–99

Basar HM., Aksoy ND., The effect of waste foundry sand (WFS) as partial replacement of sand on the mechanical, leaching and micro-structural characteristics of ready-mixed concrete. Construction and Building Materials 2012;35:508-515.

Bassuoni MT, Nehdi ML. Resistance of self-consolidating concrete to sulfuric acid attack with consecutive pH reduction. Cem Concr Res 2007;37:1070–84.

Beretka J, Taylor A. Use of granite dust for making aerated concrete and ceramics. Key Eng Mater 1991;53:512–7

Bhimani DR., Pitroda JK. and Bhavsar JJ.,”Effect of Used Foundry Sand and Pozzocrete Partial Replacement with Fine Aggregate and Cement in Concrete”, International Journal of Innovative Technology and Exploring Engineering, Volume-2, Issue-4, March 2013, ISSN: 2278-3075.

Binici Hanifi, Shah Tahir, Aksogan Orhan, Kaplan Hasan. Durability of concrete made with granite and marble as recycle aggregates. J Mater Process Technol 2008;20:299–308

BIS: 10262 - 2009, 2009. Recommended Guidelines for Concrete Mix Design. Bureau of Indian Standards, New Delhi, India.

BIS: 1237 - 2012, 2012. Indian Standard Specification for Cement Concrete Flooring Tiles. Bureau of Indian Standards, New Delhi, India.

BIS: 1489 (Part 1) - 1991, 1991. Indian Standard Specification for Portland-pozzolana cement-Fly ash based. Bureau of Indian Standards, New Delhi, India.

BIS: 2386 (Part 3) - 1963, 1963. Indian Standard Methods of test for aggregates for concrete- Specific gravity, density, voids, absorption and bulking. Bureau of Indian Standards, New Delhi, India.

BIS: 383 - 1970, 1970. Indian Standard Specifications for Coarse and Fine Aggregates from Natural Sources for Concrete. Bureau of Indian Standards, New Delhi, India.

BIS: 4031 (Part 4) - 1988, 1988. Indian Standard Methods of physical tests for hydraulic cement-Determination of consistency of standard cement paste. Bureau of Indian Standards, New Delhi, India.

BIS: 4031 (Part 5) - 1988, 1988. Indian Standard Methods of physical tests for hydraulic cement-Determination of initial and final setting time. Bureau of Indian Standards, New Delhi, India.

BIS: 456 - 2000, 2000. Indian Standard Plain and Reinforced concrete-Code of practice. Bureau of Indian Standards, New Delhi, India.

BIS: 516 - 1959, 1959. Indian Standard Methods of Test for Strength of Concrete. Bureau of Indian Standards, New Delhi, India.

BIS: 7320 - 1974, 1974. Indian Standard Specification for concrete slump test apparatus. Bureau of Indian Standards, New Delhi, India.

Bravard J, Goichot M, Gaillot S. Geography of Sand and Gravel Mining in the Lower Mekong River First Survey and Impact Assessment, EchoGéo. (2013);26

Brindha D. and Nagan S., "Utilization of Copper Slag as a Partial Replacement of Fine Aggregate in Concrete", International Journal of Earth Sciences and Engineering, Vol. 03, No. 04, August 2010, pp. 579-585, ISSN 0974-5904.

Bureau of Indian Standards (BIS). Precast Concrete Blocks For Paving — Specification. IS15658,New Delhi;2006.

Bureau of Indian Standards, IS: 2386 (Part 1)-1963. Methods of test for aggregates for concrete-Particle size and shape, New Delhi, India.

Bureau of Indian Standards, IS: 2386 (Part 3)-1963. Methods of test for aggregates for concrete- Specific gravity, density, voids, absorption and bulking, New Delhi, India.

Bureau of Indian Standards, IS:383- 1970. Coarse and fine aggregates from natural sources for concrete, New Delhi, India.

Bureau of Indian Standards. 43 Grade ordinary Portland cement – specification. IS:8112, New Delhi, India; 1989.

Bureau of Indian Standards. 43 Grade ordinary Portland cement – specification. IS:8112, New Delhi, India; 1989.

Bureau of Indian Standards. Coarse and Fine Aggregates From Natural Sources For Concrete. IS:383, New Delhi, India; 1970.

Bureau of Indian Standards. Coarse and Fine Aggregates From Natural Sources For Concrete. IS:383, New Delhi, India; 1970.

Bureau of Indian Standards. Guidelines for concrete mix proportioning. IS 10262 , New Delhi, India; 2009

Bureau of Indian Standards. Specification For Concrete Slump Test Apparatus. IS:7320, New Delhi, India; 1974.

Carette, G. G., K. E. Painter, and V. M. Malhotra. "Sustained high temperature effect on concretes made with normal portland cement, normal portland cement and slag, or normal portland cement and fly ash." Concrete International 4.7 (1982): 41-51.

Castillo C, DurraniI AJ. Effect of Transient High Temperature on High-Strength Concrete Materials Journal **;** (1990) 87 (1) p:47-53

Chavan RR. and Kulkarni DB. “Performance of Copper Slag On Strength Properties as Partial Replace of Fine Aggregate in Concrete Mix Design”, International Journal of Advanced Engineering Research and Studies, E-ISSN2249–8974.

Corinaldesi Valeria, Moriconi Giacomo, Naik TarunR. Characterization of marble powder for its use in mortar and concrete. Constr Build Mater 2010;24:113–7

CPC-18. Measurement of hardened concrete carbonation depth. RILEM Publications SARL, 1988.

CPC-18. Measurement of hardened concrete carbonation depth. RILEM Publications SARL, 1988.

CSI: Recycling concrete (Switzerland). Available from: http://www.wbcsd.org/; June, 2015.

Day K.W. Concrete Mix Design, Quality Control and Specification. 2nd Ed. CRC Press; 2003.

Debieb F., Kenai S., “The use of coarse and fine crushed bricks as aggregate in concrete, Construction and Building Materials”, Volume 22, Issue 5, May 2008, Pages 886-893, ISSN 0950-0618.

DIN 1048. EN-Testing Concrete; Determination of Depth of Penetration of Water Under Pressure in Hardened Concrete, Berlin, Germany; 1991.

Divakar Y, Manjunath S, Aswath M. Experimental Investigation on Behaviour of Concrete With the Use of Granite Fines. International Journal of Advanced Engineering Research and Studies 2012;1 ; 84-87

DMG, Rajasthan (India). Available from: http://www.dmg-raj.org/mineral-statistics.html; June, 2015.

Donza H, Cabrera O, Irassar EF. High-strength concrete with different fine aggregate. Cement and Concrete Research. 2002; 32: 1755 – 1761

EDS Analysis. Available from: http://www.apmtesting.com/testing-services/test-methods/EDS-manual.php; June, 2015.

Eldin NN. and Senouci AB., "Rubber-Tire Particles as Concrete Aggregate", Journal of Materials in Civil Engineering, Vol. 5, No. 4, November 1993, pp. 478-496.

Elmoaty AEMA. Mechanical properties and corrosion resistance of concrete modified
with granite dust. Construction and Building Materials. 2013; 47: 743–752

Felix Kala, T., 2013. Effect of Granite Powder on Strength Properties of Concrete. Int. J. Eng. Sci. 2 (12), 36-50.

Felixkala T , Partheeban P . Granite powder concrete . Indian Journal of Science and Technology . 2010;3 :311-317

Felixkala T and Sethuraman VS. Shrinkage Properties of HPC using Granite Powder as Fine Aggregate. International Journal of Engineering and Advanced Technology (IJEAT). 2013 ; 2(3) : 637-643

Felixkala T. Effect of Granite Powder on strength properties of concrete. International Journal of Engineering and Science,2013(2:36-50).

Flexikala T, Partheepan P. Granite powder concrete. Indian J Sci Technol 2010;3:311–7

Frigione M., “Recycling of PET bottles as fine aggregate in concrete, Waste Management”, Volume 30, Issue 6, June 2010, Pages 1101-1106, ISSN 0956-053X.

Gandhi Kashish, Dave Niragi. Critical review on compressive strength of concrete on-construction site. International Journal of Science & Technology 2014;4 (2):p 01-06

Gao, J.M., Qian, C.X., Liu, H.F., Wang, B., Li, L., 2005. ITZ microstructure of concrete containing GGBS. Cem. and Concr. Res. 35(7), 1299-1304.

Garas G. L., Allam M. E., Bakhoum E. S., 2014. Studies undertaken to incorporate marble and granite wastes in green concrete production. ARPN J. Eng. Appl. Sci. 9 (9), 1559-1564.

Gautam,SP, Srivastava, V. and Agarwal, VC., “Use of glass wastes as fine aggregate in Concrete”, Vol. 1(6) November 2012, ISSN: 2278-5213.

Ghosh, S.N., 2003. Advances in Cement Technology: Chemistry, Manufacture and Testing, 2nd Ed., CRC Press, New Delhi, India.

Gobinath. R, Vijayan. V, Sivakumar. N, Prakash. P, Suganya. S and Dhinesh. A3,”Strength of Concrete by Partially Replacing the Fine aggregate using M-Sand”, Scholars Journal of Engineering and Technology, 2013; 1(4):238-246, ISSN 2321-435X.

Govidrajan D., Keerthana M., Kumara raja G., Kumar RP., “Experimental Investigation on Replacement of Fine Aggregate with Bottom Ash in Concrete”, International Journal of ChemTech Research, Vol.6, No.14, pp 5570-5574, Nov-Dec 2014, ISSN: 0974-4290.

Granzotto L. and de Souza RA., “Mechanical properties of structural concrete with partial replacement of fine aggregate by tire rubber”, Acta Scientiarum Technology, Vol. 35, n. 1, p. 39-44, Jan.-March 2013, ISSN: 1806-2563.

Gupta T., Chaudhary S., Sharma RK., Assessment of mechanical and durability properties of concrete containing waste rubber tire as fine aggregate, Construction and Building Materials, Volume 73, 30 December 2014, Pages 562-574, ISSN 0950-0618.

Haider K. Ammash, Muhammed S. Muhammed and Ali H. Nahhab,"Using of Waste Glass as Fine Aggregate in Concrete", Al-Qadisiya Journal for Engineering Sciences, Vol. 2, Year 2009,

Hamza, K.K Aizboon, 2013. Effect of using granite slurry in concrete. Constr. Build. Mater., 10, 1014-1020.

Hashim Am, Agarwal Vc. Experimental Study On Strength And Durability Of Concrete With Marble And Granite Powder. International Journal of Civil, Structural, Environmental and Infrastructure Engineering Research and Development (IJCSEIERD) 2014 ; 4(2): 147-156

Hebhoub H, Aoun M, Belachia, Houari H, Ghorbel E. Use of waste marble aggregates in concrete. Constr Build Mater 2011;25:1167–71

Ho DWS, Sheim AMM, Tam CT. The use of quarry dust for SCC application. Cement and Concrete Research 2002;32: 505–11.

Hojamberdiev M, Eminov A, Yunhua Xu. Utilization of muscovite granite waste in the manufacture of ceramic tiles. Ceramics International.2011;37(3), P 871–876

Hughes BR. Rational concrete mix design. ICE Journal 1954.

Hunger M, Brouwers HJH. Natural Stone Waste Powders Applied to SCC Mix Design. Restoration of Buildings and Monuments. 2008;14(2): 131-140

Ilangovana, R., Mahendrana, N.,Nagamanib, K., 2008. Strength and durability properties of concrete containing quarry rock dust as fine aggregate. ARPN J. of Eng. and Appl. Sci. 3(5), 20-26.

Ilker Bekir Topcu, Turhan Bilir, Tayfun Uygunog. Effect of waste marble dust content as filler on properties of self-compacting concrete. Constr Build Mater

Inoue S , Yoshino A , Kuroda T , Matsui S. Application of decomposed granite as fine aggregate for concrete. Journal of the Society of Materials Science, Japan, October 2000, Vol.49(10), pp.1091-1096

IS:1237 Bureau of Indian Standards . Specification for cement concrete flooring tiles. Method for determination of resistance to wear, New Delhi, India; 1980

IS1237 Bureau of Indian Standards. Cement Concrete Flooring Tiles — Specification, New Delhi;2012.

Ismail ZZ., AL-Hashmi EA., “Recycling of waste glass as a partial replacement for fine aggregate in concrete”, Waste Management, Volume 29, Issue 2, February 2009, Pages 655-659, ISSN 0956-053X.

Ismail ZZ., AL-Hashmi EA., Reuse of waste iron as a partial replacement of sand in concrete. Waste Management 2008;28(11):2048-2053.

Ismail ZZ.,AL-Hashmi EA, “Use of waste plastic in concrete mixture as aggregate replacement”, Waste Management, Volume 28, Issue 11, November 2008, Pages 2041-2047, ISSN 0956-053X.

Joel M. Use of Crushed Granite Fine as Replacement to River Sand in Concrete Production. Leonardo Electronic Journal of Practices and Technologies. Leonardo Electronic Journal of Practices and Technologies. 2010 ; 17 : p. 85-96

Jose JP., Suganya S. and Banupriya, ”Use of Glass Powder as Fine Aggregate in High Strength Concrete”, International Journal of Science and Engineering Research, Vol 2 Issue 7 july-2014,

Kala TF. Effect of granite powder on strength properties of concrete. International Journal of Engineering And Science 2013; 2(12): 36-50.

Karmegam A, Kalidass A, Ulaganathan D. Utilization of granite sawing waste in self compacting concrete. GRAĐEVINAR .2014; 66 :(11) : 997-1006

Keerthinarayana S. and Srinivasan R., “Study On Strength and Durability of Concrete by Partial Replacement of Fine Aggregate Using Crushed Spent Fire Bricks”,

Khanbilvard R. and Afshari S., “Sludge Ash as Fine Aggregate for Concrete Mix”, Journal of Environmental Engineering, September 1995

Kothai, PS. and Malathy R., “Utilization of Steel Slag in Concrete as A Partial Replacement Material for Fine Aggregates”, Vol. 3, Issue 4, April 2014, ISSN: 2319-8753.

Kumar D., Gupta A. and Ram S.,”Uses of Bottom ash in the Replacement of fine aggregate for Making Concrete”, International Journal of Current Engineering and Technology, Vol.4, No.6 Dec 2014, ISSN 2277 – 4106.

M. Mageswari and B. Vidivelli,”The Use of Sawdust Ash as Fine Aggregate Replacement in Concrete”, Journal of Environmental Research and Development Vol. 3 No. 3, January-March 2009,

Mageswari M. and Vidivelli B., ”The Use of Sheet Glass Powder as Fine Aggregate Replacement in Concrete”, The Open Civil Engineering Journal, 2010, Volume 4, 2010, 4, 65-71,

Malik MI., Bashir M., Ahmad S., Tariq T. and Chowdhary U.,”Study of Concrete Involving Use of Waste Glass as Partial Replacement of Fine Aggregates”, IOSR Journal of Engineering (IOSRJEN), Vol. 3, Issue 7 (July. 2013), e-ISSN: 2250-3021.

Malkit Singh , Rafat Siddique. Compressive strength, drying shrinkage and chemical resistance of concrete incorporating coal bottom ash as partial or total replacement of sand ; Construction and Building Materials 68 (2014) 39–48

Mármol L, Ballester P, Cerro S, Monrós G, Morales J, Sánchez L . Use of granite sludge wastes for the production of coloured cement-based mortars . Cement and Concrete Composites , 201.;617-622

Mehta, P.K., and Monteiro, P.J.M., 2006. Concrete: Microstructure, Properties, and Materials, 3rd Ed. McGraw-Hill Professional, New York, U.S.A.

Mehta, P.K.,” Reducing the Environment Impact of Concrete”, Concrete International, October 2001.

Mindess S., Young J.F., Darwin D. Concrete. 2nd Ed. Prentice Hall, Pearson Education, Inc.; 2003.

Mohammed, H, Afolabi, KO. and Umoru, LE.,”Crushed Palm Kernel Shell as a Partial Replacement of Fine Aggregate in Asphaltic Concrete”, International Journal of Materials, Methods and Technologies, Vol. 2, No. 1, January 2014, PP: 1- 5, ISSN: 2327-0322.

Morrison C., Hooper R.,Lardner K., The use of ferro-silicate slag from ISF zinc production as a sand replacement in concrete. Cement and Concrete Research; 33(12): 2085-2089.

Murdock LJ. The workability of concrete. Magazine of Concrete Research 1960; 12,36, 135-144.

Nadeem M. and Pofale AD.,” Replacement of Natural Fine Aggregate with Granular Slag – A Waste Industrial By-Product in Cement Mortar Applications as an Alternative Construction Materials”, International Journal of Engineering Research and Applications, Vol. 2, Issue 5, September- October 2012, pp.1258-1264, ISSN: 2248-9622.

Nadeem M. and Pofale AD., ”Utilization of Industrial Waste Slag as Aggregate in Concrete Applications by Adopting Taguchi’s Approach for Optimization”, Open Journal of Civil Engineering, September 2012, 2, 96-105.

Nagabhushana and bai HS., “Use of crushed rock powder as replacement of fine aggregate in mortar and concrete”, Indian Journal of Science and Technology Vol. 4 No. 8 (Aug 2011) ISSN: 0974- 6846.

Nagnur, J. and Chetan, BA., “Effect of Copper Slag as a Partial Replacement of Fine Aggregate on the Properties of Cement Concrete”, International Journal of Research, Vol-1, Issue-8, September 2014 ISSN 2348-6848.

Nazari, A., Riahi, S., 2011. Splitting tensile strength of concrete using ground granulated blast furnace slag and SiO_2 nanoparticles as binder. Energy Build. 43(4), 864-872.

Neville A.M. Properties of Concrete. 4th Ed. Pitman Pub.; 1981.

North western University. The Science of Concrete. <http://iti.northwestern.edu/cement/index.html> (May 28, 2015)

Obilade, IO.,” Experimental Study On Rice Husk as Fine Aggregates in Concrete”, The International Journal of Engineering and Science, Vol.3, Issue 8, Pages 9-14, 2014, ISSN: 2319-1813.

Ogwuegbu M, Onyedika G, Hwang JY, Ayuk A, Peng Z, Li B, E.N.O E, Andriese M. Mineralogical Characterization of Kuru Cassiterite Ore by SEM-EDS, XRD and ICP Techniques. Journal of Minerals & Materials Characterization & Engineering 2011; 10(9): 855-863.

Otunyo AW., Friday IU., and Israel TA., ”Exploratory Study of Crushed Periwinkle Shell as Partial Replacement for Fine Aggregates in Concrete”, Journal of Emerging Trends in Engineering and Applied Sciences (JETEAS) 4(6): 823-827, 2013 ISSN: 2141-7016.

Otunyo AW., Umenwo Lucky E. and Kingsley S.,”Machine Crushed Cow Bones as a Partial Replacement of Fine Aggregates in Lightweight Concrete”, ARPN Journal of Engineering and Applied Sciences, VOL. 9, NO. 12, DECEMBER 2014, ISSN 1819-6608.

Padmapriya R., Bupesh Raja VK., Kumar VG.,Baalamurugan J. Study on Replacement of Coarse Aggregate by Steel Slag and Fine Aggregate by Manufacturing Sand in Concrete. IJCRGG 2015;8(IV), 1721-1729.

Park SB.,Lee BC., Kim JH., Studies on mechanical properties of concrete containing waste glass aggregate, Cement and Concrete Research2004;34(12):2181-2189.

Parvati VK. and Prakash KB., ”Feasibility Study of Fly Ash as a Replacement for Fine Aggregate in Concrete and its Behavior under Sustained Elevated Temperature”, International Journal of Scientific & Engineering Research, Volume 4, Issue 5, May 2013, ISSN 2229-5518.

Patel AN, Pitroda J . Stone Waste in India for Concrete with Value. Creation Opportunities International Journal of Latest Trends in Engineering and Technology (IJLTET) 2013; 2 : 113-120 Ramos T, Matos AM, Schmidt B, Rio J, Sousa-Coutinho J. Granitic quarry sludge waste in mortar: Effect on strength and durability. Construction and Building Materials 2013; 47 : 1001–1009

Penttala, V., Hannonen, P., Järvinen, M., Komonen, J., 1995. Effects of aggregates and microfillers on the flexural properties of concrete. Report of Dept. of Civ. Eng., Helsinki University of Technology, Finland.

Poon, C.S., Shui, Z.H., Lam, L., Fok, H., Kou, S.C., 2004. Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. Cem. and Concr. Res. 34(1), 31-36.

Portland Cement Association (PCA). Concrete Information: Ettringite formation and the performance of Concrete. PCA R&D Serial No. 2166, IS 417.01.

Qasrawi H., Shalabi F., Asi I., Use of low CaO unprocessed steel slag in concrete as fine aggregate. Construction and Building Materials 2009;23(II):1118-1125

Rajathi RP. and kanth JJ., “Effect of Crushed Hardened Concrete Waste as Replacement Material for Natural Sand in Concrete”, International Journal of

Emerging Technologies and Engineering, Vol. 1, Issue 8, September 2014, ISSN 2348 – 8050.

Rajgor MB, Pitroda J. A study of utilization aspect of stone waste in Indian context. Global Research Analysis 2013; 2(1), 50-53.

Raju R., Mathews M. Paul and Aboobacker KA.," Strength Performance of Concrete Using Bottom Ash as Fine Aggregate", International Journal of Research in Engineering & Technology, Vol. 2, Issue 9, Sep 2014, 111-122, ISSN(E): 2321-8843.

Ramachandran, V.S., Beaudoin, J.J., 2008. Handbook of Analytical Techniques in Concrete Science and Technology: Principles, Techniques and Applications. William Andrew Publishing/ Noyes Publications, New York, U.S.A.

Ramadevi K. and Manju R.," Experimental Investigation on the Properties of Concrete with Plastic PET (Bottle) Fibres as Fine Aggregates", International Journal of Emerging Technology and Advanced Engineering, Volume 2, Issue 6, June 2012, ISSN 2250-2459.

Ramesh ST., Gandhimathi R., Nidheesh PV., Rajakumar S. and Prateepkumar S., "Use of furnace slag and welding slag as replacement for sand in concrete", International Journal of Environment and Engineering, January 2013, 4;3.

Ramos T, Matos AM, Schmidt B, Rio J, Sousa-Coutinho J. Granitic quarry sludge waste in mortar: Effect on strength and durability. Construction and Building Materials 2013; 47; 1001–1009

Rana, A., Kalla, P., Csetenyi, L.J., 2015. Sustainable use of marble slurry in concrete. J. Clean. Prod. 1-8.

Retrieved from http://ibm.nic.in/writereaddata/files/01192015114800IMYB_2013_Vol%20III_Granite%202013.pdf/ on 27/03/2015.

Retrieved from http://cdos-india.com/ on 05/09/2015.

Retrieved from http://timesofindia.indiatimes.com/city/jaipur/Ban-on-sand-mining-hits-Jaipur-Metro-Project/articleshow/12698328.cms on 27/03/2015.

Retrieved from http://www.wbcsd.org/Pages/EDocument/EDocumentDetails.aspx?ID=11133&NoSearchContextKey=true on 27/03/2015.

Rodrigues, R., de Brito, J., Sardinha, M., 2015. Mechanical properties of structural concrete containing very fine aggregates from marble cutting sludge. Constr. Build. Mater. 77, 349-356.

Rubaninbacheran E, Ganesan N. Durability Studies on Fibre Concrete Using Partial Replacement of Cement by Granite Powder. International Journal of Emerging Technology and Advanced Engineering. 2014;4(6) : 443-452

S.M Lu,C.Lu,K.Tseng,F.Chen,C.Chen, Energy- saving potential of the industrial sector of Taiwan", Renewable and Sustainable Energy Review,Vol.21, May 2013, pp.674-683.

Saboya F, Xavier GC, Alexandre J. The use of the powder marble waste to enhance the properties of brick ceramic. Constr Build Mater 2007;21:1950–60

Sales A., Lima SA., Use of Brazilian sugarcane bagasse ash in concrete as sand replacement. Waste Management2010; 30(6): 1114-1122.

Sarkar R, Singh N, Das SK. 2010 Bull. Mater. Sci. 2010; 33: 293.

Sarshar R, Khoury GA. Material and environmental factors influencing the compressive strength of unsealed cement paste and concrete at high temperatures ; Magazine of Concrete Research, 45 (162)

Seeni A., Selvamony C., Kannan SU. And Ravikumar MR., ”Experimental Study of Partial Replacement of Fine Aggregate with Waste Material from China Clay

Industries", International Journal of Computational Engineering Research, Vol. 2 Issue. 8, December 2012, ISSN 2250-3005.

SHARIFI Y, HOUSHIAR M. and AGHEBATI B.,"Recycled glass replacement as fine aggregate in self-compacting concrete",

Shetty M.S. Concrete Technology: Theory and Practice. Revised Ed. S. Chand; 2005.

Shutira, KS., Khan, Khalid nayaz, Kumar, N.S., "Experimental Investigation Manufactured Sand as a Partial Replacement Material of Fine Aggregate in Self-Compacting Concrete", Indian Journal of Applied Research, Volume: 4, Issue: 8, August 2014, ISSN - 2249-555X.

Siddique R, Aggarwal Y, Aggarwal P, Kadri EH, Bennacer R. Strength, durability, and micro-structural properties of concrete made with used-foundry sand (UFS). Construction and Building Materials 2011; 25: 1916-1925.

Siddique R., Singh G., Belarbi R., Mokhtar KA., Kunal, Comparative investigation on the influence of spent foundry sand as partial replacement of fine aggregates on the properties of two grades of concrete. Construction and Building Materials, 2015;83: 216-222.

Siddique R.,"Effect of fine aggregate replacement with Class F fly ash on the mechanical properties of concrete", Cement and Concrete Research 33 (2003) 539–547.

Siddique, R., Aggarwal, Y., Aggarwal, P., Kadri, E.H., Bennacer, R., 2011. Strength, durability, and micro-structural properties of concrete made with used-foundry sand (UFS). Constr. Build. Mater. 25, 1916-1925.

Singh M., Siddique R.," Strength properties and micro-structural properties of concrete containing coal bottom ash as partial replacement of fine aggregate, Construction and Building Materials", Volume 50, 15 January 2014, Pages 246-256, ISSN 0950-0618.

Singh, M. and Siddique, R., 2015. Properties of concrete containing high volumes of coal bottom ash as fine aggregate. J. Clean. Prod. 91, 269-278.

Soman. K, Sasi D, Abubaker KA. Strength Properties of Concrete with Partial Replacement of Cement by Granite Quarry Dust. International Journal of Engineering Research & Technology (IJERT). 2014; 3(9) : 344-348

Soman. K., Abubaker, K.A., 2014. Strength properties of concrete with partial replacement of cement by granite quarry dust. IJERT. 3 (9), 344-348.

Sravani T., Anitha A. and Kumar DS., "Experimental Studies On Concrete Replacing Fine Aggregate with Quarry Dust Wastes", International Journal of Progresses in Civil Engineering, Volume-1, Issue-1,2014, ISSN(PRINT):2394-4676.

Su H., Yang J., Ling TC., Ghataora GS., Dirar S., Properties of concrete prepared with waste tyre rubber particles of uniform and varying sizes, Journal of Cleaner Production, Volume 91, 15 March 2015, Pages 288-296, ISSN 0959-6526.

Taha B. and Nounu G. Utilizing Waste Recycled Glass as Sand/Cement Replacement in Concrete. *J. Mater. Civ. Eng 2009;* 21(12):709–721.

Thiyagarajan A.,"Partial Replacement of Fine Aggregate on Concrete with Foundry Sand", International Journal of Advanced Research Trends in Engineering and Technology (IJARTET), Vol. II, Special Issue X, March 2015, ISSN 2394-3785.

Thomas BS., Damare A., Gupta RC., Strength and durability characteristics of copper tailing concrete, Construction and Building Materials, Volume 48, November 2013, Pages 894-900, ISSN 0950-0618.

Thomas BS., Gupta RC., Mechanical properties and durability characteristics of concrete containing solid waste materials, Journal of Cleaner Production, Available online 18 November 2013, ISSN 0959-6526.

Tomas U. Ganiron Jr, "Use of Recycled Glass Bottles as Fine Aggregates in Concrete Mixture", International Journal of Advanced Science and Technology, Vol.61, (2013), pp.17-28, ISSN: 2005-4238

Topcu, I.B., Toprak, M.U., Uygunoglu, T., 2014. Durability and microstructure characteristics of alkali activated coal bottom ash geopolymer cement. J. Clean. Prod. 81, 211-217.

Torgal F, Castro-Gomes JP. Influence of physical and geometrical properties of granite and limestone aggregates on the durability of a C20/25 strength class concrete . Construction and Building Materials 2006 ;20: 1079–1088

Tripathi B. and Chaudhary S. Performance based evaluation of ISF slag as a substitute of natural sand in concrete . Journal of Cleaner Production.2015

Tripathi B., Misra A. and Chaudhary S., "Strength and Abrasion Characteristics of ISF Slag Concrete", Journal of Materials in Civil Engineering, November 2013,25:1611-1618.

Vaitkevicius V, Serelis E, Lygutaite R. Production Waste of Granite Rubble Utilisation in Ultra High Performance Concrete. Journal Of Sustainable Architecture And Civil Engineering. 2013;2(3) : 54-60

Vieira CMF, Soares TM, Sánchez R, Monteiro SN. Incorporation of granite waste in red ceramics. Materials Science and Engineering: A. 2004; 373(1-2):P 115–121

Vijayalakshmi M, Sekar ASS, Prabhu GG. Strength and durability properties of concrete made with granite industry waste . Construction and Building Materials.2013; 46 : 1–7

Wakchaure MR., Shaikh AP. and Gite BE, "Effect of Types of Fine Aggregate on Mechanical Properties of Cement Concrete", International Journal of Modern Engineering Research, Vol.2, Issue.5, Sep-Oct. 2012 pp-3723-3726 ISSN: 2249-6645.

Wang HY., A study of the effects of LCD glass sand on the properties of concrete. Waste Manag. 2009 ;29(1):335-41.

Watcharapong Wongkeo, Arnon Chaipanich, Compressive strength, microstructure and thermal analysis of autoclaved and air cured structural lightweight concrete made with coal bottom ash and silica fume, Materials Science and Engineering: A, Volume 527, Issues 16–17, 25 June 2010, Pages 3676-3684

Williams KC , Partheeban P , Kala FT. Mechanical Properties Of High Performance Concrete Incorporating Granite Powder As Fine Aggregate. International Journal on Design and Manufacturing Technologies. 2008;2(1) : 67-73

Williams KC , Partheeban P , Kala FT. Mechanical Properties Of High Performance Concrete Incorporating Granite Powder As Fine Aggregate. International Journal on Design and Manufacturing Technologies. 2008;2 (1) : 67-73

Williams KC, Partheeban P , Kala FT. Mechanical Properties Of High Performance Concrete Incorporating Granite Powder as Fine Aggregate. International Journal on Design and Manufacturing Technologies. 2008;2 (1) : 67-73

Ying Li, Hongfa Yu, Zheng L,Wen J, Chengyou Wu, Tan Y. Compressive strength of fly ash magnesium oxychloride cement containing granite wastes. Construction and Building Materials.2013 ; 38 : 1–7

Zhao H., Poon CS., Ling TC., Utilizing recycled cathode ray tube funnel glass sand as river sand replacement in the high-density concrete. Journal of Cleaner Production 2013;5

Publication List

Papers published based on this work

SCI Journals

1. Singh, S., Nagar, R., & Agrawal, V. (2016).Performance of granite cutting waste concrete under adverse exposure conditions. Journal of Cleaner Production, 127, 172-182.

2. Singh, S., Nagar, R., & Agrawal, V. (2016). A review on Properties of Sustainable Concrete using granite dust as replacement for river sand. Journal of Cleaner Production, 126, 74-87.

3. Singh, S., Nagar, R., Agrawal, V., Rana, A., & Tiwari, A. (2016). Sustainable utilization of granite cutting waste in high strength concrete. Journal of Cleaner Production, 116, 223-235.

International Conferences

1. Singh, S., Nagar, R., & Agrawal,V.(2016). Granite cutting waste concrete a Saturn key solution for efficient stone waste management. Recycle 2016 .IIT Guwahati.

Author’s Bio-data

Author's Bio-data

The author obtained his Bachelor's degree in Civil Engineering from Government Engineering College Jhalawar in the year 2011. He enrolled for M.Tech degree in Structural Engineering in the year 2011 and completed his M.Tech degree in the year 2013 from Malaviya National Institute of Technology Jaipur. His area of interest includes sustainable construction, industrial waste management by application in low cost building material, durability of concrete and microstructure of concrete. He has been working on study of strength, durability and microstructural attributes of granite cutting waste concrete. He has also worked significantly on other stone waste like kota stone waste, marble slurry etc. sarbjeet designed low cost, innovative building materials like hollow blocks and paver blocks. Out of his research work his research work was a part of a CDOS Project, Rajasthan. His work reviewed warm welcome by international journals. And he has got published in reputed journals like Journal of Cleaner production.