STRENGTH AND DURABILITY OF CONCRETE CONTAINING DISCARDED CRUMB RUBBER TIRE

Ph.D. THESIS

by

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STRENGTH AND DURABILITY OF CONCRETE CONTAINING DISCARDED CRUMB RUBBER TIRE

This thesis is submitted

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programme in Civil Engineering

by

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MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY, JAIPUR

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“Not on my Merit. But on His Grace”

This thesis is dedicated to

My Parents, Wife, Son

&

My Uncle: Late Mr. M.V. Philip.

MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY
JAIPUR, INDIA-302017

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **'Strength and Durability of Concrete Containing Discarded Crumb Rubber Tire**' in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy and submitted to the 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, 2012 to July, 2015 under the supervision of Dr. R. C. Gupta, Professor, Department of Civil Engineering, MNIT Jaipur.

In the best of my Knowledge, the matter presented in this thesis has not been submitted by me, in part or full, to any other University or Institute for the award of any degree.

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CERTIFICATE

This is to certify that the thesis entitled **'Strength and Durability of Concrete Containing Discarded Crumb Rubber Tire'** being submitted by **Blessen Skariah Thomas** to the Malaviya National Institute of Technology Jaipur, for the award of the degree of **Doctor of Philosophy** is a bonafide record of research work carried out by him under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standard fulfilling the requirements for the degree of **Doctor of Philosophy**.

In the best of my knowledge, the matter presented in this thesis has not been submitted, in part or full, to any other University or Institute for the award of any degree.

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Date **Blessen Skariah Thomas**

ABSTRACT

Due to the huge increase in population and the uplift in living standards of people, there was a big growth in the number of vehicles. As a result of this, lots of tires are ending as waste every day. Disposal of waste tire rubber has become one of the major environmental issues in all parts of the world. Every year millions of tires are discarded or buried all over the world, representing a very serious threat to the ecology. One of the possible solutions for the use of waste tire rubber is to incorporate it into cement concrete, replacing some of the natural aggregates. This attempt is environmental friendly (as it helps to dispose the waste tires and prevent environmental pollution) and economically viable as some of the costly natural aggregates can be saved.

Many researchers have studied the properties of rubberized concrete. Waste tire rubber has been used as a partial substitute for cement and also for fine and coarse aggregates. Although many researchers have reported about their mechanical properties and density, only a few have reported about the chloride penetration, water absorption, freeze-thaw resistance, carbonation and shrinkage. A proper study is needed on their resistance to abrasion and their durability characteristics like corrosion of steel reinforcements and the resistance to aggressive environment (acid attack, sulphate attack, etc). In addition, a thorough study is required on the strength and durability properties of high strength rubberized concrete, as they were not noticed in the literature study.

In this study, M30 grade of concrete was studied in first series with a water-cement ratio of 0.4. Crumb rubber (waste tire rubber mechanically grinded into rubber crumbs) was partially substituted for fine aggregate from 0% to 20% in multiples of 2.5%. The properties of concrete such as compressive strength, flexural tensile strength, abrasion resistance, pull-off strength, water permeability, water absorption, resistance to acid and sulphate attacks, carbonation, depth of chloride penetration and corrosion of steel reinforcements were tested and Scanning Electron Microscopy (SEM) was used to study the micro structure. A total of six hundred specimens of various dimensions were casted for this series. The properties of concrete with water-cement ratios of 0.45 and 0.50 were also studied as the second and third series to determine the variation in different properties. In the fourth series, specimens with

M60 grade concrete with a water-cement ratio 0.30 was casted and the above mentioned tests were performed to study the different properties of high strength rubberized concrete.

From the results it was observed that the bulk density of concrete decreased with the increase in percentage of crumb rubber. For compressive, flexural tensile and pull-off strength tests and compressive strength test of sulphate attacked specimens, gradual decrease in strength was noticed as the amount of crumb rubber was increased in concrete. On the other hand, they showed better resistance to abrasion when compared to the control mix. The depth of water penetration has shown gradual increase when the amount of crumb rubber was increased from 0% to 20% and the water absorption of the control mix specimens was more than that of the rubberized concrete up to 7.5% substitution. Beyond 7.5% substitution, the water absorption was slightly higher when compared to the control mix concrete specimens. Similar results were obtained for the chloride ion penetration test.

The depth of carbonation of the concrete mixes in which crumb rubber was substituted from 2.5% to 15% were less than or equal to that of control mix concrete in the case a 0.4 water to cement ratio. Carbonation resistances of concrete with w/c 0.45, 0.5 and 0.3 were also studied and reported in the thesis. From the acid attack test, it was noticed that there was minimal loss in compressive strength and unit weight for the rubberized concrete when compared to the control mix concrete specimens. As all the readings obtained in the macrocell corrosion test were less than 10 μA, it was concluded that there is no significant proof of corrosion in the specimens up to 182 days of ponding. From the SEM analysis, it was observed that the bond between rubber particles and cement paste was not as good as with traditional rigid aggregates. More voids were observed in the concrete as the amount of crumb rubber was increased.

The above mentioned tests were performed and results are presented in detail in this thesis.

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CHAPTER-1

INTRODUCTION

1.1 Background

The invention of concrete has been one of the key events in evolution of mankind because of its simplicity, strength, durability and affordability for society. It is the third most widely used substance in the world after air and water. As it is a versatile construction material, it is also known as 'liquid stone' because of its ability to be moulded in to any shape allowing people to realise their dream of construction. The ingredients of concrete are cement, aggregates, water and admixtures. The most important ingredient in concrete is the ordinary looking grey powder known as cement, which is also the costliest. Aggregates constitute 60 to 75 percentage of the total volume of concrete (Gupta, 2014; http://cement.org).

The world is experiencing an acute shortage of natural aggregates that are used in concrete manufacturing. The stringent environmental protection laws and the dying rivers all over the world have raised a question mark on the availability of good quality aggregates for construction activities (http://un.org). Because of these reasons, the costs of aggregates are increasing every day. It is estimated that the world population may increase to 9.3 billion by the year 2050. This increase in population points out the increasing demands of aggregates for the current and future generations (http://lowcarboneconomy.cembureau.eu).

Solid waste disposal is a worldwide problem. With urbanization, industrialization and technological innovations in different fields, large amounts and varieties of solid waste materials are being generated by industrial, agricultural, mining and domestic activities. Flyash, marble sludge waste, incineration ash, rice husk-bark ash, bagasse ash, bottom ash, plastic waste, stone wastes, ceramic waste, copper slag, agricultural wastes, copper tailings, carbon steel slag, coal waste, mine waste, construction and demolition waste, ceramic waste, foundry slag, limestone waste, wood ash, furnace slag, welding slag, phosphogypsum slag, imperial smelting furnace (ISF) slag, wollastonite, waste tire rubber, etc, are some examples of solid waste materials that pollute the environment.

Recycling of these non-biodegradable waste materials is very difficult. In the year 2002, it was estimated that the amount of waste generation, worldwide was 12 billion tonnes annually (of which 1.6 billion was municipal solid waste and 11 billion was industrial waste). By the year 2025, the amount would be 19 billion tonnes annually. Most of the waste materials are disposed as land filling. The land requirement for this type of disposal is a challenge for the civil and environmental engineers (Tapas, 2014; Asokan et al., 2007; Krishna et al., 2014).

Several studies have been published regarding the disposal of solid waste materials in concrete as replacement for aggregates, cement, etc. Flyash has been successfully used for the past few years for the partial replacement of cement and aggregates in concrete and for the production of Portland Pozzolana Cement (PPC). Rice husk-bark ash, bagasse ash and bottom ash have been successfully used either as filler or as a partial cement replacement in concrete. Stone wastes, ceramic waste, copper slag, copper tailings, ISF slag, construction and demolition waste, etc. have also been used for the partial or complete replacement of fine and/or coarse aggregates in concrete. While using these solid waste materials, there are chances for some reduction in the strength and/or durability of the final product. Regardless the replacements helps reduce the waste, minimize environmental pollution, etc. (Amnon and Konstantin, 2004; Hui et al., 2009; Najimi et al., 2011; Cheah and Ramli, 2012; Alan et al., 2012; Martin et al., 2012; Maria et al., 2014).

Due to the huge increase in population and the uplift in living standards of people, there is a big growth in the number of vehicles. As a result of this, disposal of waste tire rubber has also become a major environmental issue in all parts of the world. It was estimated that 1.5 billion tires are manufactured in the world per annum (Rafat and Tarun, 2004; Weiguo et al., 2013). Every year millions of tires are discarded or buried all over the world, representing a very serious threat to the ecology. **It is estimated that every year almost 1000 million tires end their service life** and out of that, more than 50% are discarded to landfills or garbage, without any treatment. By the year 2030, the number would reach 1200 million yearly. Including the stockpiled tires, there would be 5000 million tires to be discarded on a regular basis (Azevedo et al., 2012). **In India alone, the total number of discarded tires would be an estimated 112 million per year after retreading twice** (Mukul, 2010).

The vehicle tires which are disposed to landfills constitute one important part of solid waste. The tires are bulky, but 75% of its volume is void and these spaces provide potential sites for the breeding of rodents. There is a tendency for the tires to rise in a land-fill and float to the surface (Neil and Ahmed, 1994; Rhyner et al. 1995). **Stockpiled tires also present a variety of health, environmental and economic risks through air, water and soil pollution** (Neil and Ahmed, 1994; Bashar et al., 2012; Weiguo et al., 2013). **The tires store water for a longer period because of its particular shape and impermeable nature providing a breeding habitat for mosquitoes and various pests.** Use of discarded tires as a fuel has been banned due to environmental issues (Gregory, 2001; Weiguo et al., 2013).

Tire burning, which is the easiest and cheapest method of disposal, causes serious fire hazards (Benazzouk et al., 2007; Mehmet and Erhan, 2011; Bashar et al., 2012). Temperature in that area rises and the poisonous smoke with uncontrolled emissions of potentially harmful compounds is very dangerous to humans, animals and plants. Once ignited, it is very difficult to extinguish as the 75% empty space can store a lot of free oxygen. It was reported that a serious fire hazard happened in Wales in an area where 10 million tires were dumped. The tires have been burning continuously for atleast 15 years causing serious health and environmental problems (Pacheco-Torgal et al., 2012; Camille and George, 2013). In addition, **the residue powder left after burning pollutes the soil**. The oil that is generated from the melting of tires can also pollute soil and water (Neil and Ahmed, 1994; Pacheco-Torgal et al., 2012).

The pyrolysis method for recycling used tires is a technique which heats whole or shredded tires in a reactor vessel in an oxygen free atmosphere. The disadvantage of pyrolysis is that, it produces **carbon black powder, which pollutes the atmosphere**. Tire retreading method is a re-manufacturing process for tires that helps to replace the tread on worn tires. It can preserve almost 90% of the material in spent tires and the material cost is about 20% compared to manufacturing a new one. (http://en.wikipedia.org)

Tire rubber can be used in a variety of civil and non-civil engineering applications such as geotechnical works, road construction, fuel for cement kilns, incineration for production of electricity, feedstock for carbon black manufacturing, reefs in marine environments and aggregate in cement-based products. Still, millions of tires are being

buried, thrown away or burnt all over the world (Segre and Joekes, 2000; Oikonomou and Mavridou, 2009; Pacheco-Torgal et al., 2012; Wang et al., 2013)

For the past few years, construction industry has taken up the challenge to incorporate sustainability in the production activities by searching for more environmental friendly raw materials or by the use of solid waste materials as aggregates in concrete. **One of the possible solutions for the use of waste tire rubber is to incorporate it into cement concrete, to replace some of the natural aggregates.** This attempt could be environmental friendly (as it helps to dispose the waste tires and prevent environmental pollution) and economically viable as some of the costly natural aggregates can be saved (Raghavan et al., 1998; Tayfun and Ilker, 2010; Khalid and Mathew, 2011; Azevedo et al., 2012).

1.2 Problem formulation

Many researchers have studied the properties of rubberized concrete. Waste tire rubber has been used as a partial substitute for cement and as a partial substitute for fine and coarse aggregates. Many researchers have reported about the mechanical properties and density. Only few authors have reported about the chloride penetration, water absorption, freeze-thaw resistance, carbonation and shrinkage. A proper study is needed on the resistance to abrasion and durability characteristics like corrosion of steel reinforcements and the resistance to aggressive environment (acid attack, sulphate attack, etc). Also a thorough study is required on the strength and durability properties of high strength rubberized concrete, as such reports were not observed in the literature study.

In this study, M30 grade of concrete was studied in first series with a water-cement ratio of 0.4. Crumb rubber (waste tire rubber mechanically grinded into rubber crumbs) was partially substituted for fine aggregates from 0% to 20% in multiples of 2.5%. The properties of concrete like compressive strength, flexural tensile strength, abrasion resistance, pull-off strength, water permeability, water absorption, resistance to acid attack and sulphate attack, carbonation, depth of chloride penetration and corrosion of steel reinforcements were tested and their micro structures were observed using Scanning Electron Microscopy (SEM). Six hundred total specimens of various dimensions were casted for this series. The properties of concrete with water-cement ratios of 0.45 and 0.50 were also studied as the second and third series to study the

variation in different properties. In the fourth series, Test specimens with M60 grade concrete with a water-cement ratio of 0.30 was casted and the above mentioned tests were performed.

1.3 Objectives of the work

The objectives of this research work are as follows:

- To arrive at a suitable concrete mix design for the use of waste tire rubber in cement concrete as a partial substitute of natural fine aggregates.
- A study is needed in such a manner that the substituting crumb rubber fits in the particular zone of the substituting aggregates.
- Specimens for both normal and high strength concrete may be designed and casted.
- The specimens may be tested for strength and durability. Especially the resistance to abrasion, corrosion resistance, behaviour in aggressive environment should be studied.
- At the end of the research, a light weight concrete that can be used for some specific works may be developed.

1.4 Organisation of the thesis

This thesis consists of 5 chapters. After abstract and acknowledgements, chapter 1 is the introduction of the solid waste materials including tire waste and the study objectives. Chapter 2 is the review of literature on the use of solid waste materials including waste tire rubber in cement concrete. Chapter 3 contains the description of ingredient materials of concrete and the methods of testing of the properties of these materials. It also includes the testing methods of concrete in fresh and hardened state. Chapter 4 explains the analysis of results obtained in the testing procedure and its discussions. The conclusions and recommendations for future work are discussed in Chapter 5. This is followed by references, bibliography, annexure, and a brief biodata of the author.

CHAPTER- 2

LITERATURE REVIEW

2.1 Solid waste materials

Solid waste means any type of garbage, refuse, and sludge generated from any wastewater treatment plant or water supply treatment plant, and all other types of discarded materials that includes solid, liquid, semi-solid, or gaseous materials, resulting from industrial, commercial, mining and agricultural operations, and from community activities. But it does not include solid or dissolved materials in domestic sewage, or solid or dissolved materials in irrigation return flows, industrial discharges that are point sources subject to permit (Department of Environmental Conservation, New York; http:// epa.gov).

Some of the different types of solid waste materials are- fly ash, rice husk-bark ash, bagasse ash, bottom ash, ceramic waste, copper slag, carbon steel slag, construction and demolition waste, coal waste, incineration ash, limestone waste, marble sludge powder, mine waste, plastic waste, furnace slag and welding slag, phospho gypsum-slag and waste tire rubber.

Fly ash is the finely divided residue from the combustion of powdered coal collected by an electrostatic precipitator. Rice husk-bark ash is obtained as a residue from the burning of rice husk-bark as a source of fuel in power plants. Bagasse ash is obtained as a by-product of burning bagasse for the generation of power in sugarcane mills. Bottom ash is the agglomerated particles of ash which are formed as a by-product of coal combustion in pulverized coal furnaces. Incineration ash is produced as a result of burning municipal solid waste in an incinerator.

Furnace slag and Welding slag are waste products from the fabric industry. Phospho gypsum-slag is a by-product generated from the production of phosphoric acid. The accumulation occupies large amount of land and creates environmental pollution. Carbon steel slag is the by-product produced during the refining of carbon steel in an arc furnace. Production of one ton of carbon steel produces almost 10 kg carbon steel slag. Copper slag is an industrial by-product obtained during the matte smelting and

refining of copper. When one ton of copper is produced, 2.2 to 3 tons of copper slag is generated.

Coal waste is a by product of energy industry. Foundry slag is a by-product material generated by metal casting process at metal foundries. They are high quality silica sands used to make the moulds for casting and when physically degraded, thrown away as waste. Ceramic waste is the non bio degradable waste products of sanitary ware like wash bowls, ceramic electric insulators, floor and roof tile, medical and laboratory vessels, etc. Mine waste is generated from the mining industries. Construction and demolition waste is produced by the demolition of concrete buildings.

Marble sludge powder is generated during the cutting and polishing of marble in stone industries. Limestone waste is obtained after the removal of arsenic from water. The arsenic gets adsorbed on the surface of the limestone during the treatment. Plastic waste is the polymeric waste generated after the disposal of the used plastic items. Waste tire rubber is the waste generated from the used tires of automotives, which creates environmental pollution.

2.2 Use of solid waste materials in concrete

Various types of solid waste materials are used in concrete for different purposes such as a substitute for aggregates, partial replacement for cement, a filler, a fibre, etc. Depending on their cementitious properties solid waste materials are divided into reactive and inert materials.

2.2.1 Reactive materials (pozzolanic materials)

Pozzolanic materials are either siliceous materials or siliceous and aluminous materials which do not have any cementitious value when they exist as such. But when they are in finely ground form, in the presence of moisture, they can chemically react with calcium hydroxide to form compounds that possess cementitious properties (Shetty, 2005).

The pozzolanic reaction can be shown as:

$$\text{Pozzolan} + \text{Calcium Hydroxide} + \text{Water} \rightarrow \text{C-S-H (Gel)}$$

2.2.1.1 Fly ash

Fly ash is obtained as the finely divided residue resulting from the combustion of coal and transported by flue gases and collected by an electrostatic precipitator. Fly ash is the most widely used pozzolanic material in the world. In India alone, more than 75 million tons of fly ash is produced every year in the thermal power plants (Shetty, 2005). As the disposal of fly ash has become a serious environmental problem, its effective usage in concrete is very much needed. It has almost become a common ingredient in concrete as it helps increase the strength and performance of concrete. Use of the right quantity of fly ash in concrete helps to reduce the water demand for the desired workability. As the quantity of water in concrete is reduced, it reduces bleeding and drying shrinkage. It also helps reduce the heat of hydration when we replace part of cement with fly ash (Shi et al., 2008; Tan et al., 2012).

2.2.1.2 Silica fume

Silica fume, also referred to as microsilica, is a product resulting from the reduction of high purity quartz with coal in an electric arc furnace during the manufacturing of silicon or ferrosilicon alloy (Neville, 1995). Silica fume rises as an oxidised vapour, which cools, condenses and is collected. It has a spherical shape and is extremely fine with its particle size being less than 1 micron with an average diameter of about 0.1 micron, which is about 100 times smaller than that of the cement particles (Shetty, 2005; Azavedo et al., 2012; Bagheri et al., 2012; Neville, 1995). Silica fume can contribute to the increment increase in strength of concrete by creating dense packing and by being pore filler of cement paste. At ordinary temperatures in the presence of moisture, silica fume is more reactive than fly ash. When silica fume is added to fresh concrete, it makes the concrete more cohesive and leads to lesser slump. Segregation and bleeding can be reduced if proper quantity of silica fume is used. The heat of hydration in the concrete with silica fume will be less than that of the concrete without silica fume (http://silicafume.org, http:// ce.memphis.edu).

2.2.1.3 Rice husk ash

Rice husk ash is obtained by burning rice husk in a controlled manner, without causing environmental pollution. When properly burnt, it has a high amount of silicon dioxide and can be used as a concrete admixture. The pozzolanic characteristics of

rice husk ash are very high. It helps increase the strength of concrete and contributes to high impermeability of concrete (http://sginstitute.in, http://civilblog.org, Shetty, 2005). Sudisht and Deodhar, (2010) have mentioned that the use of rice husk ash in concrete reduces the heat of hydration, plastic shrinkage and thermal cracking, while it improves workability of concrete. It can also reduce expansion and refine the pore structure. Due to the pozzolanic reaction of rice husk ash, the calcium hydroxide present in hydrated Portland cement paste will be consumed. This reduces the acid attack (as the acid directly attacks the calcium hydroxide) and improves the resistance to chloride penetration.

2.2.1.4 Surkhi (calcined clay pozzolana)

Surkhi is an artificial pozzolanic material made by powdering bricks or burnt clay balls. In some cases of large scale requirements, clay balls would be specially burnt and then powdered to make surkhi (http://engineeringcivil.com, http://scribd.com). It was widely used in India as a pozzolanic material. Surkhi is now known as calcined clay pozzolana. The specification and use of calcined clay pozzolana in mortar or concrete is given in Bureau of Indian Standards (IS): 1344 (1981), and the methods of testing the pozzolanic materials is given in IS: 1727 (1967).

2.2.1.5 Metakaolin

Metakaolin is the refined kaolin clay that is fired (calcined) under carefully controlled conditions to create an amorphous aluminosilicate that is reactive in concrete. Like other pozzolans, metakaolin reacts with the calcium hydroxide (lime) a by-product produced during cement hydration and this helps with the densification of cement paste and also increases the strength and decreases the permeability of concrete (Nabil, 2006). Metakaolin combines with calcium hydroxide to produce additional cementing compounds, the material responsible for holding concrete together. Erhan et al. (2008) investigated the use of metakaolin in concrete as an additive. It was explained that the addition of metakaolin increased the strength of concrete, decreased the drying shrinkage strain, enhanced the pore structure of concrete and made the concrete more impervious due to its pore filling ability.

2.2.1.6 Ground granulated blast furnace slag

Ground-granulated blast-furnace slag (GGBS or GGBFS) is a product obtained by rapidly quenching molten iron slag (a by-product of iron and steel-making) from a blast furnace in water or steam, to form glassy sand like granular material that is then dried and ground into a fine powder. It is estimated that about 7.8 million tons of blast furnace slag is produced in India every year, which is mainly used in the manufacture of slag cement (Gruyaert et al., 2012; Moruf et al., 2014).

Lubeck et al. (2012) observed that, when the slag was in larger quantities, the electrical resistivity was higher and the electrical conductivity was lower. A compressive strength between 35-60 MPa was obtained in the mixture with 50% white Portland cement and 50% slag. Electrical resistivity of the slag concrete was 5 times greater than the control mix and the cost was 14.6% lower than the control mix. Bagheri et al. (2012) replaced GBFS for cement at 15%, 30% and 50% and silica fumes replaced cement at 2.5%, 5%, 7.5% and 10%. It was reported that the use of silica fumes had only minor effect in improving the strength of concrete with slag, while there was considerable improvement in the durability properties of concrete.

Moruf et al. (2014) explained that the pore filling ability of the finely divided ground blast furnace slag in concrete helped increase the compressive strength of concrete when the quantity of GGBS was maintained as 20%. The strength achievement in palm oil based concrete with GGBFS was achieved within 3 days when compared with the gradual strength achievement in normal concrete.

2.2.2 Inert materials

There are many inert materials that are used in concrete. The commonly used inert materials in India are waste marble, different types of slags, recycled aggregates etc.

2.2.2.1 Marble waste

Marble; a well known ornamental stone, is a recrystallised and compact variety of metamorphosed limestone that is capable of taking polish. It can be excavated as blocks and can be sawed. It is crystalline in structure and is composed predominantly of calcite, dolomite or serpentine having 3-4 hardness. (http://dmg-raj.org/marble.html). It was reported by Andre et al. (2014) that the waste generated during the excavation, processing and polishing procedures of marble can be as much as 70% to 80% of the total volume of stone excavated. Almost 40% waste is generated during the quarrying operation and is dumped into empty pits, road sides, riverbeds or agricultural fields. Akbulu and Gurer (2007) mentioned that, almost 30% waste would be generated during processing and polishing procedures. This would be in the form of powder or slurry and are dumped into empty lands or river beds and causing wide-spread environmental pollution.

Hanifi et al. (2008) studied the durability of concrete made with granite and marble as recycle aggregates. They have observed minimum abrasion for the specimens containing marble aggregates. The chloride penetration depth was reduced up to 70% when compared to the control mix specimen. Better bonding of the cement and aggregates was observed and it showed higher resistance to sulphate attack. Andre et al. (2014) studied the durability performance of concrete containing industrial marble waste as coarse aggregates. Natural aggregates were replaced for 20%, 50% and 100% with coarse marble aggregates (CMA). Slight loss was observed in 28 day compressive strength as the replacement level increased. Water absorption by immersion, depth of carbonation and durability performance has shown similarity with control mix. This can be because of the similarity in microstructure properties. The chloride migration of concrete made with CMA showed increase with the increase in the percentage of replacement.

Gameiro et al. (2014) investigated the use of waste marble crumbs as a replacement for 20%, 50% and 100% of fine aggregates in concrete. Workability of fresh concrete has decreased as the substitution percentage increased. The water absorption of hardened concrete was found decreasing for 20% substitution. The resistance to carbonation has improved and chloride migration coefficient has decreased for the increase in substitution. Kelestemur et al. (2014) studied the thermal performance of

cement mortars with waste marble dust as a partial replacement for fine aggregates. It was noticed that the compressive strength increased and the porosity values decreased due to the micro filling ability of the marble dust. At high temperatures the porosity values increased, and beyond 400 degrees, the physical state of the mortar specimens deteriorated.

Ilker et al. (2009) studied the effect of waste marble dust content as filler on properties of self-compacting concrete. For this purpose, marble dust has replaced binder of SCC at certain contents of 0, 50, 100, 150, 200, 250 and 300 kg/m^3. It was observed that the fresh properties, filling properties, compressive and flexural strength etc of self-compacting concrete have improved when the replacement was below 200 kg/m^3. Bacarji et al. (2013) studied the sustainability of marble waste as filler in concrete. 5%, 10% and 20% cement was replaced by the marble and granite residues. Crystalline nature and non–pozzolanic reactivity was observed from X-ray diffraction analysis. The average water absorption and compressive strength was affected due to the replacement.

Aruntas et al. (2010) has investigated the use of waste marble dust (WMD) as an additive material in blended cement in 2.5%, 5.0%, 7.5% and 10% by weight. It was observed that the use of WMD does not affect the setting time of cement but increases the specific gravity, while the compressive strength of cement has increased by the inclusion of WMD. So it was concluded that 10% of WMD can be used as an additive material in the production of cement and it reduces the cost of cement.

Ali-Ergun (2011) studied the effects of the usage of diatomite and waste marble powder as partial replacement of cement on the mechanical properties of concrete. It was observed that the use of 5% waste marble powder for cement has improved the mechanical properties due to its filling abilities. Concrete specimens with 5% marble powder and 10% diatomite for the replacement of cement has obtained the highest compressive and flexural strength. Aliabdo et al. (2014) noticed that the setting times of cement were not affected by the marble powder, while the compressive strength increased due to the micro filling property of marble dust, when used as partial cement replacement. The steel-concrete bond strength was improved by the use of 15% marble powder for cement or sand replacement and it was comparable with the results of the control mix.

Mucteba and Mansur (2011) studied the performance of self-compacting concrete containing different mineral admixtures. It was explained that the use of marble powder as a mineral admixture has improved the mechanical properties. Good balance was found between the compressive strength and UPV of SCC mixtures. Gesoglu et al. (2012) investigated the use of marble powder as filler in self compacting concrete. Increase in the requirement of super plasticizer and increase in viscosity of the concrete has been noticed. Low sorptivity coefficient was obtained due to the filling ability of the marble powder in concrete.

Gupta (2014) studied the use of marble powder in self compacting concrete. It was concluded that self compacting concrete could be produced using marble powder up to 60% replacement for cement (used as filler) without any negative effects on strength parameters and up to 40% replacement for cement (used as filler) without any negative effects on durability properties. Vishal (2013) studied the use of marble slurry as a replacement for cement and fine aggregates. It was concluded that 15% replacement of cement as well as fine aggregates with marble slurry gave maximum compressive strength.

2.2.2.2 Slag in concrete

Slag is defined as the stony waste materials (glass like materials) that are separated from metals during the smelting or refining of ore. Usually slag is a mixture of silicon dioxide and metal oxides. There are different types of slag materials. Ground granulated blast furnace slag, Steel slag, Ferro manganese slag, Copper slag, Ground granulated Corex slag, Phospho gypsum-slag, Furnace slag, Welding slag, Carbon steel slag, Ground granulated ferro-manganese arc furnace slag etc are few examples. For the last some years, construction industry is taking up the challenge to incorporate sustainability in the production activities by searching for more environmental friendly raw materials or by the use of solid waste materials as aggregates in concrete. One of the possible solutions is to incorporate into cement based materials, to replace some of the natural aggregates.

Arabani and Azarhoosh (2012) studied the effect of steel slag and recycled concrete aggregate on the dynamic properties of asphalt mixtures. It was noticed that the fatigue life was significantly greater than the control samples and the permanent

deformation was 40% less than the control samples. Similar results were obtained by Yu-Chu and Chao-Lung (2010). Zhang et al. (2013) studied the forecasting of carbonation depth of slag on high performance concrete. It was observed that the effect produced by the ratio of carbonization depth to slag dosage of high performance concrete is small. When the dosage of slag was increased from 45% to 60%, only a slight increase in the depth of carbonation was noticed. Netinger et al. (2013) investigated the effect of high temperature (fire resistance) on the properties of steel slag aggregate in concrete. It was reported that the slag has not increased the fire resistance when it was in combination with ordinary Portland cement. It was because, the aggregate-cement paste contact have deteriorated due to the thermal expansion of the slag. For obtaining the fire resistance, the slag can be used as a partial substitute for coarse aggregate in concrete or the slag should be combined with any other binder that can adapt to the expansion of slag in high temperature.

Beushausen et al. (2012) studied the strength development, heat of hydration and early age properties of South African slags (ground granulated corex slag and ground granulated ferro-manganese arc furnace slag.) It was seen that higher slag content resulted in longer duration of setting time and it leads to significantly lower early age strength when compared to control concrete. Ground granulated ferro-manganese arc furnace slag was found effective in reducing the heat evolution in concrete.

Hadjsadok et al. (2012) studied the durability of mortar and concretes containing slag with low hydraulic activity. It was concluded that the slag could be incorporated up to 30% replacement of cement without much reduction in the mechanical properties of concrete with higher water-cement ratios. If the percentage of substitution exceeds 30%, reduced compressive strength and more damage in sulphate attacks was observed. Washington et al. (2007) studied the use of copper slag as a partial substitute for cement in concrete and the results in test concrete had shown higher mechanical and durability performance than the control mix concrete. Beggas and Jahid (2013) studied the use of slag stone concrete to improve the thermal performance of light steel buildings. It was reported that the use of this slag has reduced the heat loss/gain when compared to the ordinary concrete made with conventional aggregates.

2.2.2.3 Recycled aggregates

The construction and demolition waste, sanitary materials waste, flooring wastes etc provides a serious threat to the environment by destroying the natural beauty and creating environmental pollution. Availability of proper disposal sites is the major problem for the disposal of these waste materials. So they are mainly used in landfills. Recently, the construction and demolition waste materials are used as recycled aggregates in cement concrete, along with the natural aggregates. It helps to prevent the pollution problem and also it can save some of the natural aggregates. Sanitary waste materials and flooring waste are used to prepare special concrete.

Duan and Poon (2014) studied the properties of recycled aggregate concrete with different amounts of adhered mortars. The results have shown that the good quality recycled aggregates can be used to produce high strength concrete. The mechanical properties and durability characteristics (chloride penetration and drying shrinkage) are comparable to that of the natural aggregate concrete. Antonios et al. (2014) reported that the compressive strength was improved, flexural strength has reduced and open porosity values have increased due to the replacement of recycled aggregates with natural aggregates. Pereira-de-Oliveira et al. (2014) explained that the produced recycled aggregate concrete had lower density values and comparable compressive strength values. When compared with the control mix, 3.3% loss in compressive strength and 8% reduction in dynamic modulus of elasticity were noticed.

Hisham (2014) pointed out that the use of recycled aggregate as coarse aggregate in concrete helped to decrease in strength depending on the amount of replacement. Compressive strength reduced more than the flexural strength and there was an adverse effect on the workability, modulus of elasticity and air content when the replacement exceeded 25%. Andreu and Etxeberria (2014) studied the properties of high performance concrete made with recycled coarse aggregates (20%, 50% and 100% substitution). When the RCA (recycled concrete aggregates) was obtained by using 100% recycled aggregates, strength above 100 MPa was achieved at 28 days and the physical properties were similar to that of conventional concrete. Sorptivity values, very similar to that of control mix were obtained because of less water-cement ratio.

Bibhuti and Sudhirkumar (2014) investigated the use of nano silica to improve the properties of recycled aggregate concrete. It was observed that the nano silica (which partially replaced cement by 3%) helped to improve the compressive strength, tensile strength and non destructive parameters of recycled aggregate concrete and made it similar to that of the control mix concrete. Guneyisi et al. (2014) studied different methods of surface treatment (two-stage mixing approach, water glass dispersion, pre-soaking in HCl solution and cement–silica fume slurry) to improve the properties of self compacting concrete with recycled aggregates (100% of coarse aggregates was replaced with recycled aggregates). It was observed that the two stages mixing and the water glass dispersion method helped the concrete to have significant improvement in strength, which was comparable to the values of control mix concrete.

Alves et al. (2014) studied the properties of structural concrete with recycled ceramic aggregates (recycled brick or sanitary ware) which was substituted 20%, 50% and 100% of fine aggregates. The results has shown that the concrete with recycled brick aggregates exhibited adequate qualities of structural concrete, while the performance of concrete with sanitary ware aggregates was poor. Bogas et al. (2014) investigated the durability properties of recycled light weight concrete aggregates as substitution for coarse aggregates in concrete. The results had shown improvement in the carbonation and chloride penetration properties when the recycled concrete aggregates are used instead of natural aggregates.

2.2.2.4 Other materials

Lime stone waste: Chintalapati et al. (2009) mentioned that the use of lime stone waste as a partial replacement for fine aggregates in concrete had shown the strengths near to the control mix values. Pacheco-Torgal and Jalali (2011) pointed out that the use of mine waste as a replacement for cement in concrete results in higher resistance to abrasion and acid attack when compared to OPC concrete.

Incineration ash: Lam et al. (2011) obtained positive results on the usage of municipal solid waste incineration ash as a raw material for portland cement clinker.

Plastic waste: Youcef and Bahia (2012) studied the strength and durability of mortars with partial substitution of plastic waste for fine aggregates. The results indicated that

there was minor reduction in compressive strength, while there was higher resistance to chloride penetration and acid attack in the concrete containing plastic waste.

Marble sludge powder: Shahul et al. (2012) explained that the marble sludge powder and crushed rock dust could be used as aggregates in self compacting concrete because the strength and durability of the test concrete were almost similar to the values of control concrete.

Wollastonite: Pawan et al. (2012) studied the mechanical and durability properties of concrete containing wollastonite-flyash combination. It was reported that the wollastonite addition between 5% and 15% would be advantageous to improve the quality of concrete. Increasing replacement levels of cement with wollastonite-flyash in 45% to 55% range had caused some densification of concrete.

Ceramic waste: Anna et al. (2013) investigated the use of ceramic waste as a partial substitute for aggregates in concrete and mentioned that it exhibited high strength and abrasion resistance when compared to the control concrete.

Copper tailing: Thomas et al. (2013) studied the use of copper tailing as a partial replacement of fine aggregates. They explained that copper tailing may be used up to 60% replacement for fine aggregates, with water-cement ratios 0.4, 0.45 and 0.50.

ISF slag: Bhavna et al. (2013) studied the mechanical properties of ISF (imperial smelting furnace) slag concrete (ISF Slag is produced in Rajasthan, India) as a replacement for fine aggregates in concrete at various replacement levels with respect to different w/c and concluded that the test concrete exhibited better strength and durability properties comparable to that of the control mix specimens.

Welding slag and Furnace slag: Sreekrishnaperumal et al. (2013) have recommended that the use of 5% welding slag and 10% furnace slag as a replacement for fine aggregates in concrete would be very effective for practical purposes.

Flyash, Rice husk-bark ash and Bagasse ash: Sumrerng and Prinya (2014) studied the replacement of Portland cement with flyash, rice husk-bark ash and bagasse ash. It was observed that the level of chloride penetration and corrosion was lower in the blended concrete than the control mix.

Phosphogysum-slag: Ding et al. (2014) studied the use of super sulphated phosphogysum-slag as a binding material, and explained that the compressive strength and chloride penetration is better than OPC and Portland slag cement.

Incineration bottom ash: Tao and Zengzeng, (2014) studied the use of municipal solid waste incineration bottom ash as a replacement for coarse aggregates in concrete. Properties like improved later strength gain, progression in the pozzolanic reaction and reduced level of heavy metals (in leachate) was noticed.

Waste foundry sand: Ahmad et al. (2014) studied the concrete with waste foundry sand as a replacement of cement in concrete. It was concluded that the waste foundry sand can replace cement up to 20% and such a concrete can be applied in masonry structures.

Bottom ash and waste foundry sand: Yogesh and Rafat (2014) observed that the bottom ash and waste foundry sand as a partial replacement of fine aggregates in concrete does not affect the strength properties because the strength remained within the limits of the control mix.

2.2.2.5 Tire rubber in concrete

The vehicle tires which are disposed to landfills constitute one important part of solid waste. There is a tendency for the tires to rise in a land-fill and float to the surface (Neil and Ahmed, 1994; Rhyner et al. 1995). Stockpiled tires also present a variety of health, environmental and economic risks through air, water and soil pollution (Neil and Ahmed, 1994; Mohammed et al., 2012; Weiguo et al., 2013). Use of discarded tires as a fuel has been banned due to environmental issues (Gregory, 2001; Weiguo et al., 2013).

Tire burning, which was the easiest and cheapest method of disposal, causes serious fire hazards (Benazzouk et al., 2007; Mehmet and Guneyisi, 2011; Mohammed et al., 2012). Temperature in that area rises and the poisonous smoke with uncontrolled emissions of potentially harmful compounds is very dangerous to humans, animals and plants. The residue powder left after burning pollutes the soil. Once ignited, it is very difficult to extinguish as the 75% free space can store lot of free oxygen. Tires melt due to the high temperature and generate oil that pollutes soil and water (Neil and Ahmed, 1994; Pacheco-Torgal et al., 2012).

For the past few years, construction industry has taken up the challenge to incorporate sustainability in the production activities by searching for more environmental friendly raw materials or by the use of solid waste materials as aggregates in concrete. One of the possible solutions for the use of waste tire rubber is to incorporate it into cement concrete, to replace some of the natural aggregates. This attempt could be environmental friendly (as it helps to dispose the waste tires and prevent environmental pollution) and economically viable as some of the costly natural aggregates can be saved (Raghavan et al., 1998; Tayfun and Ilker, 2010; Khalid and Mathew, 2011; Azevedo et al., 2012).

The various forms in which tire rubber used in concrete is discussed as below.

A) As coarse aggregate replacement

Neil and Ahmed (1994) studied the strength properties and prediction of strength of rubberized concrete with the help of neural networks. Two types of tire chips were used to substitute for coarse aggregates. One was produced by mechanical cutting (sieve numbers 1.5, 1 and 0.75), while the other by cryogenic grinding process (sieve 0.25). Crumb rubber of sieve 10 was used as fine aggregates. It was observed that the workability of rubberized concrete was adequate and the unit weight was less. In the freeze thaw test, the performance of rubberized concrete was not well as the normal concrete. When the coarse aggregate was replaced with tire chips, the compressive strength has reduced up to 85% and splitting tensile strength has reduced up to 50% of the control concrete. In the case of fine aggregate replacement with crumb rubber, the reduction of compressive strength was 65%. Rubberized concrete exhibited the ability to absorb large amount of plastic energy and it did not show brittle failure under compression loading. It had also shown the ability to withstand a measurable amount of post-peak loading and post-failure displacement.

James and Masanobu (2013) studied the dynamic and static performance of rubberized concrete. They have used the rubber crumb (maximum size 6 mm) for coarse aggregate replacement in 5% to 20% by volume of aggregates. Part of cement was replaced with silica fumes to prepare rubberized silica fume concrete. Addition of rubber crumb to concrete increased the damping ratio to 62% more than the control mix. The seismic force on the rubberized concrete had decreased by 27% than the

control mix. Addition of silica fumes to rubberized concrete had helped to increase the strength by improving the bonding between the rubber crumb and the cement paste.

Marques et al. (2013) studied the post-fire properties of rubberized concrete, in which tire rubber (max size: 9.5 mm) was substituted for natural coarse aggregates. It was observed that the concrete with rubber up to 15% was not much affected by the thermal response testing. Similar loss in performance of the compressive strengths of specimens with and without rubber was noticed at 400° C and 600° C. When the rubberized concrete was exposed to 800° C temperature, there was significant loss in the compressive strength.

[Gap: Only mechanical properties were studied by Neil and Ahmed (1994); James and Masanobu (2013) and Marques et al. (2013)]

B) As fine aggregate replacement

Albano et al. (2005) studied the properties of concrete in which waste tire rubber (crumb rubber with size 0.29 mm and 0.59 mm) was substituted for 5% and 10% of fine aggregates by weight. Untreated and treated scrap rubber was used. The purpose of treatment with a solution of sodium hydroxide and a coupling agent silane was to increase the interfacial adhesion between the concrete and rubber. It was observed that the properties of concrete in the fresh state and in the time of curing were affected due to the addition of crumb rubber. Particle size, density, splitting tensile strength, compressive strength and ultrasonic pulse velocity decreased. The treatment with sodium hydroxide and silane did not make any significant improvement in the mechanical properties of concrete.

Oikonomou and Mavridou (2009) studied the chloride ion penetration resistance of mortars which are modified by the waste rubber from automobile tires. Rubber particles were used to replace fine aggregates by weight, from 0% to 15% in multiples of 2.5%. Water absorption by immersion of rubberized concrete had given better results when compared to the control mix. Similar results were obtained by Benazzouk et al. (2007). Resistance to chloride ion penetration has increased due to the addition of rubber particles in concrete. The chloride ion penetration had decreased up to the substitution of 15% of rubber particles. For 5% substitution the reduction in chloride penetration was 14.22% than the control mix and for 15%

substitution, it was 35.85%. The best results have been obtained in the mixture with 12.5% rubber particles and a bitumen emulsion. The mixture exhibited better mechanical properties and the chloride ion penetration was decreased by 55.89% when compared to the control mix concrete.

Tayfun and Ilker (2010) studied the mechanical properties and drying shrinkage of self-consolidating mortars incorporated with tire rubber particles of size 1 to 4 mm. Sand was partially replaced with rubber particles from 0% to 50% in multiples of 10%. Workability and unit weight of the concrete had decreased by the use of waste rubber particles. The rubberized concrete with water-cement ratios 0.4, 0.43 and 0.47 had caused decrease in drying shrinkage values. The compressive strength of rubberized concrete had decreased by 48% to 58% and the flexural strength reduced by 31% to 55%. In lower water-cement ratios, the use of rubber up to 30% had prevented the formation of cracks while bending.

[Gap: Only mechanical properties of treated tire were studied by Albano et al. (2005). Oikonomou and Mavridou (2009) studied only the chloride ion penetration resistance. Tayfun and Ilker (2010) experimented on the mechanical properties and drying shrinkage of self-consolidating mortars, while the other durability issues were not studied]

Mehmet and Guneyisi (2011) studied the chloride ion permeability, water sorptivity and water absorption of self compacting rubberized concrete in which water-cement ratio was 0.35 and crumb rubber substituted for 0%, 5%, 15% and 25% by volume of fine aggregates. Cement was replaced with flyash from 20% to 60%. Increase in the chloride ion penetration was observed with the increase in rubber content (28 days of curing). In 90 days curing, the flyash helped to refine the pore structure and the chloride penetration decreased drastically. Water sorptivity and water absorption was affected by the addition of rubber and it gradually increased with the amount of rubber substituted.

Mohammed et al. (2012) investigated the properties of hollow concrete blocks incorporated with crumb rubber as a partial substitute to fine aggregates at 0%, 10%, 25% and 50%. It was observed that the compressive and splitting tensile strength reduced due to the lack of adhesion of rubber particles and cement. The studies concluded that the load bearing hollow block can be produced with maximum 6.5%

crumb rubber and non-load bearing can be produced with max 40.7% crumb rubber replacement. The block with crumb rubber had lower thermal conductivity, high electrical resistivity and better sound absorption than control concrete hollow block specimens.

Mustafa et al. (2013) studied the impact load resistance of rubberized concrete in which crumb rubber (size 0.16 to 2.36 mm) was replaced for fine aggregates for 10% and 20% by volume. The behaviour of concrete was studied under static and dynamic load conditions. It was noticed that the impact load, bending load and inertial load of rubberized concrete beams increased while the static peak bending load always decreased with the increasing percentage of crumb rubber in concrete. The addition of crumb rubber had improved the flexural impact performance, toughness and deformation ability of the concrete.

[Gap: Mehmet and Guneyisi (2011) studied the chloride ion permeability, water sorptivity and water absorption of self compacting rubberized concrete. Mechanical and other durability issues were not studied. Mohammed et al. (2012) studied only the mechanical properties of hollow blocks with tire rubber. Mustafa et al. (2013) studied on the impact load resistance only.]

Wang et al. (2013) studied the durability properties of waste tire rubber powder in self compacting concrete. Waste tire rubber powder passing through #50 and #30 sieve has been used to replace part of fine aggregates in volume of 5%, 10%, 15% and 20%. Reduction in the compressive strength was noticed upon increase in the level of substitution. But the compressive strength was found best at 5% substitution with rubber powder. The ultrasonic pulse velocity decreased with increasing percentage of rubber powder in concrete. Addition of rubber powder increased the length of concrete as observed in the shrinkage test. Addition of 5% rubber powder increased the length to 35% more than the control mix specimen (with 0% rubber powder) and the addition of 20% rubber powder increased the length by 95%.

Camille and George (2013) have utilized crumb rubber (made by shredding the disposed automobile tires, in the size of 0.075 mm to 4.75 mm) from 0% to 100% for the substitution of fine aggregates. Good compressive strength was observed in the specimens where less than 25% replacement was done. Decrease in the density of the concrete up to 8% was observed for the concrete with 25% crumb rubber. Enhanced

ductility, insulation and damping property (ability to absorb vibration) was observed in rubberized concrete. Qiao et al. (2013) have studied the rubber modified concrete in which the tire rubber was treated with a silane coupling agent. It was noticed that the compressive and splitting tensile strength of concrete with treated rubber increased by 10-20% and the energy absorption capacity improved when compared to the concrete with uncoated tire rubber. The chloride ion resistance of concrete with coated rubber and the concrete without rubber were almost similar.

[Gap: Wang et al. (2013) studied the strength and shrinkage. Camille and George (2013) studied the strength, density, damping property etc; while Qiao et al. (2013) studied the strength, energy absorption and chloride resistance. All the other durability properties were missing in those papers.]

C) Combination of coarse and fine aggregates

Toutanji (1996) investigated the use of tire rubber particles in cement concrete as a replacement to mineral aggregates. Tire chips of average size 12.7 mm and specific gravity 0.61 was used to replace 25%, 50%, 75% and 100% by volume of aggregates. It was reported that the compressive and flexural strength reduced, while the toughness of concrete has increased with the incorporation of tire rubber.

Ali et al. (2008) studied the mechanical properties of concrete that contains a high volume of tire-rubber particles. They have used tire chips, tire crumbs and a combination of tire chips and tire crumbs which replaced the total mineral aggregates by volume in 12.5%, 25%, 37.5% and 50%. It was reported that as the rubber concentration increased, the unit weights had decreased. Workability of concrete with rubber as coarse aggregates were very less, while the workability of rubber as fine aggregates were in the acceptable range. Large reductions in the modulus of elasticity were noticed in case of rubberized concrete in which the percentage of rubber was above 25%. More ductile behaviour was noticed on compression testing of the rubberized concrete. Crack width of rubberized concrete was smaller than that of plane concrete and it effectively absorbs sound and shaking energy.

Arin and Nurhayat (2009) studied the use of waste tire rubber with Portland cement as a construction material. Three sizes of rubber (0-0.25 mm, 0.25-0.50mm, 0.50-1 mm) were used as 20% tire rubber with 80% flyash and 30% tire rubber with 70% flyash.

The compressive strength of concrete decreased with increase in tire rubber, while it increased by increasing the amount of flyash in concrete. The flexural strength increased in the specimens with tire rubber due to the action of rubber as a fibre and water absorption had decreased slightly in the rubberized concrete in which the size of the rubber was less.

Aiello and Leuzzi (2010) studied the fresh and hardened properties of rubberized concrete in which both fine aggregates and coarse aggregates were replaced with tire rubber particles. Larger decrease in compressive strength was noticed for the specimens in which coarse aggregate were replaced with tire rubber. The post cracking behaviour of the specimen in which fine aggregates were substituted with tire rubber were similar to the control mix, while the concrete specimens with coarse aggregate substitution had shown better energy absorption and significant residual strength even after cracking.

[Gap: Toutanji (1996); Ali et al. (2008); Arin and Nurhayat (2009) and Aiello and Leuzzi (2010) studied only the mechanical properties.]

Miguel and Jorge (2012) studied the durability related performance of concrete in which fine aggregates and coarse aggregates were replaced separately and simultaneously with 5%, 10% and 15% of the volume by tire aggregates (obtained by mechanical grinding and cryogenic technique). It was observed that the compressive strength was greatly affected with a reduction of almost 50% at the replacement level of 15%. Shrinkage of concrete increased with the amount of replacement, although the variation was small for the coarse aggregate replacement. Water absorption by immersion increased with the increase in the particle size of the tire rubber. In the concrete mixes where the coarse aggregate was replaced with tire rubber, carbonation resistance and the resistance to chloride attack was very much affected.

Azevedo et al. (2012) observed that the increase in percentage of tire rubber leads to serious loss in compressive strength. Acid resistance test was done with 10% sulphuric acid. The concrete mix containing 5% tire rubber for aggregates and 15% flyash + 15% metakaolin for cement replacement gave the results similar to that of control mix. The capillary water absorption (sorptivity) was low in the specimens with up to 15% rubber was substituted. It was concluded that partial substitution of cement

with flyash and metakaolin had helped to minimize the loss in compressive strength of rubberized concrete.

[Gap: Miguel and Jorge (2012) have not studied the resistance to aggressive environments like acid attack and sulphate attack. Azevedo et al. (2012) studied only on the compressive strength of acid attacked specimens, while the other durability issues were not studied.]

D) As cement replacement

Eshmaiel et al. (2009) investigated the rubberized concrete in which the powdered tire rubber was used in the partial replacement of cement by 5%, 7.5% and 10% and chipped rubber was used to replace 5%, 7.5% and 10% of coarse aggregates. When the amount of replacement was 5%, the reduction in compressive strength was less than 5% when compared to the control mix. In the concrete with 7.5% and 10% replacement, the reduction in compressive strength was 10% to 23% (for aggregate replacement) and 20% to 40% (for cement replacement). The concrete with chipped rubber showed more tensile strength than the concrete with chipped rubber. The reduction in flexural strength was 37% for chipped rubber concrete and 29% for rubber powder concrete as compared to the control mix. Water absorption had increased for the concrete with chipped rubber, while it had reduced for the concrete with rubber powder. The depth of water permeability in concrete has increased with increasing percentage of rubber.

[Gap: Strength, water absorption and water permeability was performed, while all the other durability studies were not performed by the authors.]

E) As an additive

Segre and Joekes (2000) studied the use of surface treated tire rubber particles as an addition to cement paste. The tire rubber in the size of 35 mesh (Max size 500 μm) were surface treated in NaOH saturated aqueous solution for 20 min. Water-cement ratio of 0.36 and 10% rubber as an addition to cement was used. It was observed that the NaOH treatment enhanced the adhesion of rubber particles to the cement paste. Compressive strength was minimized, while flexural strength and fracture energy was improved. It was concluded that the tire rubber particles may used as an addition to concrete rather than substituting for aggregates.

[Gap: Only the mechanical properties were studied.]

F) As fibres in concrete

Guoqiang et al. (2004) investigated the use of waste tire rubber in the form of chip and fibre in concrete. Coarse aggregates were replaced with rubber chips or fibres in 15% by volume. Higher strength and stiffness were observed in the waste tire fibre modified concrete when compared to the tire chip modified concrete. Both the specimens had higher post crack toughness when compared to the control specimens without rubber. To increase the strength and stiffness of rubberized concrete, the stiffness of the tire fibres can be increased and the thickness of fibres can be reduced.

[Gap: Durability issues were not studied by the authors]

G) Use of silica fumes in rubberized concrete

Guneyisi et al. (2004) studied the properties of rubberized concrete containing silica fumes. Crumb rubber and tire chips were used to replace fine and coarse aggregates respectively from 2.5% to 50% by volume. Silica fumes were used to replace cement from 5% to 20% and water-cement ratios of 0.6 and 0.4 were adopted. It was observed that the rubberized concrete with and without silica fumes were workable to a certain degree. The use of silica fumes in rubberized concrete helped to minimize the rate of strength loss. When the rubber content was 15% and water-cement ratio as 0.4, concrete with compressive strength of 40 MPa was produced. Mehmet and Guneyisi (2007) investigated the strength development and chloride penetration of rubberized concretes and pointed out that the unit weight of rubberized concrete decreased with increasing percentage of rubber. There was reduction in unit weight upto 18%. The strength development patterns for plain and rubberized concrete between 3 to 7 days were relatively high, slower rate was observed between 7 to 28 days, and relatively slower rate between 28 to 90 days. The compressive strength reduced systematically as the percentage of rubber was increased irrespective of the w/c ratio and curing period. There was a systematic increase in the depth of chloride penetration for increase in the rubber content, with and without silica fumes.

Al-Mutairi et al. (2010) explained that the use of 5% silica fumes in rubberized concrete helped to minimize the loss in compressive strength at elevated temperatures. At elevated temperature of above 400°C, the compressive strength was similar to that

of control concrete. Fernando et al. (2011) studied the effect of alkaline activation and silica fume usage on the concrete made with waste rubber particles (10% as a substitute for fine aggregates). The crumb rubber was washed with sodium hydroxide and silica fumes were added 15% by mass of concrete to act as a surface modifier. Three water-cement ratios, 0.5, 0.5 and 0.6 was used. The rubberized concrete without silica fumes had shown a reduction in strength up to 67% when compared to control mix, while that with silica fumes had shown only 14% reduction in strength.

[Gap: Guneyisi et al. (2004), Fernando et al. (2011) and Al-Mutairi et al. (2010) studied only the mechanical properties. Mehmet and Guneyisi (2007) investigated only on the strength development and chloride penetration.]

Zhang and Li (2012) studied the abrasion resistance of concrete in which silica fumes and crumb rubber were taken as the additives. It was reported that the addition of crumb rubber reduced the compressive strength but increased the abrasion resistance of the concrete. The addition of silica fume enhanced both compressive strength and abrasion resistance of rubberized concrete. Concrete with silica fumes had a better abrasion resistance than control concrete and the rubberized concrete had better resistance to abrasion when compared to the silica fume concrete. The abrasion resistance of rubberized concrete increased with the increase of rubber content. James and Masanobu (2013) have mentioned that the bonding between the cement paste and the crumb rubber can be improved by the addition of silica fumes in concrete, which is proven by the increase in compressive strength of the rubberized silica fume concrete.

Obinna and Daman (2014) studied the properties of concrete containing pre-coated crumb rubber and silica fumes. They have observed significant increase in the compressive and tensile strengths of the concrete and Considerable improvement in the resistance to chloride penetrability. Due to the action of crumb rubber as insulation material, the electrical resistivity of concrete had improved. Mohamed Elchalakani, (2014) studied rubberized concrete containing silica fumes. Tire-rubber particles composed of a combination of crumb rubber and fine rubber powder. They were used to replace the total weight of the fine mineral aggregate by 10%, 20%, 30%, and 40%. The fresh rubberised concrete exhibited lower unit weight and acceptable workability when compared to plain concrete. Considerable reductions were noticed in axial

strength, flexural strength, and tangential modulus of elasticity. Cube Drop tests showed good resilience of the rubberised concrete.

[Gap: Zhang and Li (2012) studied only the abrasion resistance. James and Masanobu (2013) studied the compressive strength only. Obinna and Daman (2014) have not studied any durability issues other than chloride penetration and electrical resistivity. Mohamed Elchalakani, (2014) have not studied any durability issues.]

2.3 Research gaps identified

From the literature studies, the following observations were made.

1) Most of the studies were concentrated on the mechanical properties of rubberized concrete. In literatures, In-depth studies were not observed on the durability characteristics of rubberized concrete.

2) Most of the studies on rubberized concrete were performed outside India. There would be differences in the quality of tire rubber and all other constituent materials. So, a proper study should be done on the materials locally available in India.

3) In most of the studies, researchers used single size rubber particles for the replacement. So the total fine/coarse aggregates may change from the particular zone. So a study is needed such that the substituting crumb rubber also fits in the particular zone of the substituting aggregates.

4) Studies are required on abrasion and corrosion properties of steel reinforcements in rubberized concrete as much data was not observed from literature. The resistance of rubberized concrete to aggressive environment (acid attack, sulphate attack, etc) should be properly studied.

5) A proper study on the durability properties of rubberized concrete (with silica fumes) was noticed in any literatures.

CHAPTER- 3

MATERIALS AND METHODS

3.1 Introduction

In this chapter, the properties of constituent materials and the experimentation programme (methodology) to study the mechanical and durability properties of cement concrete containing discarded tire rubber (crumb rubber) as a partial substitute for natural fine aggregates have been reported. Such a concrete is known as Rubberized Concrete. The material properties and tests on concrete like compressive strength, flexural tensile strength, pull off strength, abrasion resistance, water permeability, carbonation, acid and sulphate resistance, corrosion etc were performed. For achieving this goal, the physical properties of the materials that are used in the design of rubberized concrete viz. cement, fine aggregates, coarse aggregates and crumb rubber (obtained by the mechanical grinding of waste tire rubber) were determined as per the procedures laid down by different Indian Standard Codes. Four series of concrete were designed as per IS 10262:2009. In the first series, M30 grade concrete with water-cement ratio 0.4 was fixed for maximum exposure conditions. In the second and third series, water-cement ratios of 0.45 and 0.5 were studied. In the fourth series, M60 grade concrete was studied to understand the performance of high strength rubberized concrete. Trial mixes were cast for checking the workability and compressive strength. Based on the results; the proportions of the constituent materials were modified. Control mix concrete and rubberized concrete were prepared and the tests in fresh stage and hardened stage were carried out.

3.2 Material investigations

The physical and mechanical properties of the cement, fine aggregates, coarse aggregates and the crumb rubber were determined. The physical properties like specific gravity, fineness, water absorption, etc and the mechanical properties like compressive strength of cement were conducted on the constituent materials as per Indian Standards. The constituent materials are:

(a) Cement: Ordinary Portland Cement of 43 grade was procured from the local market (commercial name-Binani), It conforms to IS 8112:1989.

(b) Fine aggregate: Natural river sand from river Banas (Falls under Zone II of IS 383:1970).

(c) Coarse aggregate: Aggregates of size 20 mm and 10 mm were procured locally. They were conforming to IS 383:1970.

(d) Crumb rubber: Waste tire rubber (crumb rubber supplied by S&J Granulate Solutions, Mumbai, India) was in three sizes (powder form of 30 mesh (600 Microns), 0.8 to 2 mm, 2 to 4 mm). The specific gravity of rubber powder was 1.05 and that of the other two sizes were 1.13. The three sizes of crumb rubber were mixed in definite percentages to get it in to zone II as per IS 383: 1970. The most suitable proportion was 2 to 4 mm size in 25%, 0.8 to 2 mm size in 35% and rubber powder in 40% by weight.

(e) Water: Potable water available in the Institute was used.

(f) Super plasticiser: Glenium sky 8777, manufactured by BASF.

3.2.1 Properties of cement

The properties of cement such as normal consistency, soundness, initial and final setting time, fineness and compressive strength (3, 7 and 28 days) were identified as per the code for specifications in IS 8112:1989 and IS 4031:1996.

Normal consistency of the cement was determined using Vicat apparatus. It is the consistency which permits the plunger of the Vicat apparatus to penetrate to a depth of 5 to 7 mm from the bottom of the mould of the Vicat apparatus. First, weighed quantities of cement and water were mixed to prepare the cement paste. Gauging was done between 3 to 5 minutes and the cement paste was placed in the mould of the Vicat apparatus. The plunger of the apparatus was released and allowed to sink in the cement paste. The depth of penetration was noted. With varying percentages of water, trial mixes were done until the amount of water needed to make the normal consistency was obtained.

Le-Chateliar's apparatus was used to determine the Soundness (expansion) of cement. Weighed quantities of cement and water are mixed properly (by gauging 0.78 times the water required for normal consistency) and prepared a cement paste. The paste was then filled in the mould. Glass plates were used to cover on both sides of the mould. After 30 minutes, the mould was placed in water (kept at $27^{\circ} \pm 2^{\circ}C$) for another 24 hours. The distance between the two indicators was accurately measured

and the whole assembly was then placed in boiled water for 30 minutes. The distance between the indicators was again measured. The difference between the initial and final measurements gives the soundness of cement.

To measure the initial and final setting time of cement, cement paste was prepared by mixing 0.85 times the water required for normal consistency. The prepared cement paste was placed in the mould of the Vicat apparatus and the needle released and depth of penetration was measured. The period elapsed between the time when water was added to the cement and the time at which the needle fails to pierce the test block at 5.0 ± 0.5 mm from the bottom of the mould was recorded as the initial setting time. To determine the final setting time, the needle with annular attachment was used. The period elapsed between the time when water was added to the cement and the time at which the attachment fails to make an impression on the surface of the test block was taken as the final setting time.

To determine the Fineness of cement, 100 grams of cement was placed in 90 micron sieve and properly sieved. The residue left on the sieve was taken and weighed. The ratio of the residue to the initial measured cement was expressed as percentage. It should not be more than 10%.

To determine the compressive strength of the cement, 9 mortar cubes having an area of 50 cm^2 were prepared by mixing cement and the standard sand in the ratio 1:3. The amount of water was taken as (P/4+3) % of the combined weight of the sand and cement, where P is the percentage of water needed for the normal consistency. After the moulds were filled in 2 layers and each layer was prodded 20 times, the mould was vibrated for 2 minutes and was placed in room temperature for 24 hours. Then the specimens were de-moulded and immersed in water and 3 cubes each were tested for 3, 7 and 28 days on a compression testing machine.

The properties of cement are tabulated in Table 3.1 and Table 3.2

Table 3.1: Properties of cement

S. No.	Name of Test	Results	Requirements as per IS 8112:1989
1	Normal (standard) Consistency	34%	-
2	Initial Setting time	99 minutes	30 (minimum)
3	Final Setting time	180 minutes	600 (maximum)
4	3 day Compressive Strength	25 N/mm^2	23 N/mm^2
5	7 day Compressive Strength	36 N/mm^2	33 N/mm^2
6	28 day Compressive Strength	45 N/mm^2	43 N/mm^2
7	Fineness (% retained on 90 micron sieve)	1%	10%
8	Soundness	2 mm	-

Table 3.2: Chemical composition of cement

S. No.	Requirements	Test Results*	Requirements as per IS 8112:1989
1	Lime Saturation Factor	0.96	0.66-1.02
2	Ratio of Alumina to that of Iron Oxide	1.70	0.66 (Minimum)
3	Insoluble residue (% by mass)	2.69	3.0 (Maximum)
4	Magnesia (% by mass)	1.77	6.0 (Maximum)
5	Sulphuric Anhydride (% by mass)	2.25	3 (Maximum)
6	Total loss on Ignition (%)	2.66	5 (Maximum)
7	Total Chlorides (%)	0.020	0.10 (Maximum)

*Test Certificate (No. R/15-21, Dated 11-06-2013) issued by Binani Cements Limited, India

3.2.2 Properties of fine aggregate

Natural river sand from river Banas was used as the fine aggregates for preparing the concrete. As per the different parts of IS 2386: 1963; sieve analysis, water absorption and specific gravity were determined.

As the fine aggregate consist of particles of different sizes, their distribution should be analysed to understand their suitability in making concrete. Sieve analysis was done for this analysis. The standard set of sieves used were 80 mm, 40 mm, 20 mm, 10 mm, 4.75 mm, 2.36 mm, 1.18 mm, 600 micron, 300 micron, and 150 micron. A pan was placed at bottom to collect the particles that are finer than the smallest sieve. One kg of oven dried sample of sand was randomly taken and placed on the top sieve after cooling at room temperature for 24 hours. The set of sieves were covered and placed on the sieve shaker. After shaking, the materials that are retained on each sieve was taken and weighed and the percentage passing through each sieve was calculated.

Pycnometer was used to determine the specific gravity of fine aggregate. First the empty weight of pycnometer (W_1) was taken. The fine aggregate samples were oven dried at $60^{\circ} \pm 5^{\circ}C$ for 3 days (72 hours) and then cooled at room temperature for 24 hours. The pycnometer was filled almost one-third with the fine aggregates and the weight of aggregates and pycnometer was taken (W_2.) Pycnometer was half filled with water and vigorously stirred to remove the entrapped air. Then the pycnometer completely filled with water and wiped clean from outside. Weight of pycnometer with sample and water was taken (W_3.) The water and sample were emptied and weight (W_4) was taken by filling the water completely in the pycnometer. The specific gravity was calculated as:

$$Specific\ Gravity, (G) = \frac{W_2 - W_1}{(W_2 - W_1) - (W_3 - W_4)}$$

To determine the water absorption of fine aggregate, the sample was properly washed to remove the dust and dirt. It was then immersed in distilled water, where the temperature would be maintained at $27^{\circ} \pm 2^{\circ}C$ for 24 ± 1/2 hours. At the end of the soaking period, the aggregates were taken out and surfaces dried for 10 minutes. Then the weight W_1 was taken. Then the aggregate were placed on a tray, kept in oven and dried at $100^{\circ} \pm 5^{\circ}C$ for 3 days. After taking it out from oven, the aggregate were cooled at room temperature and weight W_2 was taken. The water absorption of aggregate was calculated as:

$$Water\ Absorption = 100 \times \frac{W_1 - W_2}{W_2}$$

The results of various tests conducted on fine aggregate are given in Table 3.3

Table 3.3: Physical properties of fine aggregate

S. No.	Name of Test		Fine Aggregate
1	Sieve Analysis	Sieve Size	% Finer
		80 mm	100.00
		40 mm	100.00
		20 mm	100.00
		10 mm	100.00
		4.75 mm	094.45
		2.36 mm	086.90
		1.18 mm	068.35
		600 micron	045.15
		300 micron	015.00
		150 micron	003.55
2	Specific Gravity		2.63
3	Water Absorption		1.5%
4	Fineness Modulus		2.83

3.2.3 Properties of coarse aggregate

Two different types of coarse aggregate (20 mm and 10 mm) were used. Physical properties like specific gravity, sieve analysis and water absorption were determined separately for 20 mm and 10 mm coarse aggregate, as per the different parts of IS 2386.

Sieve analysis for coarse aggregate was done similar to that of fine aggregates. 5 kg of oven dried and then cooled sample was sieved and the weight retained on each sieve was measured so as to calculate the percentage of material passing through each sieve. Specific gravity and water absorption of the coarse aggregate were determined similar to the fine aggregates. The physical properties of coarse aggregate are given in Table 3.4.

Table 3.4: Physical properties of coarse aggregate

S. No.	Name of Test		Coarse Aggregate	
			20 mm	10 mm
1. Sieve Analysis		Sieve Size	% Finer	
		80 mm	100.00	100.00
		40 mm	100.00	100.00
		20 mm	67.70	100.00
		10 mm	0.78	095.5
		4.75 mm	0.23	028.8
		2.36 mm	0.00	0.00
		1.18 mm	0.00	0.00
		600 micron	0.00	0.00
		300 micron	0.00	0.00
		150 micron	0.00	0.00
2	Specific Gravity		2.63	2.63
3	Water Absorption (%)		0.25	0.30
4	Fineness Modulus		7.312	5.573

3.2.4 Properties of crumb rubber

Specific gravity of crumb rubber was determined with the help of Le Chatelier's Flask. For the experiment, kerosene was used instead of water because irregular values were obtained while determining with water. The specific gravity of water and the crumb rubber was almost similar. So it will take much time for the crumb rubber to settle in water. Kerosene allows the crumb rubber to settle down quickly, being a lighter liquid than water. When kerosene was used, constant specific gravity was obtained. The tire rubber was grinded into three sizes (powder form of 30 mesh, 0.8 to 2 mm, 2 to 4 mm).

Figure 3.1: Rubber powder and crumb rubber of size 0.8-2 mm

The Specific gravity of rubber powder was 1.05 and that of the other two sizes were 1.13. The certificate for the chemical composition of crumb rubber was provided by S&J Granulate Solutions, Mumbai, India. It is reported in Table 3.5. Sieve analysis of crumb rubber is reported in Table 3.6. Images of the rubber powder and crumb rubber are given in Figure 3.1.

Table 3.5: Chemical composition of crumb rubber*

Sl. No	Test	Results
1	Ash Content %	05.11
2	Carbon Black Content %	28.43
3	Acetone Extract %	09.85
4	Volatile Matter %	00.56
5	Hydrocarbon Content %	56.05
6	Polymer Analysis	SBR

*Test certificate provided by S&J Granulate Solutions, Mumbai, India.

Table 3.6: Sieve analysis of crumb rubber

Sieve Size	% Finer		
	Crumb Rubber 2-4 mm	Crumb Rubber 1-2 mm	Rubber Powder
80 mm	100.00	100.00	100.00
40 mm	100.00	100.00	100.00
20 mm	100.00	100.00	100.00
10 mm	100.00	100.00	100.00
4.75 mm	100.00	100.00	100.00
2.36 mm	072.00	100.00	100.00
1.18 mm	004.40	019.20	099.60
600 micron	000.60	000.40	098.80
300 micron	-	-	014.50
150 micron	-	-	000.70

3.2.5 Super plasticizer

Master Glenium SKY 8777 is a super plasticiser based on second generation poly carboxylic ether-polymers, developed using nano-technology. It is free of chloride & low alkali and compatible with all types of cements. The solid content is not less than 40% by weight (http://assets.master-builders-solutions.basf.com/) This super plasticiser has been primarily developed for applications in high performance ready-mix concrete to facilitate total performance control.

3.3 Testing of concrete in fresh stage

Fresh concrete is a plastic concrete that can be moulded to any shape. Hundred per cent compaction of fresh concrete is an important parameter to enable maximum strength for concrete. A highly workable concrete can ensure full compaction. Workability of concrete is the ease with which concrete can be mixed, handled and compacted. There are numerous methods like slump test, compacting factor test etc, to qualitatively measure the workability of concrete. The ratio of partially compacted concrete to the ratio of fully compacted concrete is calculated as the compacting factor

value. It is a rational method than slump test and suitable for dry mixes with low slump.

3.3.1 Workability of concrete by compacting factor test

Workability of concrete was determined by compacting factor test. This test was preferred to slump test because it gives more precise results in case of low water-cement ratios.

Figure: 3.2: Concrete mixer and compacting factor apparatus

The compacting factor apparatus as shown in Figure 3.2 consists of two hopper vessels A and B with a hinged bottom and a bottom cylinder, C. After cleaning and oiling the three vessels, the vessel A was filled with concrete sample. The hinge door of A was opened and concrete falls in to vessel B. Hinge door of B was opened, so that concrete falls to cylinder, C. The surplus concrete in the cylinder was struck off with steel float and the weight of concrete W1 was calculated as the weight of concrete with cylinder minus the weight of the empty cylinder. The cylinder with concrete was vibrated to have full compaction and concrete was filled completely. New weight W2 was taken by the weight of fully compacted concrete with cylinder minus the empty weight of cylinder. Compacting factor = W1/W2

3.4 Testing of concrete in hardened stage

To understand the effect of crumb rubber as a partial substitute for fine aggregates in concrete, the properties like compressive strength, flexural strength, pull-off strength,

oven dry density, water absorption and abrasion resistance were measured as per the procedures given in various codes, after the hardening of the concrete.

The tests to determine the compressive and flexural tensile strength were performed after 7, 28 and 90 days of water curing. Water absorption test, dry density test, pull off strength and abrasion resistance tests were performed after 28 days of water curing. To obtain the test result of a particular sample, average of test results on three specimens were taken. As per IS: 516–1959, specimens stored in water should be tested immediately on removal from the water, while they are still in the wet condition. In our research, the specimens were removed from water and allowed to surface dry for 15-20 minutes and then tested.

3.4.1 Compressive strength test

To test the compressive strength, concrete cube specimens of size 100 mm were cast with varying percentages of crumb rubber (0% to 20% in multiples of 2.5%) and varying water-cement ratios (0.4, 0.45, 0.5 and 0.3). The specimens were de-moulded after 24 hours and kept for curing in clean fresh water whose temperature is maintained at $27^{\circ} \pm 2^{\circ}C$. The specimens are tested for compressive strength after 7, 28 and 90 days of curing (As per IS 516:1959). Three specimens were tested from each sample and the average value was taken.

Figure 3.3: Compression testing machine

The cube specimen was placed on the compression testing machine in such a manner that the load was applied to the opposite side of cubes as cast (not to the top and bottom.) The load was applied without shock and increased gradually at a rate of 140 kg/sq cm/min until the resistance of the specimen breaks down to a stage where no greater load can be sustained. The maximum load was recorded and the compressive strength was calculated by dividing the maximum failure load divided by the cross-sectional area of the specimen. The compressive strength testing machine is shown in Figure 3.3.

3.4.2 Flexural tensile strength test

Concrete beam specimens of size 100mm x 100mm x 500mm were casted with varying percentages of crumb rubber and varying water-cement ratios. The specimens were de-moulded after 24 hours and kept for curing in clean fresh water. The temperature of water is maintained at $27^{\circ} \pm 2^{\circ}C$. The beam specimens are tested on a flexural testing apparatus for 7, 28 and 90 days as per IS 516:1959. Three specimens were tested from each sample and the average value was taken.

Figure 3.4: Flexural tensile strength testing on a universal testing machine

The specimen was placed in the universal testing machine (given in Figure 3.4) and the axis of the specimen was carefully aligned with the axis of the loading device. Four point loading beam arrangement was adopted. The rate of loading was kept as 180 kg/minute. The load was increased until the specimen failed and the maximum load applied to the specimen was recorded. The flexural strength of the specimen was calculated as the modulus of rupture.

3.4.3 Abrasion resistance test

The abrasion test was done to measure the resistance to wear. It was performed according to IS 1237:1980 on 28 days cured concrete cubes (which are oven dried at $60^{\circ} \pm 5^{\circ}C$ for 3 days) of 100 mm size. Weight of the specimens was taken to the nearest 0.5 g. The grinding path of the disc of the abrasion testing machine was evenly spread with 20 grams of abrasive powder. As per IS 1237:1980; the abrasive powder used for the test should be rounded in shape and have the aluminium oxide content for not less than 95% by mass; in the sieve analysis 0-15% by mass can be retained on 250 micron IS sieve, minimum 15% should be retained on 212 micron IS sieve, minimum 70% shall be retained on 180 micron IS sieve and not more than 3% shall be passed through 150 micron IS sieve.

The specimen was fixed on the holding device of the abrasion testing machine (Figure 3.5) such that the surface to be abraded faces the disc, and a load of 600 N was applied on the specimen as the surface area exposed to wear was 100 cm^2. (As per the code, the load shall be 300 N for the surface area of 50 cm^2. As the surface area is doubled, the load is also doubled). The grinding disc is put on motion with 30 revolutions per minute. With the help if a brush, the abrasive powder is continuously fed back to the grinding path. After every 22 revolutions, the face of the specimen and the grinding path is brushed to remove the abraded powder, and the specimen is kept back on the holding device after turning an angle of 90^0 about the vertical axis in the clockwise direction. Fresh abrasive powder of 20 g was applied on the grinding path. This procedure is repeated 9 times, so that the total number of revolutions would be 220. When the procedure of 220 revolutions is over, the specimen is reweighed and the average loss in thickness,'t' is calculated. As per the code, in general purpose tiles, the average maximum wear shall not exceed 3.5 mm and wear on any individual specimen shall not exceed 4 mm. For heavy duty floors, it is 2 mm and 2.5 mm, respectively.

Figure 3.5: Abrasion testing machine

The average loss in thickness, 't' is calculated by the following equation

$$t = \frac{(W_1 - W_2) \times V_1}{(W_1 \times A)}$$

Where,

t = Average loss in thickness (in mm)

W_1 = Initial mass of the specimen (in grams)

W_2 = Final mass of the specimen (in grams)

V_1 = Initial volume of the specimen in mm^3.

A = Surface area of the specimen in mm^2.

3.4.4 Pull-off strength test

The tensile strength on the cover zone concrete is termed as pull-off strength (performed as per BS 1881 Part 207:1992). This test was done on concrete specimens after 28 day curing. After cleaning the surface of the specimen, 50 mm diameter iron discs were perfectly bonded to the concrete using an epoxy adhesive. It was tested after 24 hours of pasting with the epoxy adhesive. The standard loading rate of 5-10 kN/minute was applied. The force that was required to pull-off the disc, along with the

surface area of the concrete was measured as the pull-off strength. The procedure of pull-off strength is given in Figure 3.6 and 3.7.

Figure 3.6: Attaching the iron disc on concrete specimen

Figure 3.7: Procedure showing pull-off strength test

3.4.5 Bulk density test

The bulk densities of concrete mixes were determined as per IS 6441:1972 (Part-1) from 100 mm concrete cube specimens that was water cured for 28 days. After the curing period was over, the cubes were oven dried at $60^{\circ} \pm 5^{\circ}$C temperature for 3 days to get constant weight. The specimens were cooled at room temperature and the weight was taken immediately. The weight divided by volume of the cubes gives the bulk density of the concrete.

3.5 Durability properties of rubberized concrete in hardened stage

The durability parameters of rubberized concrete in hardened state were evaluated by performing the water penetration test, water absorption test, acid attack test, sulphate attack test, chloride ion permeability test, carbonation test and corrosion test. All these tests were done on concrete specimens after 28 days of curing.

3.5.1 Water penetration as per DIN 1048

One of the characteristics that influence the durability of concrete is its permeability to the ingress of water and other potentially deleterious substances.

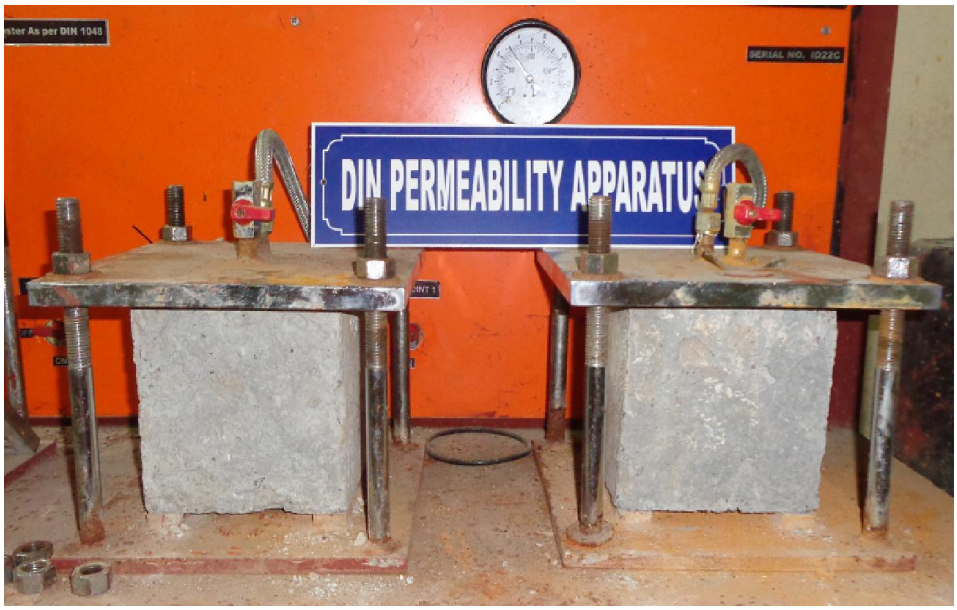


Figure 3.8: Water penetration apparatus as per din 1048

Water penetration test was done according to DIN 1048 (Part 5), on 28 days cured concrete cube specimens of 150 mm size. The German Standard Code was preferred to the IS code (IS 3085:1965) for performing this test because the rate of water penetration as per the IS code is very low. According to DIN 1048 (apparatus given in Figure 3.8), the specimen should be exposed from above, a constant water pressure of 0.5 N/mm^2 acting normal to the mould-filling direction, for a period of 3 days. To provide a water pressure of 0.5 N/mm^2 according to the IS code, a water column of 50 metres should be provided, which is practically not possible.

Figure 3.9: Splitting of concrete specimens to two halves

After the 3 days of exposure to the water pressure, the specimen were removed from the apparatus and split down the centre in to two halves (splitting method given in Figure 3.9). After 5-10 minutes drying, the maximum depth of penetration was measured from the 3 specimen and mean of the measurement was calculated as the depth of penetration. If the depth of water penetration is less than 3 cm, it is termed as low penetration. If it is between 3 cm and 6 cm, it is medium penetration and if the depth is above 6 cm, it is termed as high penetration (Eshmaiel Ganjian et al., 2009).

3.5.2 Water absorption test

The test was done as per ASTM C 642 (2006). The concrete cube specimens of 100 mm size were dried in a ventilated oven at $60^{\circ} \pm 5^{\circ}C$ for 3 days and then kept at room temperature for atleast 1 day (24 hours) and weight W_1 is taken. Then it was immersed in water such that about 50 mm water was maintained on the top surface of the specimen. After 48 hours, the specimens were taken out of the water and allowed to drain for 1 minute by placing them on a dry cloth and the final weight W_2 was taken immediately. The water absorption values of rubberized concrete are compared with the water absorption values of the control specimens.

The measured water absorption was expressed as a percentage of the dry weight of the specimen.

$$Water\,Absorption = \frac{W_2 - W_1}{W_1} \times 100$$

3.5.3 Acid attack test

Degradation can take place if the concrete is exposed to aggressive sulphuric acid environments. It is one of the key durability issues that affect the maintenance costs and life cycle performance of all the concrete structures. There can be presence of sulphuric acid in chemical waste, ground water, etc. In the case of concrete structures in industrial zones, there can be possibility of deterioration due to acid rains in which sulphuric acid can be one of the key components. Sulphuric acid attack is more disastrous than sulphate attack because of the fact that there would be a dissolution effect by the hydrogen ions in addition to the attack by sulphate ions. Corrosion of concrete due to the action of sulphuric acid can be characterized by the following reactions (Bassuoni and Nehdi, 2007).

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

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

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

Gypsum enables volume expansion in concrete, which induces tensile stresses that result in cracking and spalling. Further reaction of gypsum with calcium aluminate can lead to the formation of ettringite which leads to further expansion and more micro and macro cracking. In addition to this, sulphuric acid decalcifies the calcium-silicate-hydrate (C-S-H) and thus decomposes the cementitious matrix and leads to the strength loss of concrete (Bassuoni and Nehdi, 2007).

Resistance to sulphuric acid attack test was performed as per ASTM C 267-97 for a period of for total 84 days. Sulphuric acid of 3% by weight of water was taken as a medium for acid resistance test. Concrete cube specimens of 100 mm size were immersed in a container with dilute sulphuric acid solution. To maintain constant concentration, the H_2SO_4 solution was replaced first after 24 hours of immersion, then at 3rd day, and then at every 7 days. Surface treatments were not performed on the acid attacked specimens before testing them (Attiogbe and Sami, 1988; Bassuoni and Nehdi, 2007).

The following tests were done on acid attacked specimens:

3.5.3.1 Water absorption of acid attacked concrete

The water absorption test was done to study the changes in porosity of concrete due to acid attack. The concrete specimens were tested for water absorption after 28, 56 and 84 days of immersion in dilute sulphuric acid. The test was done as per ASTM C 642 (2006). The concrete cube specimens of 100 mm size were dried in a ventilated oven at $60^{\circ} \pm 5^{\circ}C$ for 3 days and then kept at room temperature for atleast 1 day (24 hours) and weight W_1 was taken. Then it was immersed in water such that about 50 mm water was maintained on the top surface of the specimen. After 48 hours, the specimens were taken out of the water and allowed to drain for 1 minute by placing them on a dry cloth and the final weight W_2 was taken immediately. The values are compared with the water absorption values of the non-acid attacked specimens.

$$Water\,Absorption = \frac{W_2 - W_1}{W_1} \times 100$$

3.5.3.2 Variation in weight (weight loss) of acid attacked concrete

Weight measurement of acid attacked specimens was done after 28, 56, and 84 days of immersion in dilute sulphuric acid. The concrete specimens were allowed to dry in room temperature for 24 hours and then kept in a ventilated oven at 60°C for 3 days. The specimens were allowed to cool at room temperature for atleast 1 day (24 hours) and weight was taken. The variation in weight was compared with the initial oven dried weight before immersion in acid solution.

3.5.3.3 Compressive strength (reduction) of acid attacked concrete

The compressive strength was determined after 28, 56 and 84 days of immersion in acid solution as per ASTM C 579-01. It was compared with the compressive strength of normal concrete (non-acid attacked), which was water cured for 28 days after casting. The results are represented in percentage. The variation in the dimension of the specimen after the exposure was not taken into account while calculating the compressive strength.

3.5.4 Chloride ion penetration

The silver nitrate solution spray method is a simpler and quicker method to determine the chloride ion migration depth of concrete. The test specimens (100 mm concrete cubes) after 28 days of water curing, were subjected to continuous soaking for 91 days in 4% NaCl solution. To maintain constant concentration, the NaCl solution was replaced first after 24 hours of immersion, then at 3rd day, and then at every 7 days. The test specimen were periodically withdrawn at 28, 56 and 91 days from the soaking tank and tested for depth of chloride penetration. The cubes were split into two halves from the middle and the freshly split pieces were sprayed with 0.1N Silver Nitrate ($AgNO_3$) solution. The $AgNO_3$ reacts with the free chloride on the concrete surface and form a white precipitate of silver chloride (AgCl). In the places where the free chlorides are absent, $AgNO_3$ reacts with hydroxide to form a brown precipitate of silver oxide (AgO). Thus, the boundary of colour change indicates the depth of chloride penetration. The formation of silver chloride (white colour) occurs only when the concentration of free chloride ion is greater than 0.15% by weight of cement (Guneyisi et al., 2007 & 2009).

3.5.5 Resistance to sulphate attack

Ordinary Portland cement is susceptible to the attack of sulphates, especially to magnesium sulphates. Sulphates are found in a variety of sources like ground water, sea water, mining pits, high clay content soils, sewer pipes, organic materials in marshes, etc. The common sulphates include magnesium, potassium, calcium, sodium and ammonium. Sulphates reacts with the hydrate of calcium aluminates to form calcium sulphoaluminates (the volume will increase approximately 227% of the volume of the original aluminates) and with the free calcium hydroxides in cement to form calcium sulphate. This reaction leads to the formation of gypsum, ettringite and/or thaumasite and causes detrimental effects like spalling, cracking, softening, expansion loss of strength and other forms of concrete damage. The expansion results in the formation of cracks and subsequent disruption of concrete. This phenomenon is known as the sulphate attack, which will be accelerated if subjected to alternate wetting and drying. This normally takes place in marine structures which are in the zone of tidal variations.

As explained by Nader et al. (2008), sulphate attack is a three step process. Due to the reaction between the tri calcium aluminate in the cement and the sulphate ions from internal and/or external sources, ettringite forms in the cement matrix as the first step. It is shown as below.

$$3CaO.Al_2O_3 + 3(CaSO_4.2H_2O) + 26H_2O \longrightarrow 3CaO.Al_2O_3.3CaSO_4.32H_2O$$

C_3A — Gypsum — Ettringite ($C_6AS_3H_{32}$)

The sulphate ions from ettringite react with remaining tri calcium aluminate to form tetra calcium aluminate monosulphate-12-hydrate, which is known as monosulphoaluminate. The chemical reaction is given below.

$$2(3CaO.Al_2O_3) + 3CaO.Al_2O_3.3CaSO_4.32H_2O + 4H_2O \longrightarrow 3(4CaO.Al_2O_3.SO_3.12H_2O)$$

Monosulfoaluminate

When the monosulphoaluminate is in contact with any new source of sulphate ions, ettringite is formed again as the third step.

$$4CaO.Al_2O_3.SO_3.12\,H_2O + 2(CaSO4.\,H_2O) + 16H_2O \longrightarrow 3CaO.Al_2O_3.3CaSO_4.32H_2O$$

ettringite

When ettringite is continuously formed within the solid concrete, it creates lot of internal pressure that leads to expansion and cracking. Continuous and progressive loss in mass and strength of concrete occurs when it is exposed to sodium sulphate or magnesium sulphate from outside. The sulphate ions react with calcium hydroxide from the cementitious material to form gypsum.

$$Na_2SO_4 + Ca(OH)_2 + 2H_2O \longrightarrow \text{Gypsum} + 2NaOH$$

$$Mg_2SO_4 + Ca(OH)_2 + 2H_2O \longrightarrow \text{Gypsum} + Mg(OH)_2$$

Sulphate attack test was performed according to ASTM C 1012-89. The test specimens (100 mm size concrete cubes) after 28 days of water curing, was taken saturated weight and then were subjected to continuous soaking for 6 months in 3% $MgSO_4$ solution. To maintain constant concentration, the $MgSO_4$ solution was replaced first after 24 hours of immersion, then at 3rd day, and then at every 7 days (Paulo and Kimberly, 2003; Nader et al., 2008). Surface treatments were not

performed for the sulphate attacked specimens before conducting the tests. The test specimens were periodically withdrawn from the soaking tank and the following tests were performed.

3.5.5.1 Variation in weight

Weight measurement of sulphate attacked specimens was done after 28, 91, and 182 days of immersion. The concrete specimens were taken out of the tank and allowed to surface dry in room temperature for 10 to 15 minutes and the weight was noted. The variation in weight was compared with the initial saturated surface dried weight of the specimen.

3.5.5.2 Compressive strength

The compressive strength was determined after 91 and 182 days of immersion in $MgSO_4$ solution. It was compared with the compressive strength of normal concrete (non-sulphate attacked), which was water cured for 28 days after casting. The results are represented in percentage. The variation in the dimension of the specimen after the exposure was not taken into account while calculating the compressive strength.

3.5.5.3 Water absorption

The water absorption test was done (as per ASTM C 642-2006) to study the changes in porosity of concrete due to sulphate attack. The concrete cubes were tested for water absorption after 91 and 182 days of immersion in $MgSO_4$ solution. The concrete cube specimens of 100 mm size were oven dried in a ventilated oven at $60^{\circ} \pm 5^{\circ}C$ for 3 days and then kept at room temperature for atleast 1 day (24 hours) and weight W_1 was taken. Then it was immersed in water such that about 50 mm water was maintained on the top surface of the specimen. After 48 hours, the specimens were taken out of the water and allowed to drain for 1 minute by placing them on a dry cloth and the final weight W_2 was taken immediately. The values were compared with the water absorption values of the non-sulphate attacked specimens.

3.5.6 Test for carbonation in concrete

Carbonation of concrete is a process by which CO_2 in the ambient air penetrates the concrete and reacts with the hydroxides to form carbonates. Carbonation significantly lowers the alkalinity of the concrete which is needed to protect embedded steel from

corrosion. Once this protective layer is lost, the reinforcement may start to corrode and the concrete cover will subsequently fail (Lo and Lee, 2002; Jack et al., 2002)

The depth of carbonation in concrete was measured according to CPC-18, RILEM on concrete cube specimens after 28 days of water curing. Six concrete cubes of 100 mm size were oven dried for 48 hours. Each cube was divided to four pieces of 50 mm width and 100 mm depth with the help of a concrete cutter given in Figure 3.10. These pieces were oven dried 60-70^{0}C at for 2 weeks. After that 2 coat of epoxy paint was applied on the longitudinal surface of the cubes as given in 3.11. After drying and marking, the samples were introduced to the CO_2 chamber given in Figure 3.11. Inside the chamber, the relative humidity is controlled at 50-55%, Carbon dioxide concentration kept at 5 ± 0.2%, Temperature was 27 ± 2^{0}C. After 2, 4, 6, 8, 10, and 12 weeks of CO_2 exposure, 3 pieces from each sample were taken and tested.

Figure 3.10: Concrete cutter

Figure 3.11: Carbonation chamber and epoxy coated concrete samples

The samples were broken into two halves from the longitudinal side and phenolphthalein pH indicator (A solution of 1% phenolphthalein in 70% ethyl alcohol) was sprayed on the freshly broken faces. In carbonated areas where the pH is less than 9.2, the solution remain colourless and in non-carbonated areas where the pH is greater than 9.2, the phenolphthalein indicator turns purple red. The average depth of carbonation and carbonation coefficient was reported for each specimen.

$$Carbonation\cdot Coefficient = \frac{Carbonation\cdot Depth}{\sqrt{Days}}$$

3.5.7 Test for corrosion of steel reinforcements

To measure the corrosion of steel reinforcements, chloride induced corrosion technique was adopted. Macro-cell method was used to measure (monitor) the corrosion activities of embedded steel bars in concrete. The potential difference between anode and cathode across a standard resister of 100 Ω was measured (Song and Saraswathy, 2006; Pradhan and Bhattacharjee, 2009).

To prepare the specimens for corrosion test, three TMT steel bars as given in Figure 3.13. (12 mm diameter and 350 mm length) were taken and properly cleaned with a wire brush for removing the dirt and rust on the surface. Rubber shrink tube was firmly affixed on the two ends of the steel bars at a length of 75 mm. This was done to prevent that area (which is exposed outside the specimen) from getting corroded. Concrete specimens of size 250 mm X 200 mm X 120 mm as given in Figure 3.13 were prepared as per ASTM G 109-2005. The two steel bars were embedded centrally at the bottom area (with a cover of 30 mm from bottom) and one steel bar was placed

centrally at the top (with a cover of 15 mm.) The top steel bar behaves as the anode and the two bottom bars behave as the cathode. A reservoir of 15 mm was made on the top of the specimen for ponding with 3% sodium chloride solution.

After casting, the corrosion specimens were cured in water for 28 days by maintaining the temperature at $27^{\circ} \pm 2^{\circ}$C. The specimens were taken out of curing tank and dried at room temperature for 1 month. All the four vertical sides of the concrete specimen were then coated with two layers of epoxy paint. With the help of electric wires, a standard resister of 100 Ω was connected between the common terminal of the bottom steel bars and the terminal of the top steel bar. On the reservoir at the top of the specimen, a solution of 3% sodium chloride (by weight) was poured. Then the specimens were subjected to alternate wetting and drying cycles as given in Figure 3.14 (2 weeks wetting with sodium chloride solution, followed by 2 weeks drying).

The potential measurements were taken for both the wetting and drying cycles. The first reading for the macro-cell corrosion was taken at the beginning of the second week of the ponding and after this; readings were taken after every 2 weeks. The potential difference between the anode and cathode was taken with a high impedance voltmeter as given in Figure 3.12. The macro-cell current was calculated by the following equation:

$$I_j = \frac{V_j}{100}$$

Where, V_j = Voltage across 100 Ω resistor.

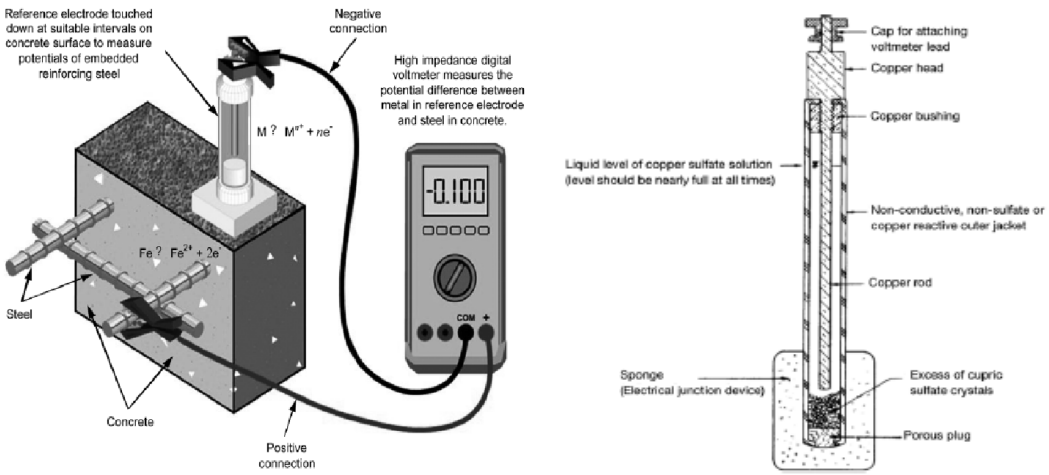


Figure 3.12: From ASTM C 876 (a) reference electrode circuitry- high impedance voltmeter (b) sectional view of copper-copper suiphate electrode

Figure 3.13: Steel bars and concrete specimens

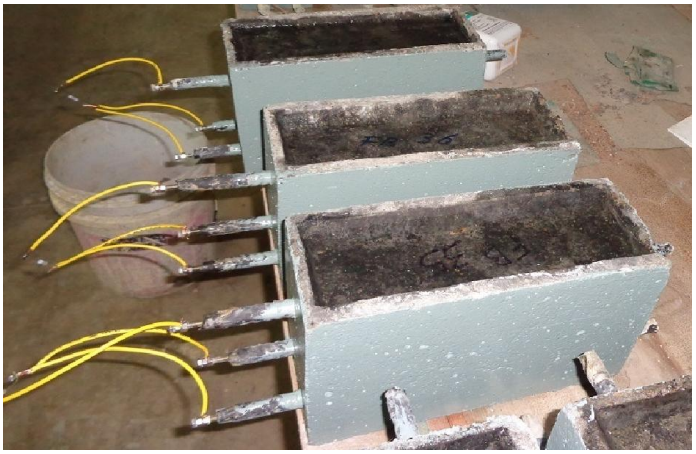


Figure 3.14: Epoxy coated specimens with 3% NaCl Solution

The total integrated current is obtained from the following equation:

$$TC_j = TC_{j-1} + [(t_j - t_{j-1}) \times \frac{(i_j + i_{j-1})}{2}]$$

Where,

TC = Total corrosion (coulombs)

t_j = Time in seconds at which measurement of the macro cell current is carried out

i_j = Macro cell current (amps) at time t_j.

3.5.8 Microstructure by SEM

The microstructure was analysed with the help of a Nova Nano Field Emission Scanning Electron Microscope (FE-SEM) given in Figure 3.15. It is used to provide ultra high resolution characterisation and analysis giving precise, true nanometer scale information. The machine gives a resolution of 1.4 nm at 1 kv (TLD-SE) and 1 nm at 15 kv (TLD-SE) The FE-SEM is coupled with an EDX detector for measuring the elemental chemical composition of the nano materials.

The instrument has a very fine cold field emission electron source, consisting of a tungsten tip cathode of only 100 nm in radius of curvature, and two anodes, the first causing electrons to be emitted from the cathode via an electric field (hence "field emission"), with the second anode then causing the emitted electrons to be accelerated at high velocity. The resulting high emission intensity allows improved resolution combined with a high signal to noise ratio.

Concrete pieces of 1cm size were cut from the top mortar portion (that contains the crumb rubber and fine aggregates) of the concrete cube specimens and done the gold coating in the coating apparatus. Then they are examined under the lens of an FE-SEM apparatus and taken the images at different focus of the lens. Cement, sand, crumb rubber and silica fumes were also examined in the similar manner.

Figure 3.15: FE-SEM machine with EDX attachment.

3.6 Proportioning of mix

For the proportioning of Rubberized concrete, no definite methods for mix design are available. As many researchers have used different quality and different sizes of waste tire rubber, those designs may not work with other set of constituent materials. Most of the researchers have used a single size crumb rubber. When the fine or coarse aggregates (which consist of particles of different sizes) were replaced either partially or completely with a single size crumb rubber, it creates a gap in proper filling of voids. Also in the case of fine aggregates, it will deviate from the particular zone.

The waste tire rubber (crumb rubber) was to be used as a partial substitute for aggregates in concrete. From the literatures, it became clear that the use as a substitute for coarse aggregates would result in huge loss in mechanical properties. So it was decided to use the crumb rubber as a partial substitute only for fine aggregates in concrete.

So the tire rubber was made into crumbs of three sizes (powder form of 30 mesh, 0.8–2 mm and 2–4 mm). The specific gravity of rubber powder was 1.05 and that of the other two sizes were 1.13. The three sizes of crumb rubber were mixed in definite percentages (40% of rubber powder, 35% of 0.8-2 mm size fraction and 25% of 2-4 mm size fraction) to get it in to zone II as per IS 383:1970.

3.6.1 Mix design procedure

In order to achieve the best proportions of the constituent materials, trial mixes were cast and tested at every step.

(a) The grade of concrete (for severe exposure condition) was fixed as M30. OPC 43 grade cement conforming to IS 8112 was selected. Maximum size of aggregates was 20 mm. Minimum cement content was 320 kg/m^3 and maximum was 450 kg/m^3. Maximum water-cement ratio as per IS 456:2000 was 0.45.

(b) The water-cement ratio was fixed as 0.40 and target strength for M30 grade obtained as 38.25 N/mm^2. The water content was fixed based on the trial mixes using super plasticizer. Water content divided by water-cement ratio gives the cement content. It should be greater than the minimum content as specified in the code.

(c) The volume of aggregate was divided into fine aggregates and coarse aggregates. As per the sieve analysis, the coarse aggregate were divided to 20 mm (60%) and 10 mm (40%). They are mixed in a proportion in a way that the final gradation matches with that given in IS: 383-1970 for 20 mm well graded aggregates.

(d) Thus, the mass of constituent materials (cement, water, aggregate and chemical admixture) for one cubic meter concrete was obtained.

(e) Trial mix was done to check for workability and compressive strength (3 days and 7 days)

3.6.2 Trial mix

Trial mix was done for M30 grade concrete with water-cement ratio 0.4. Fine aggregates were replaced by crumb rubber from 0% to 50% by weight. The compressive strength results were taken for 3 days and 7 days. It was observed that there was huge drop in the strength beyond 20% of substitution. Also the variations between the compressive strength of BT and BT 0, BT 0 and BT 1 is very large. The mixture proportions are reported in Table 3.7 and the results for the compressive strength are reported in Table 3.8.

Table 3.7: Mixture proportions for the trial mix

Cement kg/m^3	Water kg/m^3	Coarse Aggregate 10 mm, kg/m^3	Coarse Aggregate 20 mm, kg/m^3	Fine Aggregate kg/m^3	Admixture %
388.000	155.000	486.000	729.000	684.000	0.8

The mixture proportion of the control mix is given in the Table 3.7. Crumb Rubber was replaced for fine aggregate in 10% to 50% in multiples of 10%.

Table 3.8: Compressive strength results for the trial mix

ID	BT	BT 0	BT 1	BT 2	BT 3	BT 4
% of Rubber	0	10	20	30	40	50
3 Day Strength	19.33 N/mm^2	13.11 N/mm^2	10.88 N/mm^2	7.08 N/mm^2	3.56 N/mm^2	2.67 N/mm^2
7 Day Strength	27.11 N/mm^2	16.22 N/mm^2	12.45 N/mm^2	8.45 N/mm^2	3.56 N/mm^2	2.90 N/mm^2

3.6.3 Final composition

Based on the results of the trial mix, it was decided to study the mechanical properties and durability characteristics of concrete in which the natural fine aggregate would be partially replaced with waste tire rubber (crumb rubber). As there was much variation in the results when the substitution was in the amount of 10% each, it was decided to do the substitution in the amount of 2.5%. So the study would be with the substitution of crumb rubber for fine aggregate in cement concrete from 0% to 20%, in multiples of 2.5%. M30 grade concrete was designed with water-cement ratio 0.4. To study the variation in different properties of concrete, the mixes with water-cement ratio 0.45 and 0.50 was also made. The ratio of cement, fine aggregate and coarse aggregate are 1: 1.8: 3.1. The mixture proportions are given in the Table 3.9.

Table 3.9: Mixture proportions of fresh concrete (control mix) with w/c 0.4, 0.45 and 0.5

Water-cement ratio	Cement kg/m^3	Water kg/m^3	Coarse Aggregate 10 mm kg/m^3	Coarse Aggregate 20 mm kg/m^3	Fine Aggregate kg/m^3	Admixture %
0.40	388.0	155.0	465.0	737.2	698.4	0.65
0.45	388.0	174.6	465.0	737.2	698.4	0.30
0.50	388.0	194.0	465.0	737.2	698.4	0

Crumb Rubber was partially substituted for fine aggregate by weight from 2.5% to 20% in multiples of 2.5%. Water-cement ratios of 0.45 and 0.5 were also studied. In the case of water-cement ratio 0.45, the amount of water was 174.6 kg/m^3 and admixture was 0.3% by weight of cement. In the case of water-cement ratio 0.5, the amount of water was 194.0 kg/m^3 and no admixture was used.

A mix of M60 grade concrete was designed to study the properties of waste tire rubber in High Strength Concrete. The ratio of cement, fine aggregates and coarse aggregates are 1: 1.48: 2.67 and the water-binder ratio were 0.30. The mixture proportions are given in the Table 3.10.

Table 3.10: Mixture proportions of fresh concrete (control mix) with water-binder ratio 0.3

Cement kg/m^3	Water kg/m^3	Silica Fumes kg/m^3	Coarse Aggregate 10 mm, kg/m^3	Coarse Aggregate 20 mm kg/m^3	Fine Aggregate kg/m^3	Admixture %
450.0	140.0	27.0	355.0	848.0	666.0	2

The mixture proportions of the control mix are given in Table 3.10. Crumb Rubber was partially substituted for fine aggregate by weight from 2.5% to 20% in multiples of 2.5%.

CHAPTER-4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter deals with the presentation of results obtained in the experimentation programme and the discussion of the results. Total 4 series of concrete were cast with 36 different mixes. In the first series, Test specimens with M30 grade of concrete with a water-cement ratio of 0.4 were casted. Crumb rubber was partially replaced for natural fine aggregate from 0% to 20% in multiples of 2.5%. The properties of concrete with water-cement ratios of 0.45 and 0.50 were also studied as the second and third series to study the variation in different properties. To study the properties of high strength rubberized concrete, Test specimens with M60 grade of concrete were cast with a water-cement ratio of 0.3 as the fourth series. Crumb rubber was partially replaced for natural fine aggregate from 0% to 20% in multiples of 2.5%. Tests for workability, compressive strength, flexural tensile strength, pull-off strength, bulk density, abrasion resistance, water penetration, water absorption, carbonation resistance, chloride ion penetration, acid attack, sulphate attack, and corrosion of the specimens were conducted to determine the fresh and hardened properties of concrete and the observations were recorded. SEM analysis was done for the micro structural studies. The recorded results have been tabulated and discussed below.

In the graphs, it is mentioned as 7 day, 28 day, 91 day, 182 day etc. For mechanical properties, they are the results after the particular day of curing (For example, compressive strength after 7, 28 and 91 days of water curing). For the durability studies, they are the results obtained after the particular day of exposure (For example, the result after 28 and 84 of exposure in carbon dioxide gas, sulphuric acid, etc.)

4.2 Properties of fresh concrete

Workability of fresh concrete was has been calculated by compacting factor test and is presented in the Table 4.1.

Table 4.1: Workability of fresh concrete by compacting factor test

% of Rubber	0	2.5	5	7.5	10	12.5	15	15.5	20
w/c=0.4	0.95	0.95	0.96	0.98	0.97	0.97	0.96	0.98	0.97
w/c=0.45	0.95	0.94	0.94	0.95	0.96	0.95	0.95	0.95	0.94
w/c=0.5	0.95	0.95	0.95	0.96	0.96	0.95	0.95	0.95	0.96
w/c=0.3	0.94	0.94	0.95	0.94	0.95	0.94	0.94	0.95	0.94

The results for the compacting factor test conducted on the concrete with and without crumb rubber for all the four series of water-cement ratios indicate that all the values were in the range from 0.94 to 0.98. Proper workability was achieved by using the sufficient quantities of super plasticizer which was finalized by several trial mixes. For the entire series with w/c ratio 0.4, the amount of admixture used was 0.65% by weight of cement and for the mixture with w/c 0.45, it was 0.3%. In the series with w/c 0.3, the amount of admixture was 2% by weight of cement. Addition of crumb rubber to the concrete has not affected the workability as the compaction factor ranges from 0.94 to 0.98 in the entire mixes.

4.3 Properties at hardened stage

Tests for compressive strength, flexural tensile strength, pull-off strength, bulk density, abrasion resistance, water penetration, water absorption, carbonation resistance, chloride ion penetration, acid attack, sulphate attack, and macro cell corrosion were conducted on the specimens for determining the strength and durability in the hardened stage.

4.3.1 Compressive strength

The compressive strength of the specimens was taken after 7, 28 and 90 days of curing. Graphs showing the variations in the compressive strength with respect to their water-cement ratios and with respect to the percentage of crumb rubber are given in Figures 4.1-4.4. **The limit for compressive strength was kept as 30N/mm^2 for M30 grade concrete and 60 N/mm^2 for M60 grade concrete.** 100mm concrete specimens were used as per IS: 516-1959, clause 2.8.

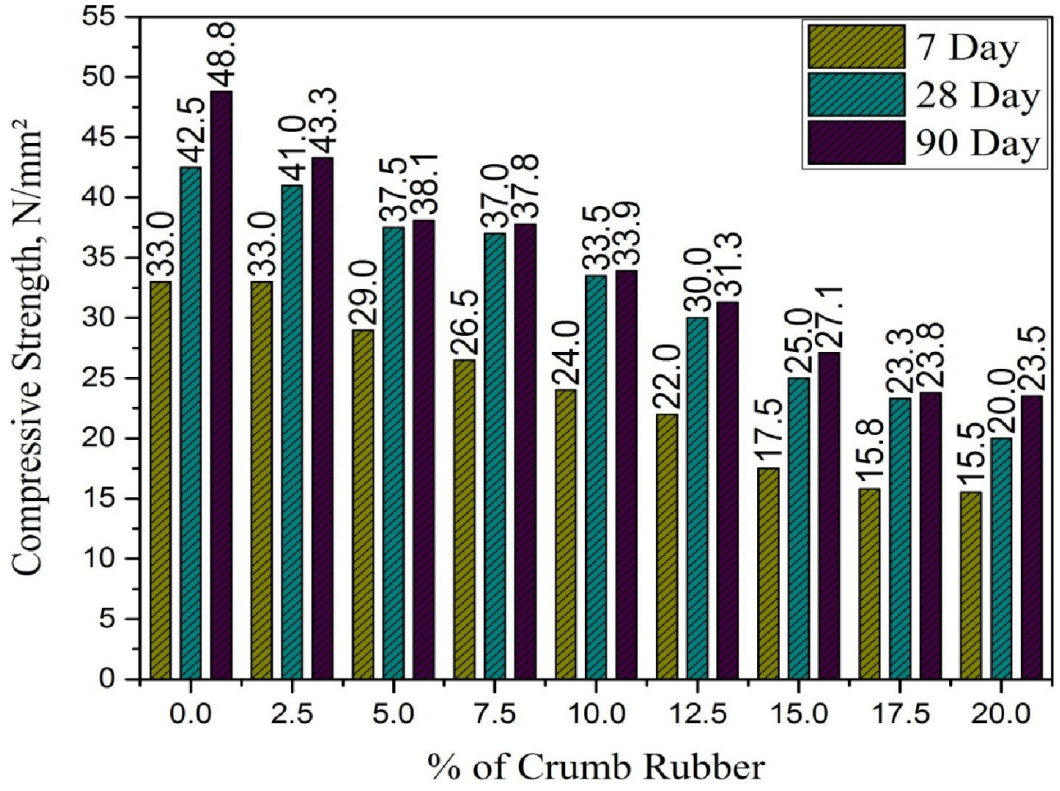


Figure 4.1: Compressive strength of specimens with w/c 0.4

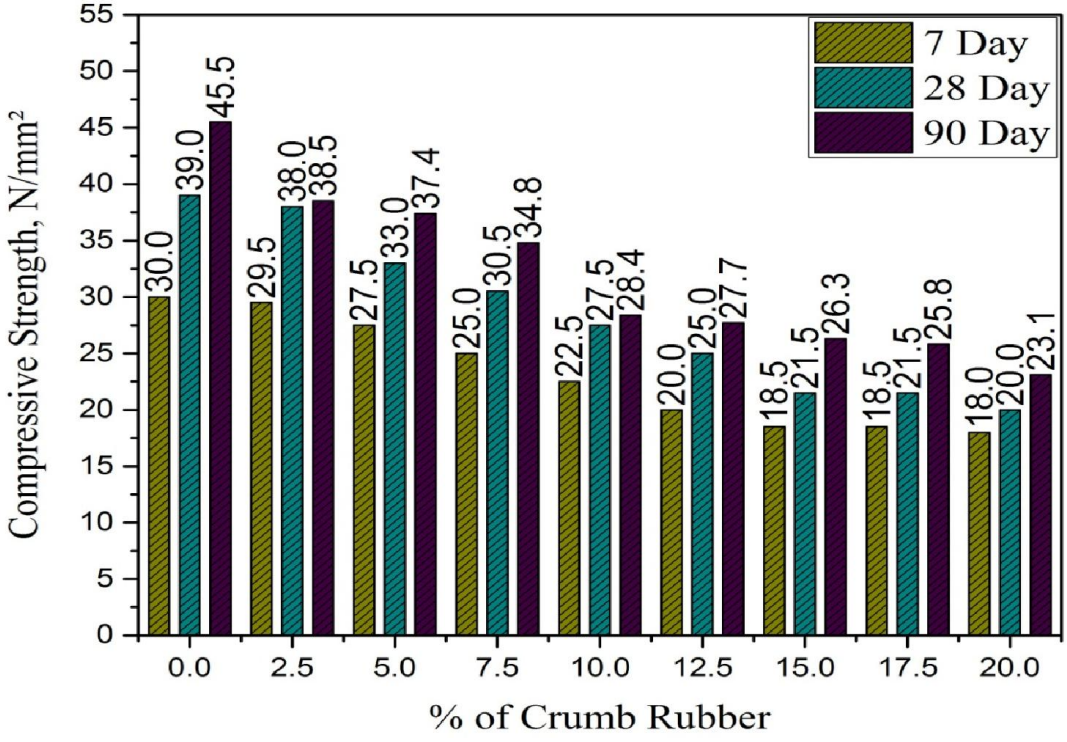


Figure 4.2: Compressive strength of specimens with w/c 0.45

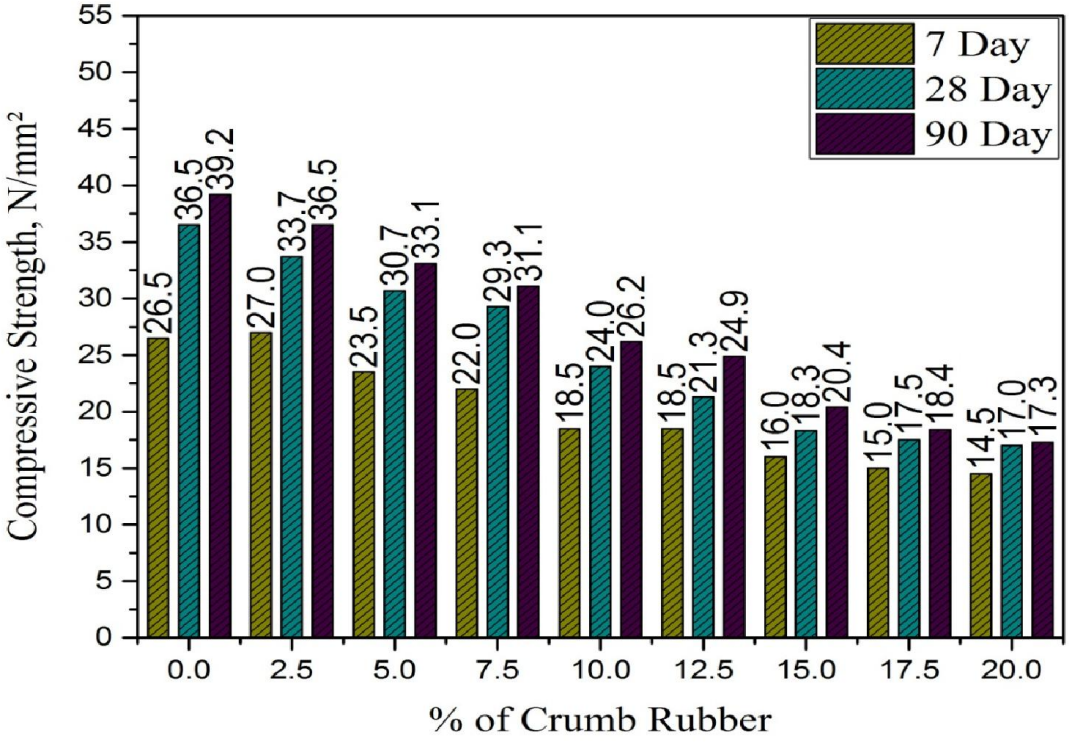


Figure 4.3: Compressive strength of specimens with w/c 0.5

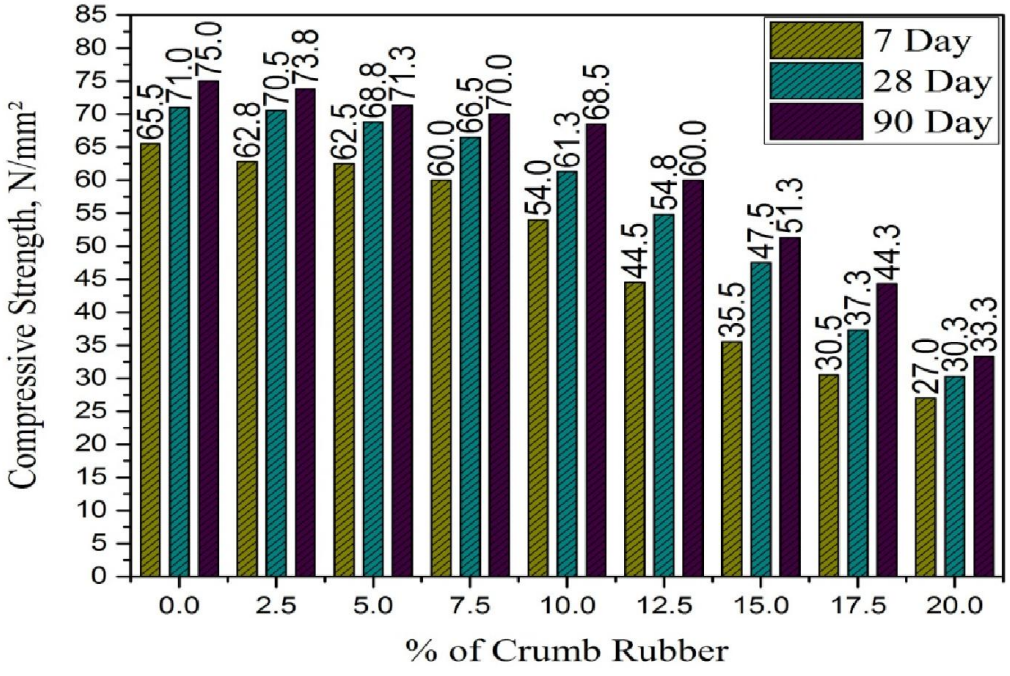


Figure 4.4: Compressive strength of specimens with w/c 0.3

In the concrete mixes with water-cement ratios 0.4, 0.45 and 0.5, gradual decrease in the compressive strength of concrete was noticed as the amount of crumb rubber was increased from 0% to 20%. When the water-cement ratio was 0.4, maximum value for

compressive strength (48.8 N/mm^2) was obtained in the case of control mix concrete and the minimum value (23.5 N/mm^2) was obtained for the concrete mix with 20% crumb rubber. Although there was a decreasing trend in the compressive strength for the increase of crumb rubber, a value above 30 N/mm^2 was obtained for all the 6 mixes in which crumb rubber was substituted from 0% to 12.5% of fine aggregate. Similarly, in the case of water-cement ratios 0.45 and 0.5, a compressive strength above 30 N/mm^2 was observed for the concrete mixes in which the crumb rubber was substituted from 0% to 7.5%. In all the water-cement ratios, the concrete mix with 20% crumb rubber has recorded a reduction of above 50% of that of the control mix concrete specimens. Substantial gain in compressive strength was observed after 90 days of curing. As sufficient amount of water was available for full hydration of concrete, the pore spaces in the concrete were filled by the products of hydration.

In the case of high strength concrete mixes with water-cement ratio 0.3, gradual decrease in compressive strength was noticed as the percentage of crumb rubber increased. The reduction in compressive strength of the mix with 20% crumb rubber was more than 50% than the value obtained in the control mix concrete. At 7 days, the maximum compressive strength (65.5 N/mm^2) was obtained for the control mix with 0% crumb rubber and the minimum value (27 N/mm^2) was obtained for the mix with 20% crumb rubber. Similar trend was observed for the compressive strength at 28 and 90 days. Although there was a decreasing trend in the compressive strength upon increase in the amount of crumb rubber, all the mixes in which the crumb rubber was substituted from 0% to 12.5% crossed the value of 60 N/mm^2 at 90 days of curing.

Figure 4.5: Failure pattern of control specimen and rubberized specimen after compressive loading

The control specimens exhibited brittle failure while the rubberized concrete **did not show brittle failure under compression loading** (given in Figure 4.5). Horizontal cracks were observed for the specimens with rubber and inclined cracks were observed in the control specimens. The loss in mechanical properties of rubberized concrete was supported by the results obtained by various researchers like Al-Mutairi et al. (2010); Anh et al. (2012); Pelisser et al. (2011, 2012); etc.

Ganjian et al. (2009) have mentioned the reasons for the decrease in compressive strength of the rubberized concrete. (a) The aggregates would be surrounded by the cement paste containing rubber particles. This cement paste would be much softer than that without rubber. This results in rapid development of cracks around the rubber particles while loading and this leads to quick failure of specimens. (b) There would be lack of proper bonding between rubber particles and cement paste, as compared to cement paste and natural aggregates. This can lead to cracks due to non uniform distribution of applied stresses. (c) The compressive strength depends on the physical and mechanical properties of the constituent materials. If part of the materials is replaced by rubber, reduction in strength will occur. (d) Due to low specific gravity of rubber and lack of bonding of rubber with other concrete materials, there is a tendency for the rubber to move upwards during vibration leading to higher rubber concentration at the at top layer. Such a non-homogeneous concrete sample leads to reduced strengths.

4.3.2 Flexural tensile strength

Figures 4.6-4.9 show the variations in flexural tensile strength observed at 7, 28 and 90 days with respect to the percentage of crumb rubber. **The limit was kept as 3.83 N/mm^2 for M30 grade concrete and 5.42 N/mm^2 for M60 grade concrete (Flexural strength= 0.7$\sqrt{F_{ck}}$ as per IS: 456-2000).**

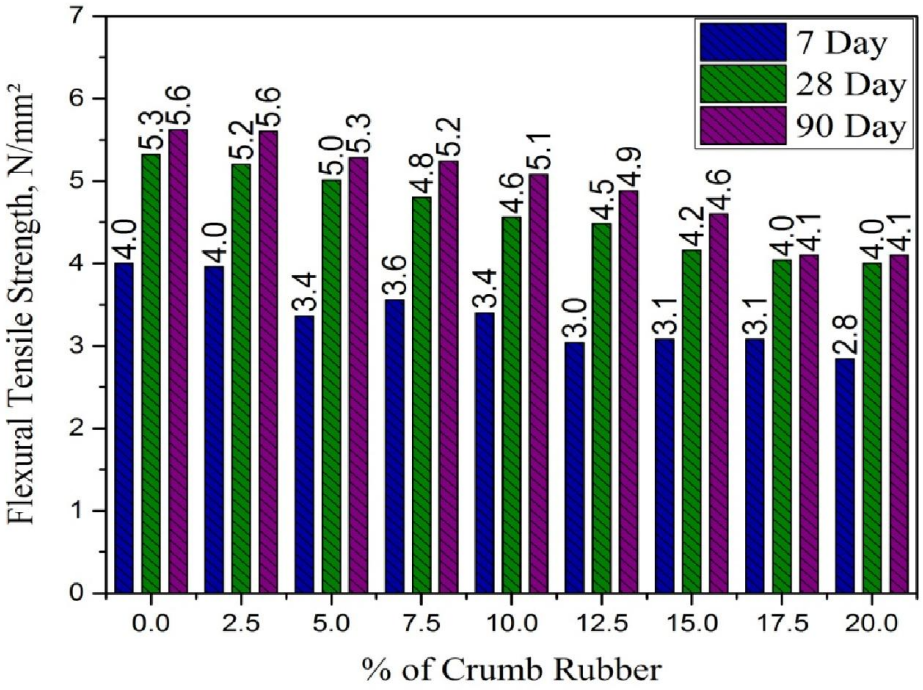


Figure 4.6: Flexural tensile strength of specimens with w/c 0.4

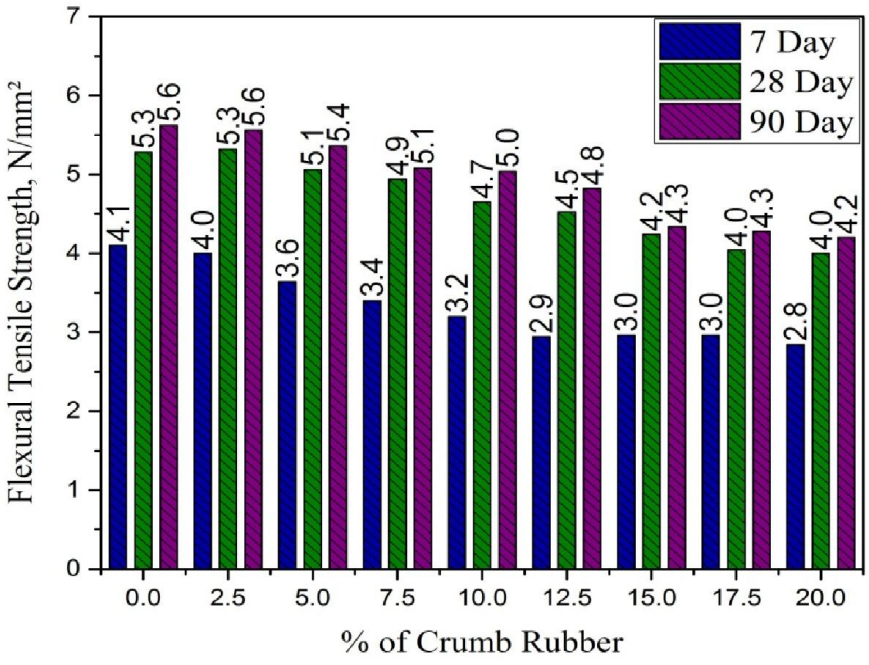


Figure 4.7: Flexural tensile strength of specimens with w/c 0.45

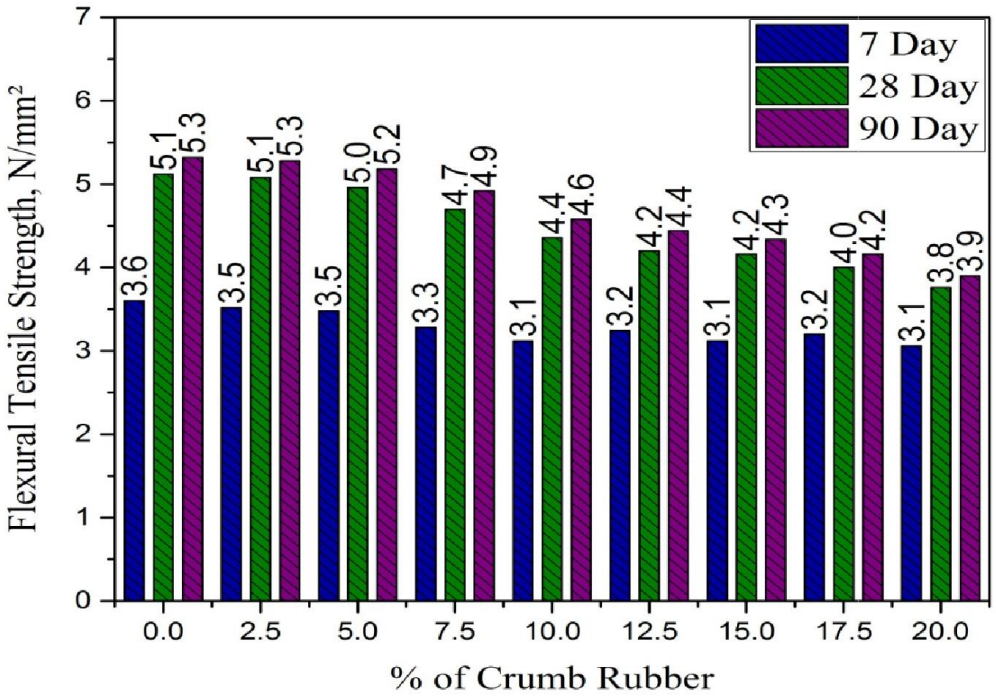


Figure 4.8: Flexural tensile strength of specimens with w/c 0.5

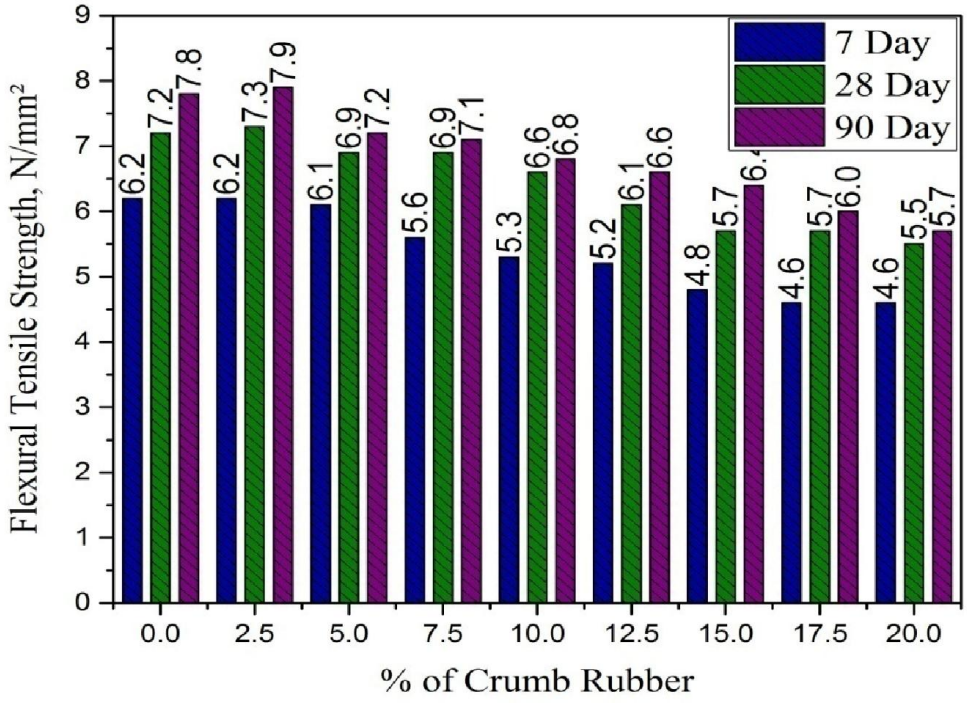


Figure 4.9: Flexural tensile strength of specimens with w/c 0.3

In the case of concrete specimens with water-cement ratios 0.4, 0.45 and 0.5, gradual reduction in flexural tensile strength was observed when the percentage of crumb rubber was increased. When the water-cement ratio was 0.4, flexural tensile strength

reached its maximum of 5.6 N/mm^2 at 90 days for the control mix concrete and minimum of 4.1 N/mm^2 for the mix with 20% crumb rubber substitution. Similar trend was observed for the other water-cement ratios also. It could be noticed that the reduction in flexural strength for the mix with 20% crumb rubber was only 25-27% for the entire mixes when compared to the control mix.

When we observe the 7 days flexural tensile strength of the high strength concrete mixes with water-cement ratio 0.3, the maximum value (6.2 N/mm^2) was observed for the mixes with 0% and 2.5% crumb rubber and minimum value (4.6 N/mm^2) observed for the mixes with 17.5% and 20% crumb rubber. At 28 days, the maximum value (7.3 N/mm^2) was obtained in the mix with 2.5% crumb rubber and minimum value (5.5 N/mm^2) was obtained for the mix with 20% crumb rubber. The flexural tensile strength was expected to decrease if the percentage of crumb rubber is increased further. At 90 days a trend similar to that of 28 days was observed, where the maximum and minimum values were 7.9 N/mm^2 and 5.7 N/mm^2 respectively. When the 90 days strength was considered, the reduction in tensile strength of the mix with 20% crumb rubber was 26% than that of the control mix.

Figures showing the pattern of failure of specimens under flexural loading are displayed in Figure 4.10. It was observed that the control specimens exhibited brittle failure and was broken to two pieces under loading **while the rubberized concrete did not show brittle failure under flexural tensile loading.** They have shown cracks of failure. This was also observed by Ali et al. (2008) and Neil and Ahmed (1994).

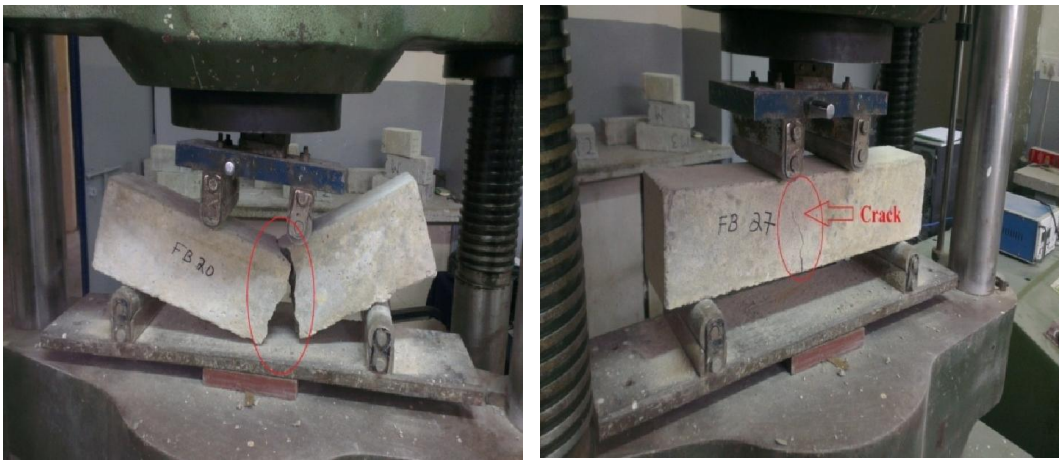
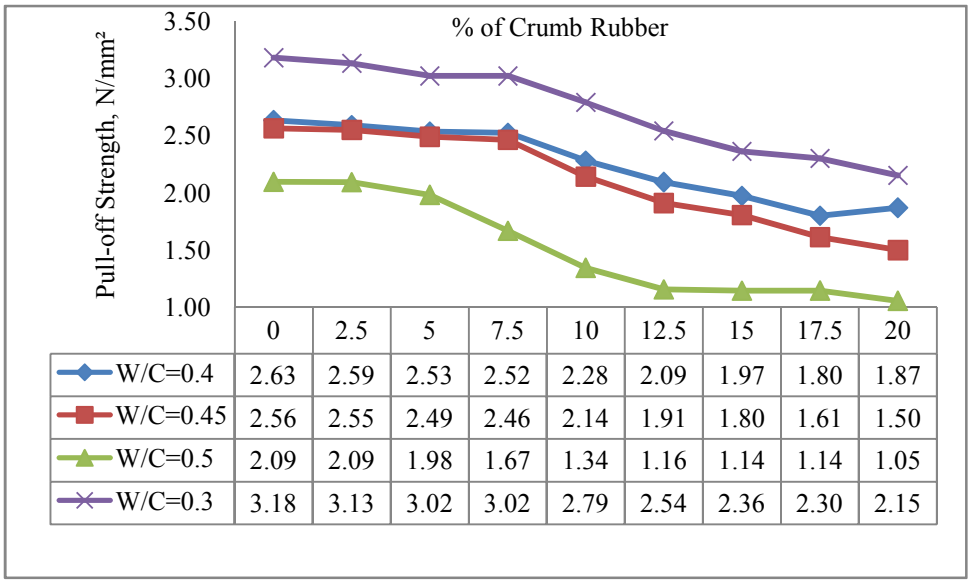


Figure 4.10 : Failure of control mix specimen and the specimen with 20% crumb rubber under flexural loading

4.3.3 Pull-off strength

The pull-off strength test for the entire series of concrete mix was performed on the concrete specimens after 28 days curing. The results are presented in Figure 4.11.



	0	2.5	5	7.5	10	12.5	15	17.5	20
W/C=0.4	2.63	2.59	2.53	2.52	2.28	2.09	1.97	1.80	1.87
W/C=0.45	2.56	2.55	2.49	2.46	2.14	1.91	1.80	1.61	1.50
W/C=0.5	2.09	2.09	1.98	1.67	1.34	1.16	1.14	1.14	1.05
W/C=0.3	3.18	3.13	3.02	3.02	2.79	2.54	2.36	2.30	2.15

Figure 4.11: Pull-off Strength of specimen for all the four series

In M30 series, the highest strength (2.63 N/mm²) was obtained for the control mix concrete with water-cement ratio 0.4. Gradual decrease in the pull-off strength was observed as the percentage of crumb rubber substitution was increased. Similar trend was observed for the mixes with water-cement ratios 0.45 and 0.5. In M60 grade series, the highest strength (3.18 N/mm²) was obtained for the control mix and lowest value (2.15 N/mm²) was observed for the mix with 20% crumb rubber.

It was clear from the results that the variation in pull-off strength closely follows the trends of the corresponding compressive strength results of the mixes as reported by Pereira and Medeiros (2012). They have mentioned that the results of the compressive strength and pull off strength exhibit the same pattern.

4.3.4 Bulk density

The bulk densities of concrete mixes were determined by taking the weights (in grams) and dividing by volume (cm^3). The graph showing the variations in the bulk density with respect to the percentage of crumb rubber is given in Figure 4.12.

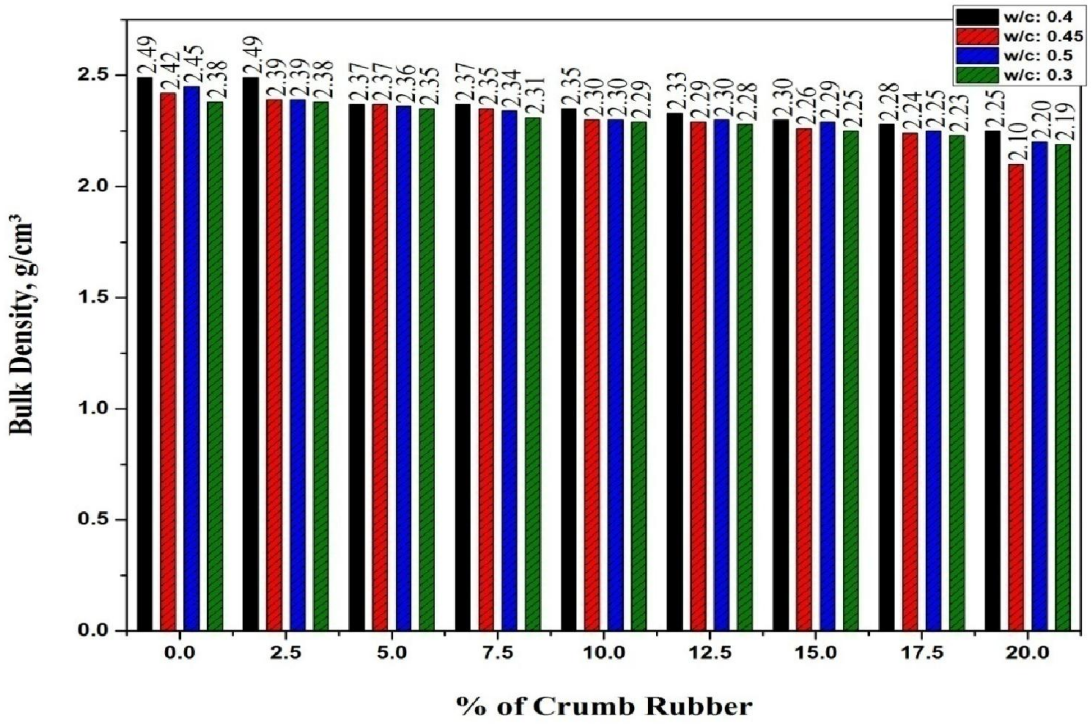


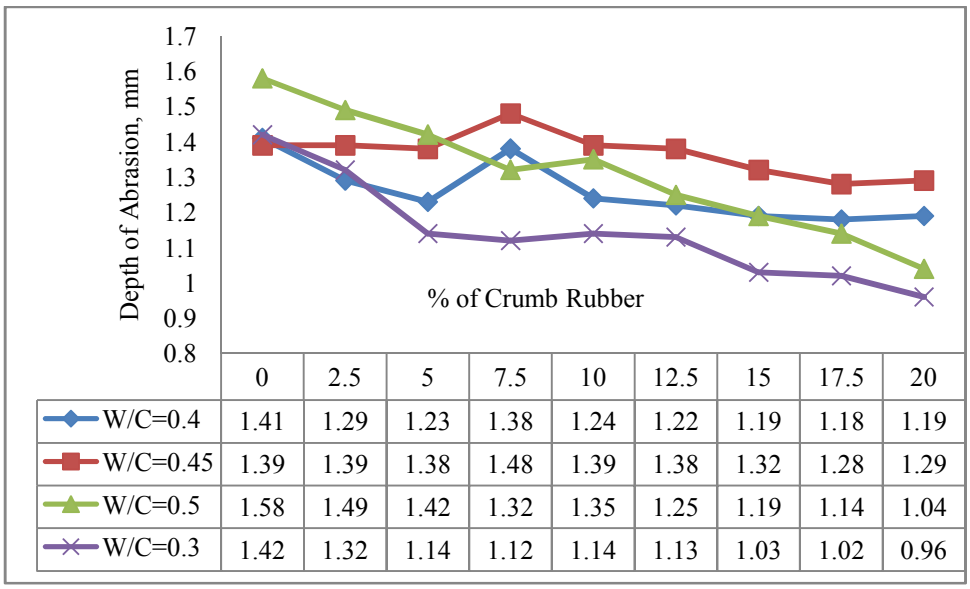
Figure 4.12: Bulk density of specimen for all the four series

From the results, it was clear that the bulk density of the concrete decreased with increase in the amount of crumb rubber. For the entire series, the highest density was observed in the control mixes with 0% crumb rubber and the least density was observed in the mixes with 20% crumb rubber. This decrease in density of concrete is due to the use of crumb rubber which is having much lower specific gravity when compared to the river sand.

4.3.5 Abrasion resistance

Deterioration of concrete can take place due to abrasion caused by various exposures (rubbing, skidding or sliding of the object) on the surface of concrete. Figure 4.13 shows the variations in the depth of surface wear (abrasion) with respect to the percentage of crumb rubber. It was observed that the rubberized concrete exhibited better resistance to abrasion than the control mix. When the water-cement ratio was 0.4, the depth of abrasion was 1.41 mm for the control mix and the abrasion depth for all the mixes up to 20% crumb rubber substitution was less than 1.41 mm. When the water-cement ratio was 0.45, the mix with a rubber content of 7.5% showed less abrasion resistance than that of the control mix, while all the other mixes showed

better resistance to abrasion than the control mix. The abrasion test result of water-cement ratio 0.5 was similar to that of 0.4, where the rubberized concrete showed better resistance to abrasion than the control mix. At water-cement ratio 0.3, the maximum depth of abrasion (1.42 mm) was observed for the control mix with 0% crumb rubber and the minimum value (0.96 mm) was obtained in the concrete with 20% crumb rubber. All the mixes with crumb rubber showed better resistance to abrasion when compared to the control mix.



	0	2.5	5	7.5	10	12.5	15	17.5	20
W/C=0.4	1.41	1.29	1.23	1.38	1.24	1.22	1.19	1.18	1.19
W/C=0.45	1.39	1.39	1.38	1.48	1.39	1.38	1.32	1.28	1.29
W/C=0.5	1.58	1.49	1.42	1.32	1.35	1.25	1.19	1.14	1.04
W/C=0.3	1.42	1.32	1.14	1.12	1.14	1.13	1.03	1.02	0.96

Figure 4.13: Abrasion resistance of specimen for all the four series

Figure 4.14: Surface of the control mix (with 0% crumb rubber) after abrasion test

Figure 4.15: Surface of the rubberized concrete after abrasion test

Table 4.2: Permissible depth of wear as per IS: 1237-1980

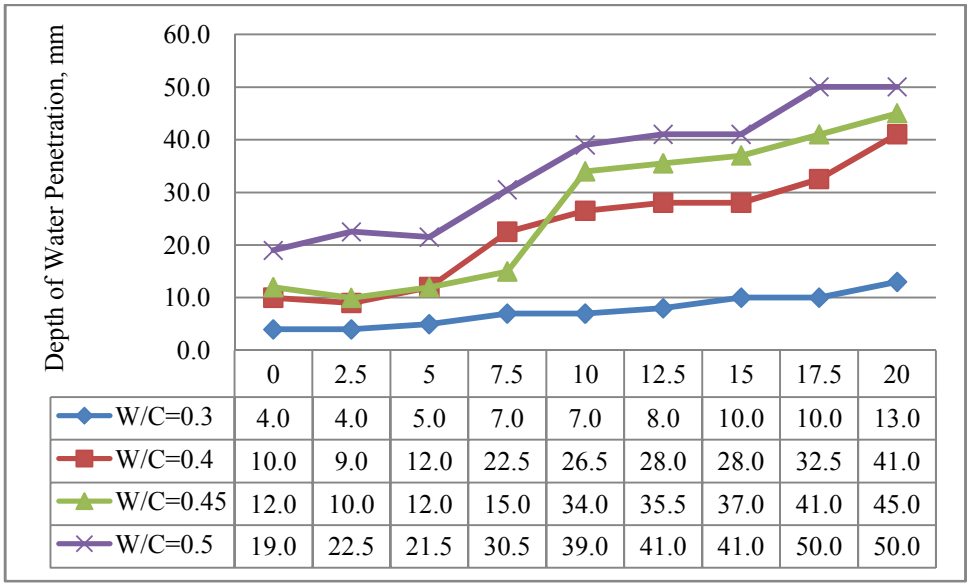
No	Type	Depth of wear
1	General Purpose Tiles- tiles used in floorings subjected to light loads such as office buildings, schools, colleges, hospitals and residential buildings. (i) Average wear (ii) Wear on individual specimen	 3.5 mm 4.0 mm
2	Heavy Duty Floor Tile- tiles used in heavy traffic conditions, such as footpaths, entrances and staircases of public buildings, passages of auditoriums and storage godowns. (i) Average wear (ii) Wear on individual specimen	 2.0 mm 2.5 mm

The permissible values of depth of wear for heavy duty tiles and general purpose tiles as mentioned by IS: 1237-1980 are shown in Table 4.2. As all the values were less than 2 mm, rubberized concrete mixes can be incorporated in both general purpose tiles and heavy duty floor tiles. From the figures given in Figures 4.14 and 4.15, it

appears that during the abrasion test, the crumb rubber particles present in the rubberized concrete projected beyond the smooth surface of the concrete and restricted the grinding/rubbing of the concrete surface by acting like a brush. This minimized the action of abrasive powder on the surface of concrete and hence the rubberized concrete became more resistant to abrasion when compared to the control mix.

4.3.6 Water penetration

Depth of water penetration of various mixes was evaluated as per DIN 1048. Figure 4.16 shows the variations in the depth of water penetration with respect to the percentage of crumb rubber (which was used as a partial substitute for fine aggregates in concrete). Figure 4.17 shows the concrete specimens showing the depth of water penetration.



	0	2.5	5	7.5	10	12.5	15	17.5	20
W/C=0.3	4.0	4.0	5.0	7.0	7.0	8.0	10.0	10.0	13.0
W/C=0.4	10.0	9.0	12.0	22.5	26.5	28.0	28.0	32.5	41.0
W/C=0.45	12.0	10.0	12.0	15.0	34.0	35.5	37.0	41.0	45.0
W/C=0.5	19.0	22.5	21.5	30.5	39.0	41.0	41.0	50.0	50.0

Figure 4.16: Water Penetration of specimen for the entire four series

Figure 4.17: Measurement of depth of water penetration

In the case of water-cement ratios 0.4 and 0.45, the depth of penetration has decreased from the control mix, to the specimen with 2.5% substitution, reached similar to that of control mix for the specimen with 5% substitution and then it gradually increased for the mixes with crumb rubber up to 20%. In the case of w/c 0.4, the water penetration of control specimen was 10 mm. It was 9 mm for the mix with 2.5% crumb rubber and it was 41 mm for the mix with 20% crumb rubber. When the water-cement ratio was 0.5, the depth of water penetration of control mix was 19 mm. The penetration has decreased for the specimen with 5% crumb rubber and then it started to increase gradually, and reached 50 mm in the specimen with 20% crumb rubber. In the M60 grade concrete mixes, the minimum value of 4 mm was observed for the mixes with 0% and 2.5% crumb rubber and the maximum value of 13 mm was observed for the mixes with 17.5% and 20% crumb rubber. It can be concluded that all the mixes with w/c 0.4, 0.45 and 0.5 exhibited low to medium permeability, while the entire mixes of M60 grade (w/c 0.3) concrete exhibited low permeability (According to Eshmaiel Ganjian et. al., 2009. **Range is given in Annexure-4**).

4.3.7 Water absorption

Water absorption of oven dried samples was observed after 48 hours of submergence in water. The results showing the variations in the values are reported in Figures 4.18 and 4.19.

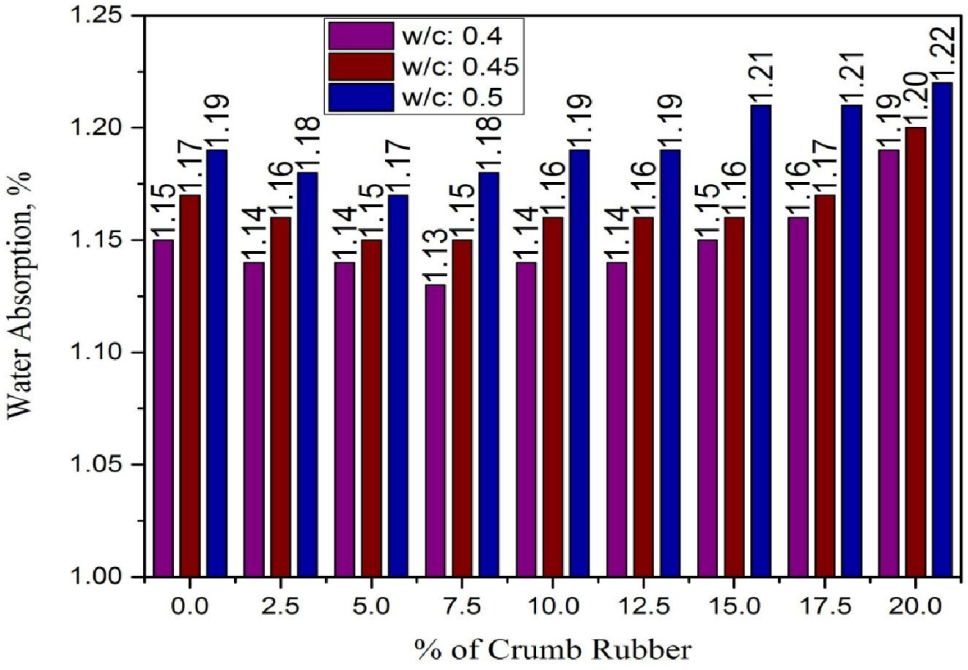


Figure 4.18: Water absorption of specimens with w/c 0.4, 0.45 and 0.5

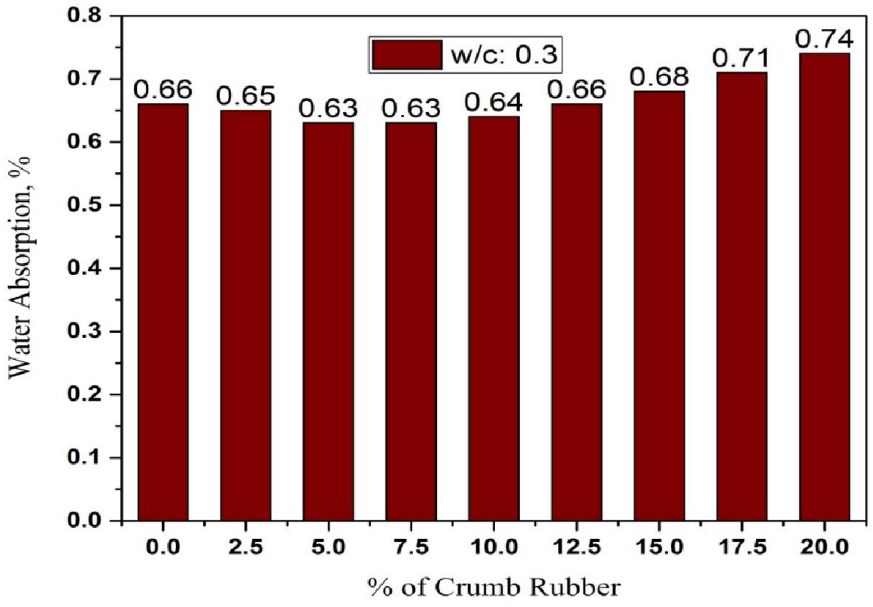


Figure 4.19: Water absorption of specimens with w/c 0.3

In the series with water-cement ratio 0.4, the water absorption of control mix was 1.15% while the absorption of the specimens with 20% crumb rubber was 1.19%. The water absorption value has a decreasing trend for the specimens with 0% to 7.5% crumb rubber. Then it started to increase gradually for the concrete specimens with 10% to 20% crumb rubber. Similar trend was seen in water-cement ratio 0.45. In the case of mixes with w/c 0.5, the decreasing trend was in the specimens from 0% to 5%

crumb rubber substitution. In the specimens with water-cement ratio 0.45, the water absorption of control mix and that of the specimens with 20% crumb rubber were 1.17% and 1.20% respectively. While in the specimens with water-cement ratio of 0.5, it became 1.19% and 1.22% respectively. In all the three series, maximum amount of water absorption was observed in the specimens with 20% crumb rubber. A gradual reduction in the water absorption was observed from the results of the control mix specimens to the mixes with 5% to 7.5% crumb rubber. This is due to the fact that the rubber particles are impervious and does not absorb water. Hence, as the percentage of crumb rubber increased, the water absorption decreased. However beyond 7.5%, the water absorption increased and it may be due to the lack of internal packing of the concrete. This phenomenon can be clearer if we observe the SEM images in Figures 4.70-4.74.

Observing the results concrete mixes with water-cement ratio 0.3, all the mixes with 2.5% to 12.5% crumb rubber had exhibited lesser than or equal water absorption when compared with the control mix. The water absorption values showed a gradual decreasing trend for the mixes in which crumb rubber was substituted from 0% to 7.5% for fine aggregates, and then it started to increase gradually in the mixes with 10% to 20% crumb rubber. The water absorption value for control mix with 0% crumb rubber was 0.66%. It was 0.64% in the mix with 10% crumb rubber and 0.74% for the mix with 20% crumb rubber.

The results reported here are similar to the report of Arin and Nurhayat (2009) and Benazzouk et al. (2007) who observed decrease in the water absorption upon increase in the rubber particles in the concrete. The results are similar to the observations of Oikonomou and Mavridou (2009) who observed decrease in water absorption of rubberized concrete by the method of immersion. Several researchers like Miguel and Jorge (2012), Azevedo et al. (2012), Mehmet and Guneyisi (2011) etc have obtained increase in the amount of water absorption in rubberized concrete. This may be due to the use of single size crumb rubber for the replacement of aggregates, which leads to increased porosity. In our study, the decreasing trend up to 7.5% substitution may be because we have mixed and used three different sizes of crumb rubber to fall in the zone of the replaced sand. It has better pore structure than in the case of the specimens with single size crumb rubber. Beyond 7.5% crumb rubber, the porosity may be very high and the water absorption started to increase.

4.3.8 Carbonation resistance

Figures 4.20-4.23 shows the results of the carbonation resistance of concrete with water-cement ratios 0.4, 0.45, 0.5 and 0.3. The specimens showing the depth of carbonation is reported in Figure 4.24.

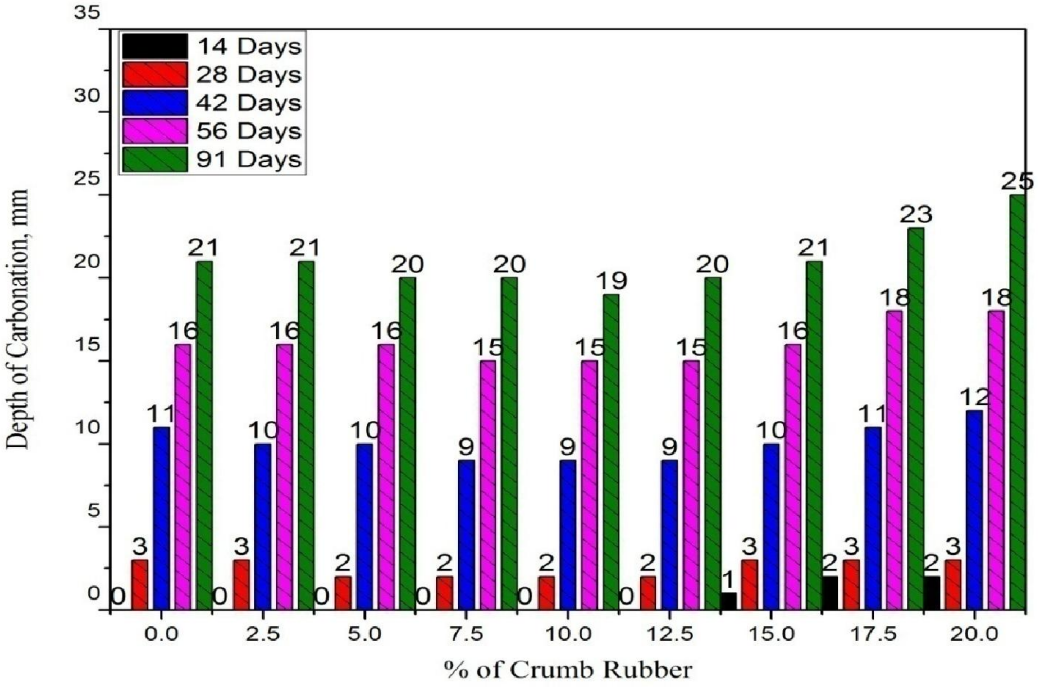


Figure 4.20: Carbonation resistance of specimens with w/c 0.4

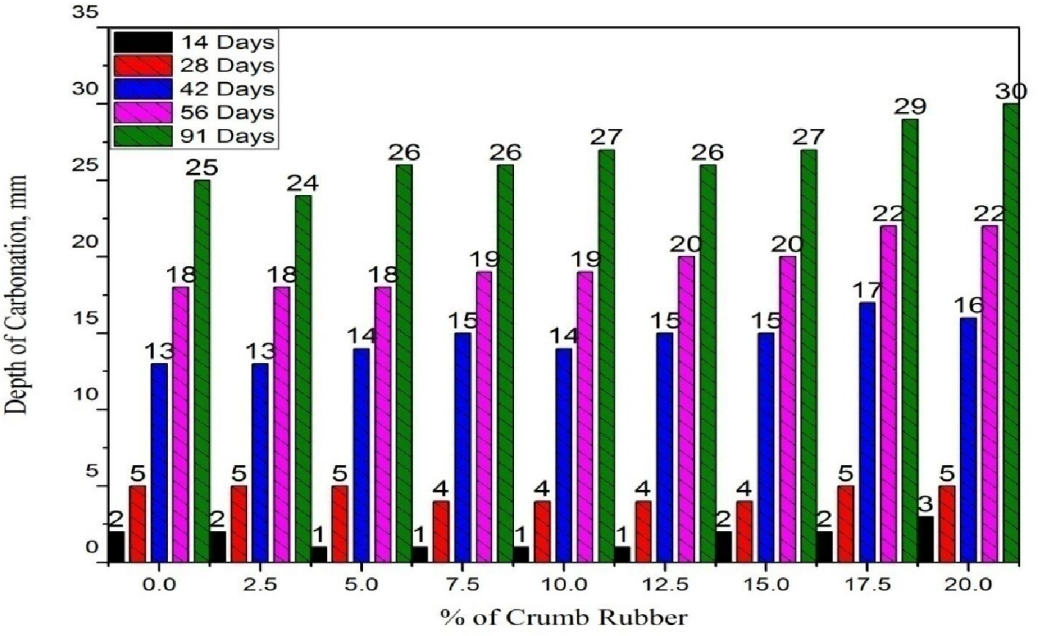


Figure 4.21: Carbonation resistance of specimens with w/c 0.45

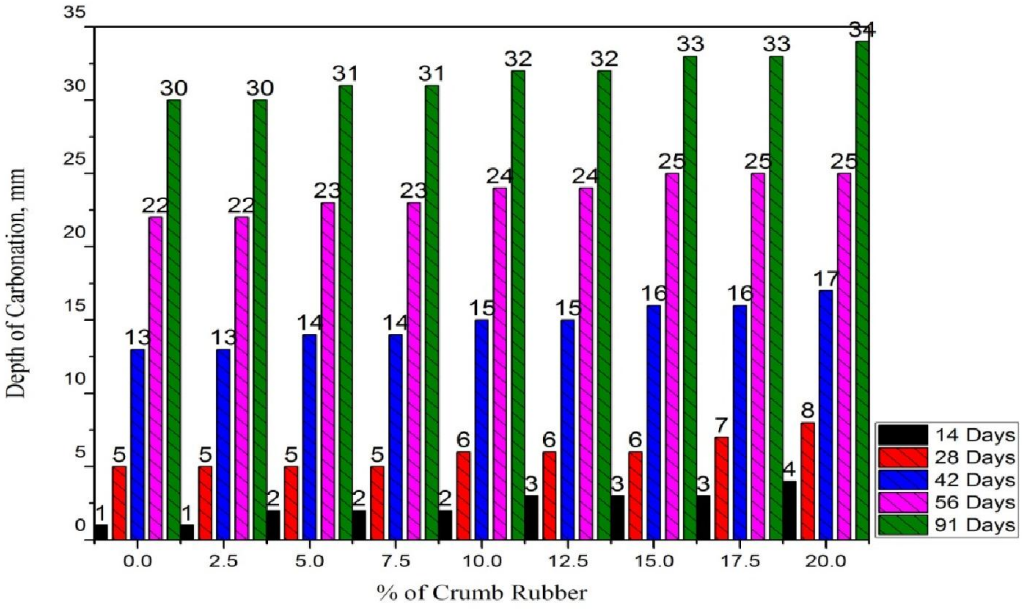


Figure 4.22: Carbonation resistance of specimens with w/c 0.5

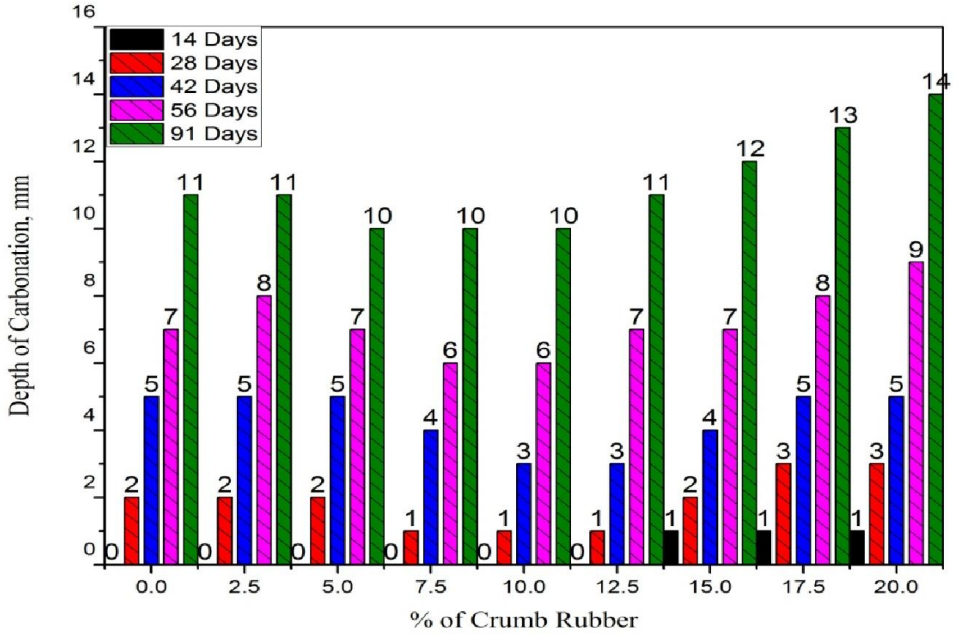


Figure 4.23: Carbonation resistance of specimens with w/c 0.3

From the results we could notice that the depth of carbonation of the concrete mixes with 2.5% to 15% crumb rubber, were less than or equal to that of control mix concrete in case of w/c 0.4. The depth of carbonation of the mixes with 17.5% and 20% crumb rubber were slightly higher than that of the control mix. In the case of water-cement ratio 0.4, at 91 days, the depth of carbonation reached 21 mm for the control mix, while the depth was 25 mm for the mix with 20% crumb rubber. The

depth of carbonation was decreasing in the specimens with 0% to 10% crumb rubber substitution and then it started to increase gradually in the specimens containing 12.5% to 20% crumb rubber. In the series with w/c 0.45 and at 56 days of exposure, the depth of carbonation have shown gradual increase when the amount of crumb rubber was increased in concrete. At 91 days, the carbonation values in the mixes with 0% to 12.5% crumb rubber were not showing any clear trend. Gradual increase and decrease was noticed in some mixes. When the water-cement ratio was 0.5, gradual increase in the depth of carbonation was observed for the increase in the amount of crumb rubber. At 91 days, the depth of carbonation for control mix was 30 mm and it was 34 mm for the mix with 20% crumb rubber. Increase in the amount of carbonation for higher water-cement ratios may be because of the increase in pore sizes of the concrete specimens.

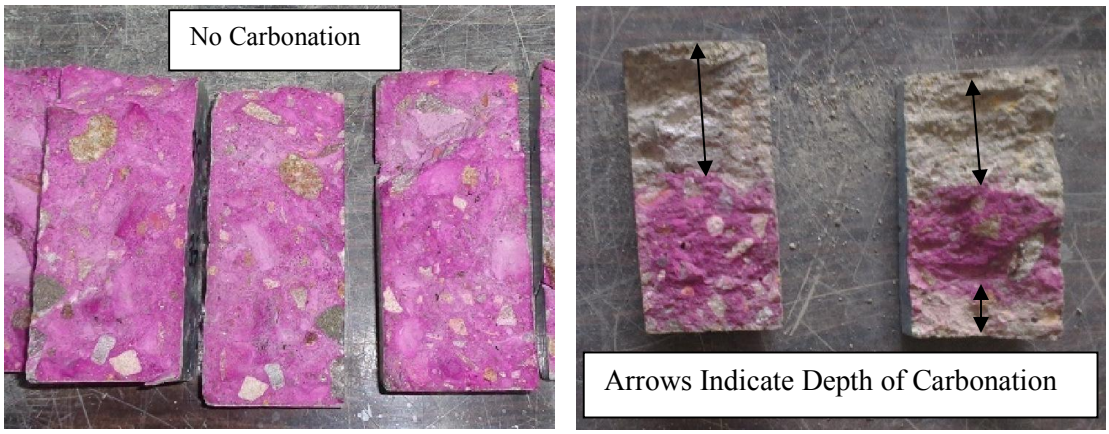


Figure 4.24: Specimens showing the depth of carbonation

In the case concrete with water-cement ratio 0.3, it was noticed that the depth of carbonation of the mixes with 2.5% to 12.5% crumb rubber were less than or equal to that of control mix concrete. A gradual decreasing trend was noticed in the specimens with 0% to 10% crumb rubber. Beyond 10% and up to 20% crumb rubber, there was gradual increase in the depth of carbonation. At 91 days, the depth of carbonation in control mix and in the mix with 20% crumb rubber was 14 mm (the maximum value). Minimum depth (10 mm) was observed in the mix with 5%, 7.5% and 10% crumb rubber.

Reduction in the depth of carbonation was observed at lower water-cement ratios. This can be attributed to the improved pore structure at reduced water-cement ratios. Miguel and Jorge, (2012) had mentioned that, when the tire aggregates were replaced

for the coarse aggregates in concrete, the carbonation depth had increased. In our case for lower water-cement ratios, the depth of carbonation had decreased up to 10% crumb rubber. This could be because of the reason that the fine aggregates and the replaced crumb rubber were almost the same size (Zone II) and these closely packed rubber particles along with the natural aggregates in the concrete may prevent the entry of carbon dioxide gas in to the concrete. The rubber powder might have provided a filler effect in the concrete to reduce the depth of carbonation. Better pore structures in the case of mixes with lower water-cement ratios can also help in reducing the depth of carbonation. Increase in the depth of carbonation beyond 10% crumb rubber would be due to the lack of internal packing in the concrete specimens.

Some of the mixes did not show any carbonation at 14 days of exposure. Hence carbonation coefficients were calculated for the exposure of 28 days onwards. The carbonation coefficients calculated for the series with water-cement ratios 0.4, 0.45, 0.5 and 0.3 have been shown in Tables 4.3-4.6 and the variations are shown in Figures 4.25-4.28.

Table 4.3: Results for the carbonation coefficient of concrete mixes with w/c 0.4

Days ⇒ / % of Crumb Rubber ⇓	28	42	56	91
0	0.57	1.69	2.14	2.20
2.5	0.57	1.54	2.14	2.20
5	0.38	1.54	2.14	2.09
7.5	0.38	1.39	2.01	2.09
10	0.38	1.39	2.01	1.99
12.5	0.38	1.39	2.01	2.00
15	0.57	1.54	2.14	2.20
17.5	0.57	1.69	2.41	2.41
20	0.57	1.85	2.41	2.62

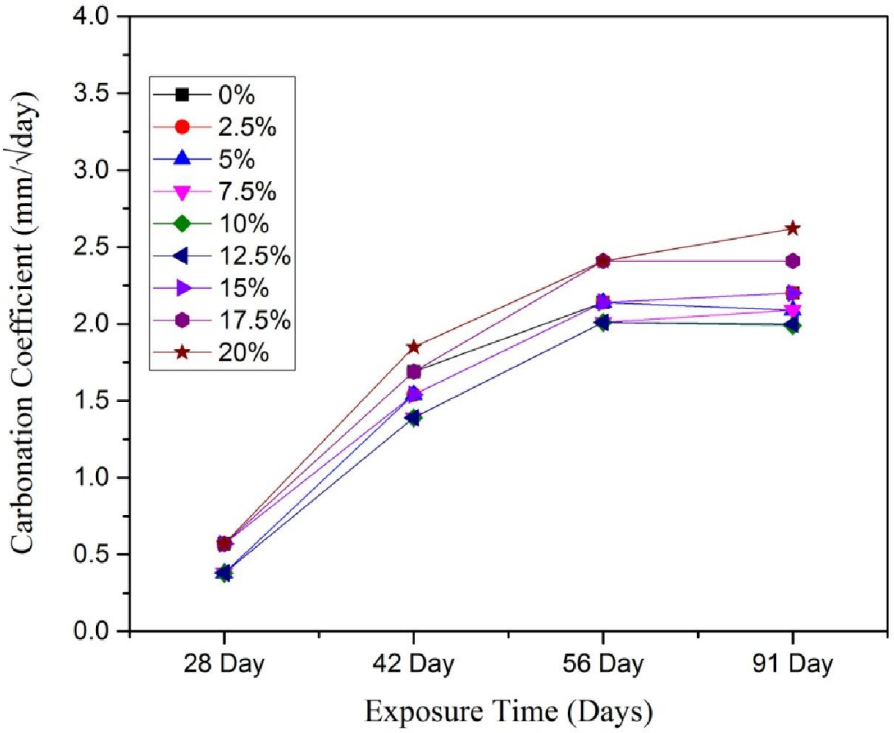


Figure 4.25: Carbonation coefficient for the series with w/c 0.4

Table 4.4: Results for the carbonation coefficient of concrete mixes with w/c 0.45

Days ⇨ / % of Crumb Rubber ⇩	28	42	56	91
0	0.94	2.01	2.41	2.62
2.5	0.94	2.01	2.41	2.52
5	0.57	2.16	2.41	2.73
7.5	0.57	2.31	2.54	2.73
10	0.57	2.16	2.54	2.83
12.5	0.76	2.31	2.67	2.73
15	0.76	2.31	2.67	2.83
17.5	0.94	2.62	2.94	3.06
20	0.94	2.47	2.94	3.14

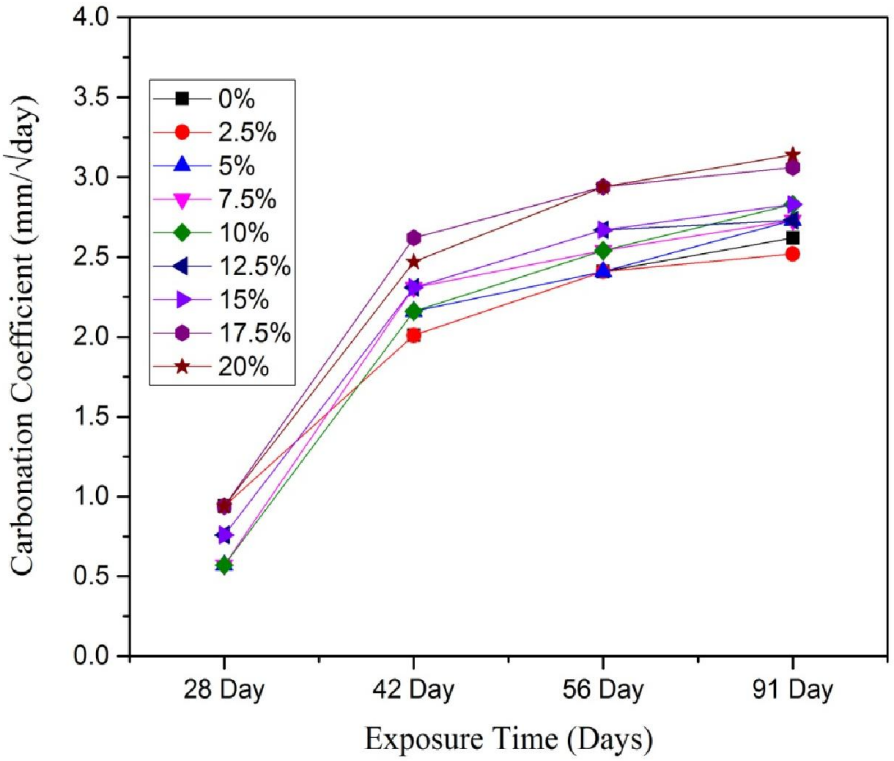


Figure 4.26: Carbonation coefficient for the series with w/c 0.45

Table 4.5: Results for the carbonation coefficient of concrete mixes with w/c 0.5

Days ⇒ / % of Crumb Rubber ⇓	28	42	56	91
0	0.76	2.47	2.94	3.14
2.5	0.94	2.31	2.94	3.14
5	0.94	2.16	3.07	3.25
7.5	0.94	2.16	3.07	3.25
10	0.76	1.85	3.21	3.35
12.5	0.76	1.85	3.21	3.35
15	0.76	1.85	3.34	3.46
17.5	0.76	2.01	3.34	3.46
20	0.94	2.31	3.34	3.56

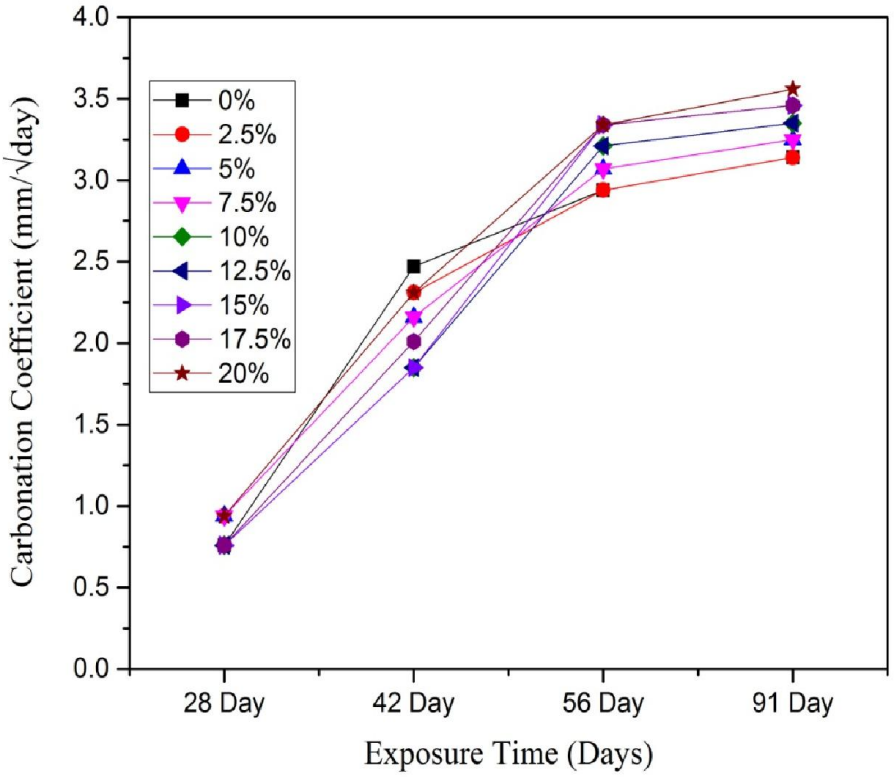


Figure 4.27: Carbonation coefficient for the series with w/c 0.5

Table 4.6: Results for the carbonation coefficient of concrete mixes with w/c 0.3

Days ⇨ / % of Crumb Rubber ⇩	28	42	56	91
0	0.38	0.77	0.94	1.15
2.5	0.38	0.77	1.07	1.15
5	0.38	0.77	0.94	1.05
7.5	0.19	0.62	0.80	1.05
10	0.19	0.46	0.80	1.05
12.5	0.19	0.46	0.94	1.15
15	0.38	0.62	0.94	1.26
17.5	0.57	0.77	1.07	1.36
20	0.57	0.77	1.20	1.47

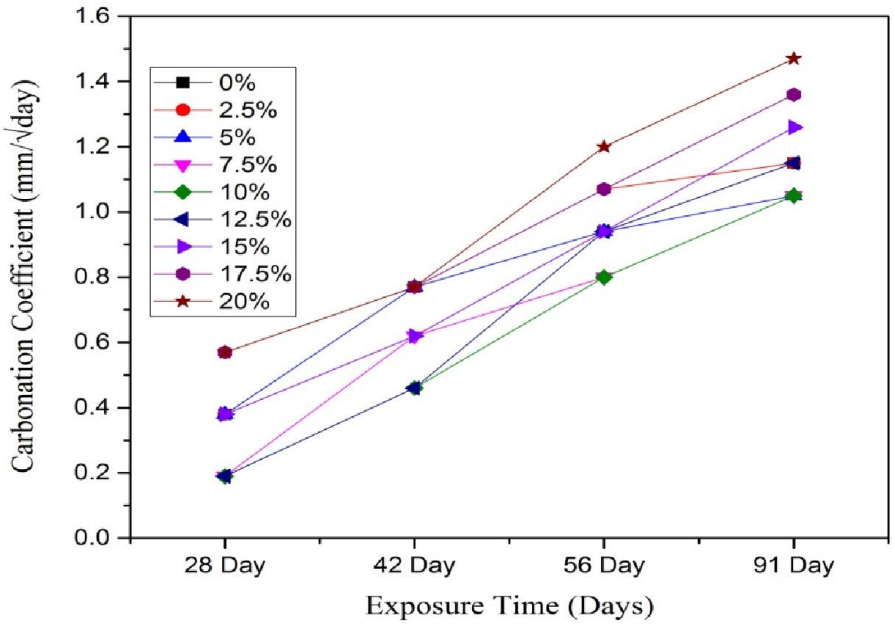


Figure 4.28: Carbonation coefficient for the series with w/c 0.3

In the series with water-cement ratio 0.4, signs of carbonation has started showing by 28 days of testing. A flattening trend of carbonation coefficient was observed at 91 days of exposure for the water-cement ratios 0.4, 0.45 and 0.5. In the series with water-cement ratio 0.5, the carbonation coefficient showed a trend which was about to get flattened up at 91 days of exposure. In the series with w/c ratio 0.3, all the mixes with 0% to 12.5% crumb rubber showed a flattening trend in the carbonation coefficient at 91 days. The mixes with 15%, 17.5% and 20% crumb rubber showed an increasing trend at 91 days of exposure.

Results indicated that the concrete mixes with lower w/c ratios offered more resistance to carbonation. In the mixes with higher water-cement ratios, the depth of carbonation of rubberized concrete up to 7.5% of substitution was less than or similar to that of control mix. The resistance to carbonation decreased as the percentage of crumb rubber increased.

4.3.9 Chloride ion penetration

The graphs showing the variation in the depth of chloride ion penetration with respect to the percentage of crumb rubber are given in Figures 4.29-4.32 and the photograph of the specimens after silver nitrate spraying test are given in Figure 4.33 and 4.34.

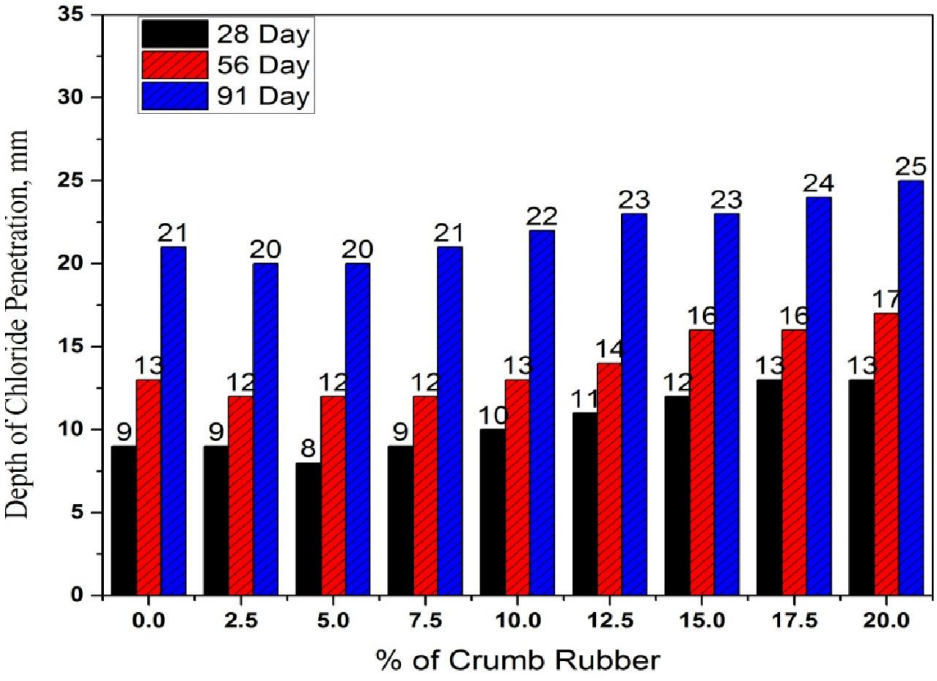
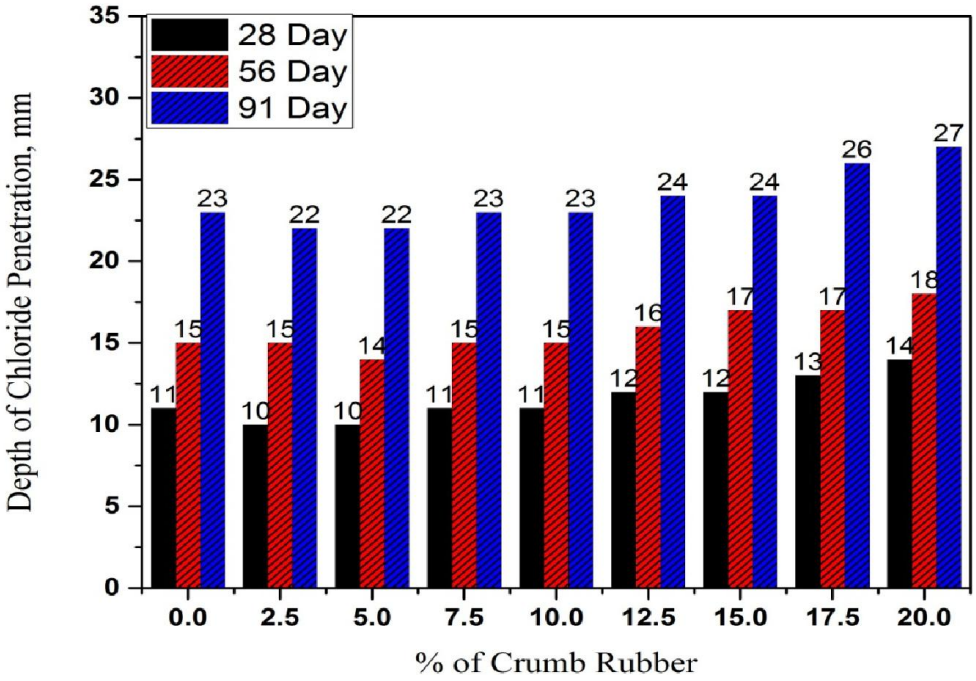


Figure 4.29: Chloride ion penetration of concrete mixes with w/c 0.4



4.30: Chloride ion penetration of concrete mixes with w/c 0.45

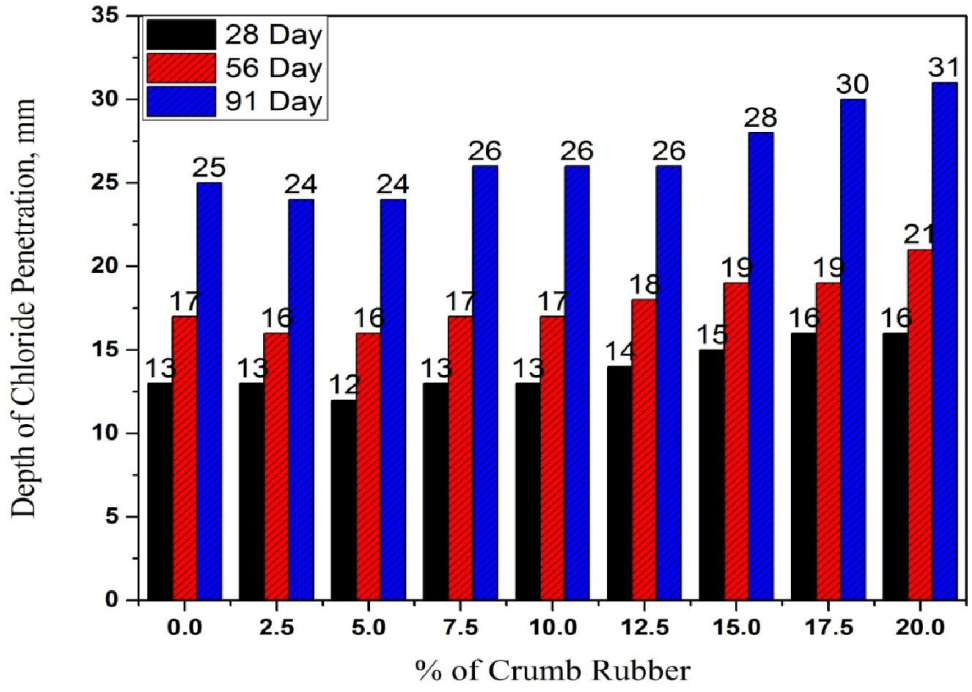


Figure 4.31: Chloride ion penetration of concrete mixes with w/c 0.5

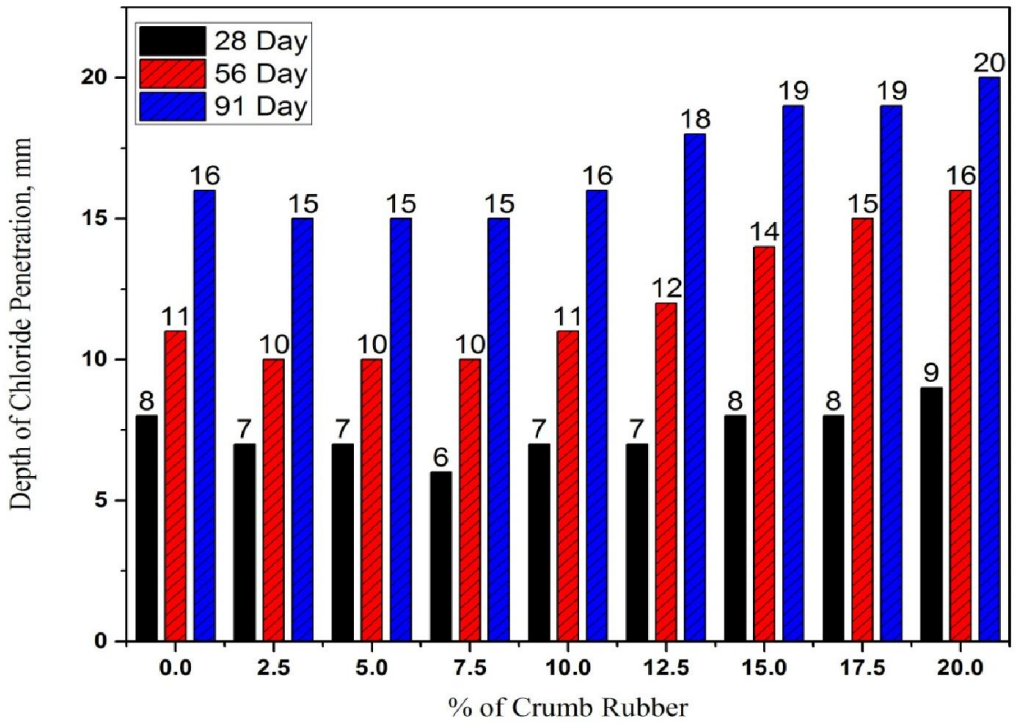


Figure 4.32: Chloride ion penetration of concrete mixes with w/c 0.3

Figure 4.33: Freshly splitted concrete specimen and the control specimen showing depth of chloride penetration after 28 days (arrow shows depth of chloride penetration)

Figure 4.34: Specimens with crumb rubber showing the depth of chloride penetration after 28 days test

When we consider the concrete mixes with water-cement ratio 0.4, the depth of chloride penetration of the mixes with 0% to 7.5% crumb rubber were less than or equal when compared with the value of the control mix. A gradual increase in the depth of chloride penetration was observed in the specimens beyond 7.5% substitution with crumb rubber. At 91 days, the depth of penetration was 21 mm for the control mix (0% crumb rubber), 22 mm for the mix with 10% crumb rubber and 25 mm for the mix with 20% crumb rubber. Similar trend was observed for the mixes with water-cement ratio 0.45. In the case of the series with w/c 0.5, the depth of chloride penetration of the concrete mixes with 0% to 5% crumb rubber was less than that of the control mix. A decreasing trend in the depth of chloride penetration was observed for the concrete mixes with 0% to 5% crumb rubber for fine aggregates. In the mixes where crumb rubber was above 5%, there was gradual increase in the depth of chloride ion penetration.

In the case of high strength concrete with water-cement ratio 0.3, the depth of chloride penetrations of the mixes with crumb rubber up to 10% of fine aggregates was less than or similar to the values of the control mix. The mixes with 12.5% to 20% crumb rubber had shown higher depth of chloride penetration than that of the control mix. The chloride ion penetration exhibited gradual reduction for the mixes with 0% to 7.5% crumb rubber. Gradual increase in the depth of chloride ion penetration was observed for the mixes with 10% to 20% crumb rubber. In 28 days, the chloride penetration value of the control mix specimen was 8 mm, that of the specimen with 10% crumb rubber was 7 mm, and it was 9 mm for the specimen with 20% crumb rubber. A similar trend was observed at 56 days and 91 days of immersion. At 91

days, the value of control mix was 16 mm. Minimum value of 15 mm was obtained for the mix with 2.5%, 5% and 7.5% crumb rubber and the maximum value of 20 mm was obtained for the mix with 20% crumb rubber.

The reason for the gradual reduction in the depth of chloride penetration from the mixes with 0% to 5% crumb rubber (for w/c 0.4) would be due to the fact that the rubber particles are impervious and does not absorb water and simultaneously does not allow the passage of chloride ions. As the percentage of crumb rubber increased, the depth of chloride penetration decreased. However beyond 7.5% crumb rubber, the chloride penetration increased and it may be due to the lack of internal packing of the concrete.

4.3.10 Acid attack

The concrete specimens were immersed in dilute sulphuric acid for a period of 84 days and the following tests were done.

4.3.10.1 Reduction in compressive strength of acid attacked specimens

The compressive strength of acid attacked specimens was calculated at 28, 56 and 84 days of immersion and the results were compared with the compressive strength of non-acid attacked specimen at 28 days of curing. The amount of loss was calculated and expressed in percentage in the graphs given in Figures 4.35-4.38.

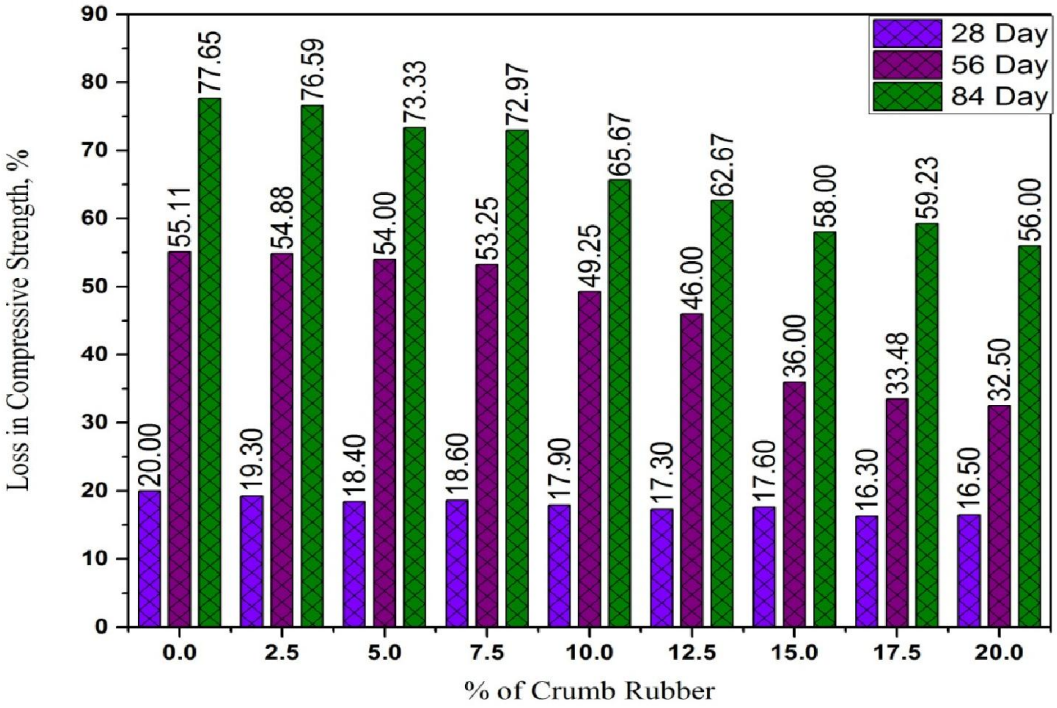


Figure 4.35: Reduction in compressive strength (%) of acid attacked concrete specimens with w/c 0.4

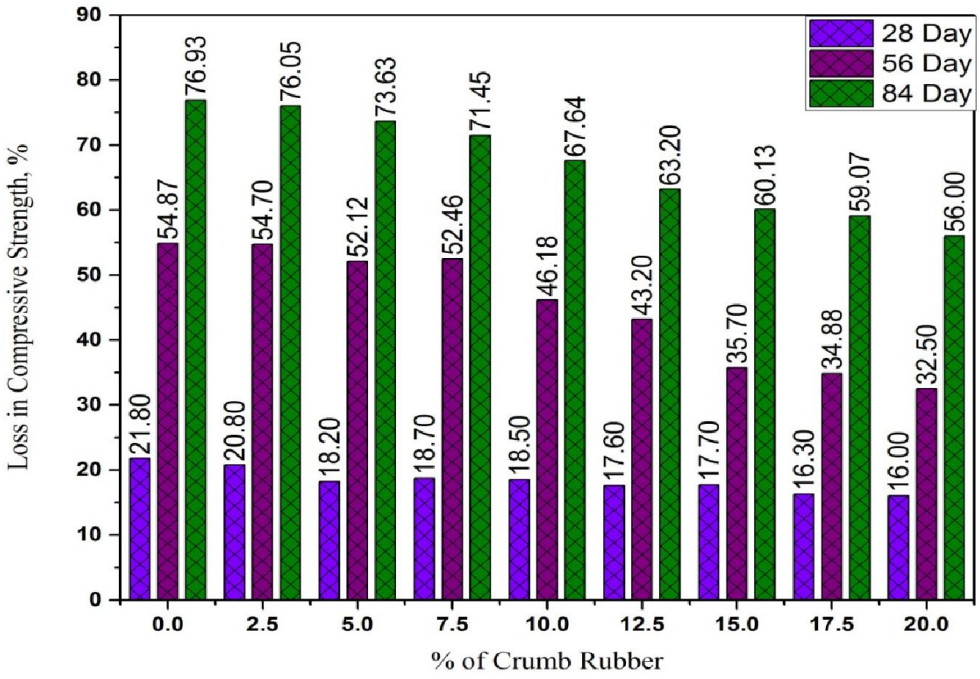


Figure 4.36: Reduction in compressive strength (%) of acid attacked concrete specimens with w/c 0.45

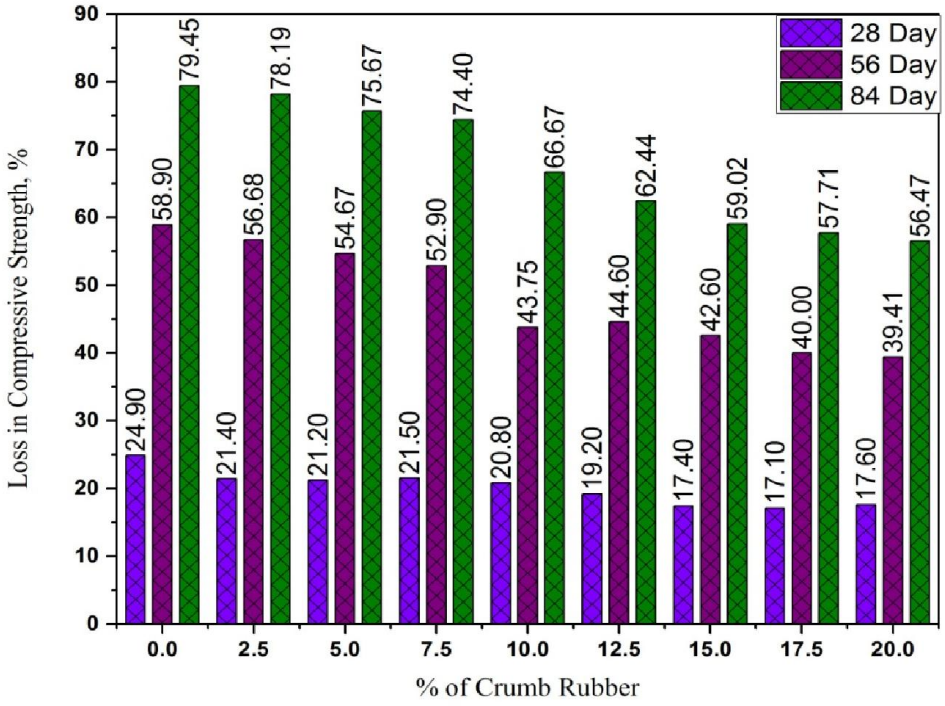


Figure 4.37: Reduction in compressive strength (%) of acid attacked concrete specimens with w/c 0.5

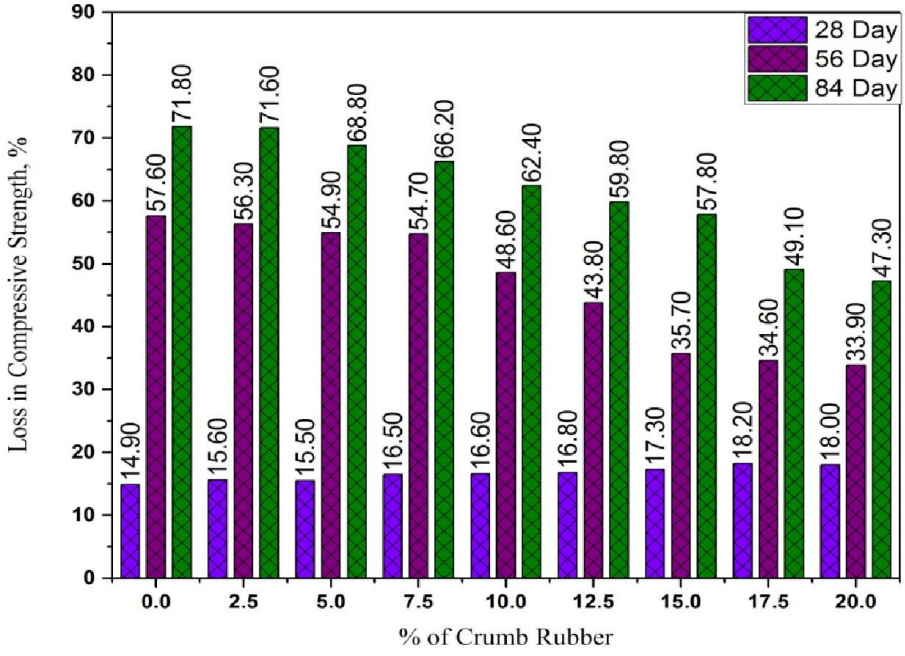


Figure 4.38: Reduction in compressive strength (%) of acid attacked concrete specimens with w/c 0.3

In the case of concrete mixes with w/c 0.4, 0.45 and 0.5, more reduction in compressive strength was observed with the increase of exposure time in sulphuric acid. Also, gradual reduction in the 'loss' was observed with the increase in the percentage of crumb rubber in concrete. In water-cement ratio 0.4, the maximum loss in compressive strength (77.65%) was recorded for the control mix specimen with 0% crumb rubber at 84 days of exposure. The value was 65.67% for the specimen with 10% crumb rubber and it was 56% for the specimen with 20% crumb rubber. Similar trend has been observed for the specimens with water-cement ratios 0.45 and 0.5.

In high strength concrete with water-cement ratio 0.3, more loss in compressive strength was observed with the increasing amount of crumb rubber at the end of 28 days of exposure. The compressive strength loss in the specimen with 0% crumb rubber was 14.9% and that for the specimen with 20% crumb rubber was 18%. At the end of 56 and 84 days, a trend opposite to that of 28 day was obtained. Gradual reduction in the 'loss' was observed with the increase in the percentage of crumb rubber in concrete. The loss in compressive strength of the specimen with 0% crumb rubber at 56 days was 57.6% and was 71.8% at 84 days. The loss for the specimen with 20% crumb rubber was 33.9% at 56 days and 37.3% at 84 days.

In the case of control mix concrete, it was noticed that all the six surfaces were affected by acid attack and 100% of top surface layer got deteriorated. In the case of rubberized concrete, all the six surfaces were affected by acid but less than 100% surface layer got deteriorated. Reduction in cross section of control mix was more than that of the rubberized concrete. After the acid attack, the net cross section of rubberized concrete was more than the control mix specimens as shown in the Figures 4.39 and 4.40. It was also observed that the specimens with more amount of crumb rubber had shown small increase in the cross section area (above 100 mm^2) after 84 days of acid attack.

Figure 4.39: Images of acid attacked specimen at 28 days. The specimen with 0%, 10% and 20% crumb rubber

Figure 4.40 : Images of acid attacked specimen at 84 days. The specimen with 0%, 10% and 20% crumb rubber

From the images given in Figures 4.39 and 4.40, we could understand that the crumb rubber particles present in the rubberized concrete was holding the constituent particles of the concrete from breaking away by preventing the formation of cracks and material separation. While in the concrete with no crumb rubber or less amount of crumb rubber, more cracks were developed and the constituent materials were easily separated. This may be one of the reasons for reduced loss in compressive strength for rubberized concrete.

4.3.10.2 Variation in weight of acid attacked specimens

The weight of acid attacked specimens was calculated at 28, 56 and 84 days of immersion and the results were compared with the weight at non-acid attacked situation after 28 days of water curing. The amount of loss was calculated and expressed in percentage in the graphs given in Figures 4.41-4.44.

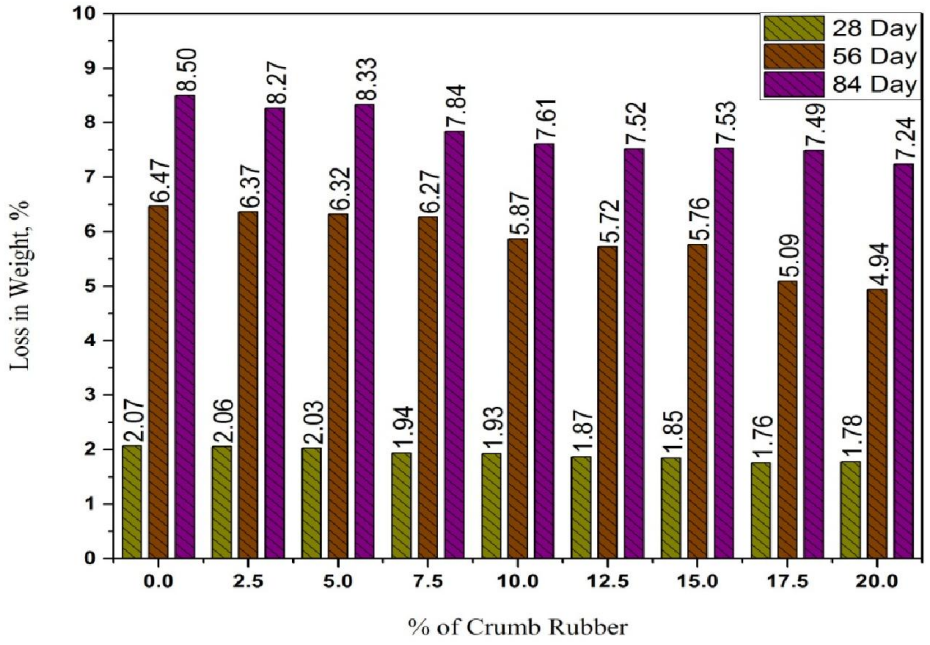


Figure 4.41: Weight loss (%) of acid attacked concrete specimens with w/c 0.4

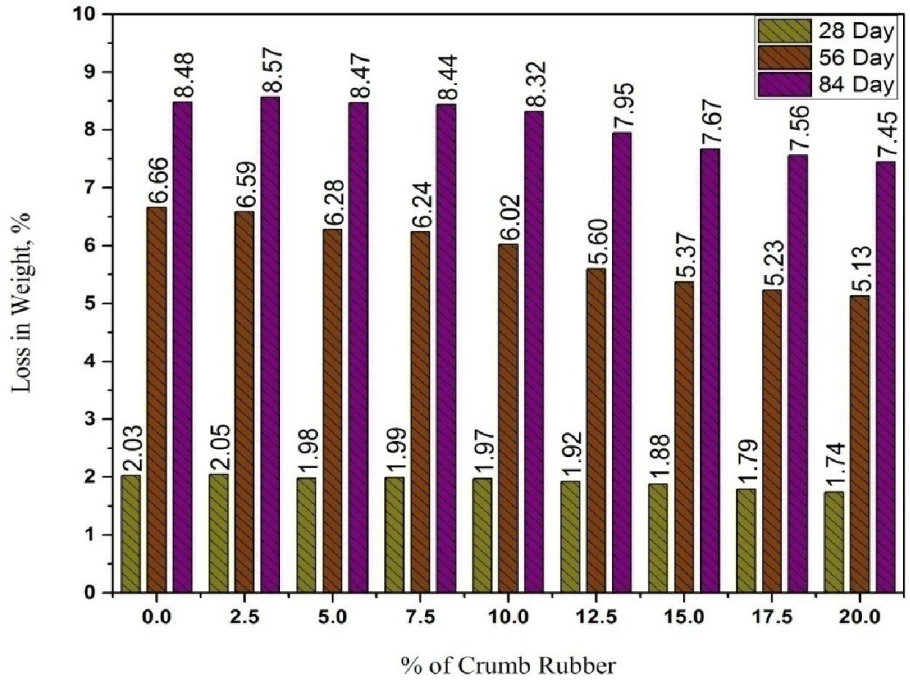


Figure 4.42: Weight loss (%) of acid attacked concrete specimens with w/c 0.45

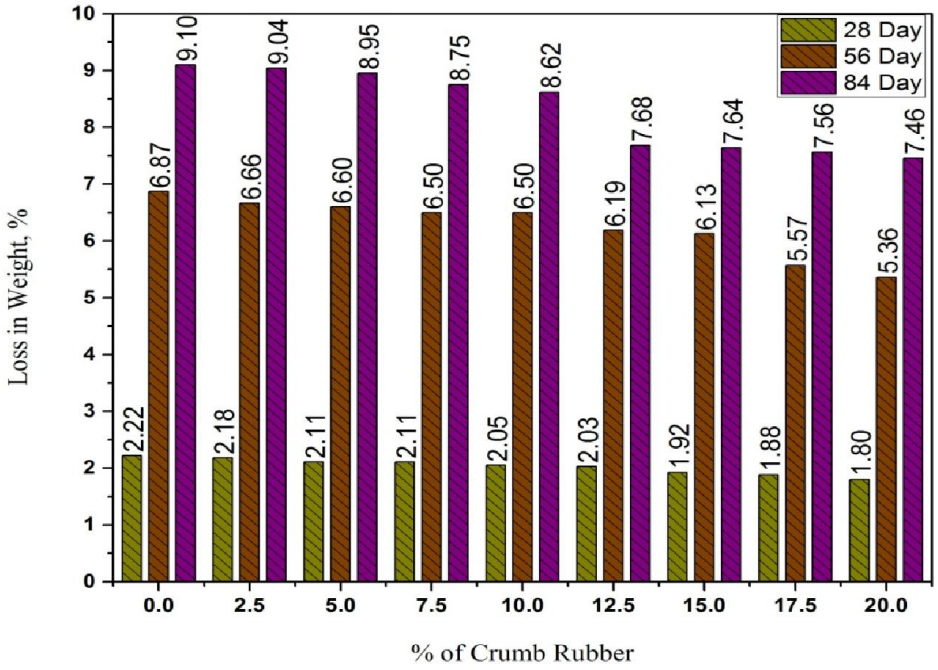


Figure 4.43: Weight loss (%) of acid attacked specimen of concrete specimens with w/c 0.5

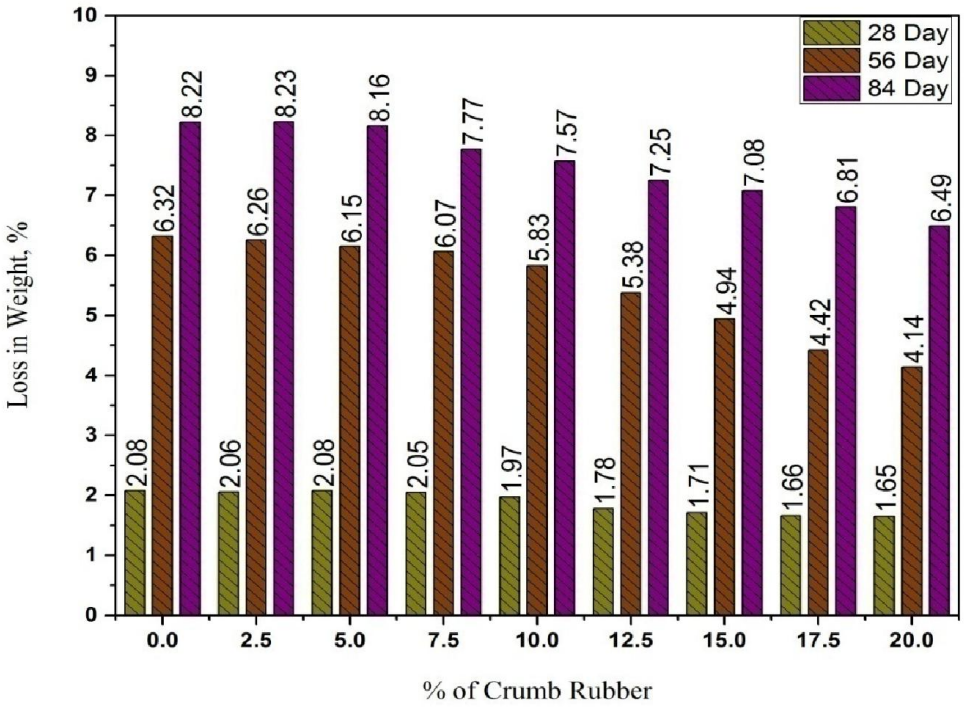


Figure 4.44: Weight loss (%) of acid attacked specimen of concrete specimens with w/c 0.3

At water-cement ratios of 0.4, 0.45 and 0.5; more loss in weight was observed in the control mix specimens and it was found decreasing as the amount of crumb rubber was increased in the concrete. It means that the control mix specimens have recorded maximum loss in weight and the specimens with 20% crumb rubber have recorded the least loss in weight. In the case of w/c 0.4, Maximum weight loss (8.5%) was recorded for the control mix and minimum weight loss was for the mix with 20% crumb rubber (7.24%) at 84 days of exposure. The loss was 7.61% for the mix with 10% crumb rubber. Similar trend has been observed for the series with water-cement ratios 0.45 and 0.50.

In the case of 28 days of exposure of high strength concrete with a water-cement ratio of 0.3, the percentage was found decreasing from the control mix specimen, to the specimen with 2.5% crumb rubber, and then it started to increase in the specimen with 5% crumb rubber and then a decreasing pattern was observed in the specimens with 7.5% to 20% crumb rubber. The loss in weight for mix with 0% crumb rubber was 2.08% and that in the mix with 20% crumb rubber was 1.65%. Similar pattern of weight loss could be observed at the exposure period of 56 and 84 days. At 84 days, the loss in weight for specimen with 0% crumb rubber was 8.22%, and it was 6.49%

for the specimen with 20% crumb rubber. Maximum loss of 8.23% was observed for the specimen with 2.5% crumb rubber and minimum loss was of 6.49% for the specimen with 20% crumb rubber.

The crumb rubber particles present in the rubberized concrete was holding the constituent particles of the concrete from breaking away, by preventing the formation of cracks and material separation. While in the concrete with no crumb rubber or less amount of crumb rubber, more cracks were developed and the constituent materials were easily separated. From Figure 4.38, it could be clear that the control mix specimen was more attacked by acid when compared with the specimen having 20% crumb rubber. Reduction in cross section of control mix specimen was more than that of the rubberized concrete.

4.3.10.3 Water absorption of acid attacked specimens

Figures 4.45-4.48 shows the variations in the amount of water absorption of acid attacked specimens (expressed in percentage) with respect to the amount of crumb rubber.

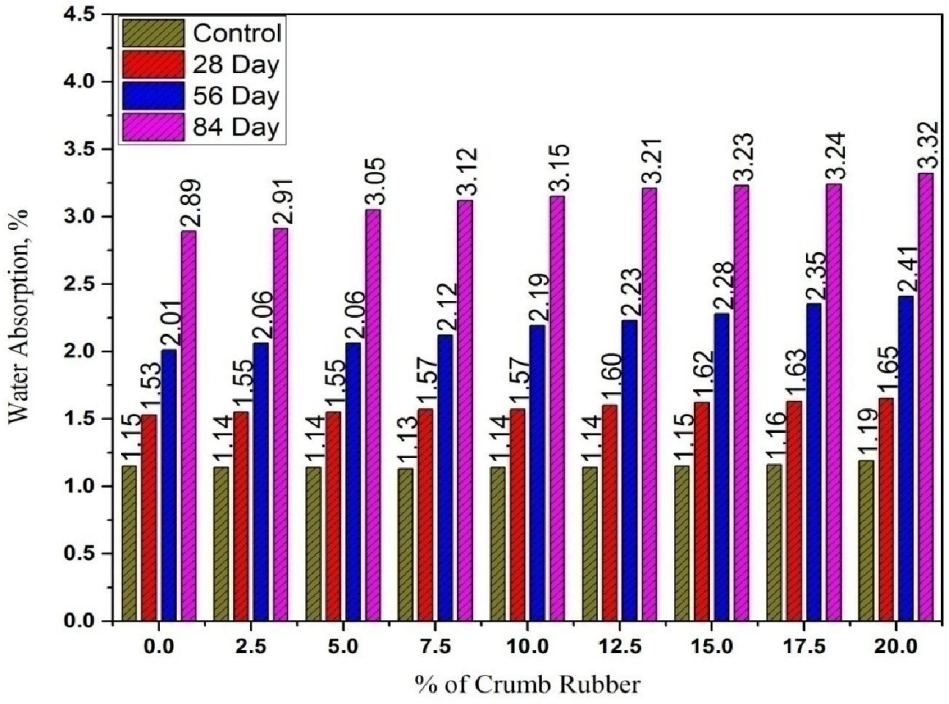


Figure 4.45: Water absorption (%) of acid attacked concrete specimen with w/c 0.4

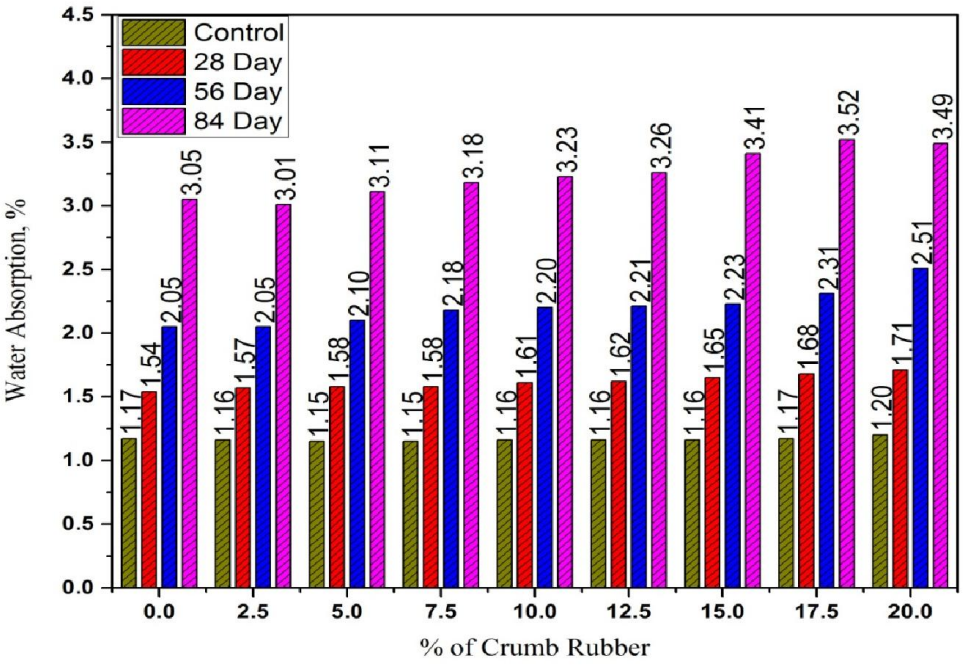


Figure 4.46: Water absorption (%) of acid attacked concrete specimens with w/c 0.45

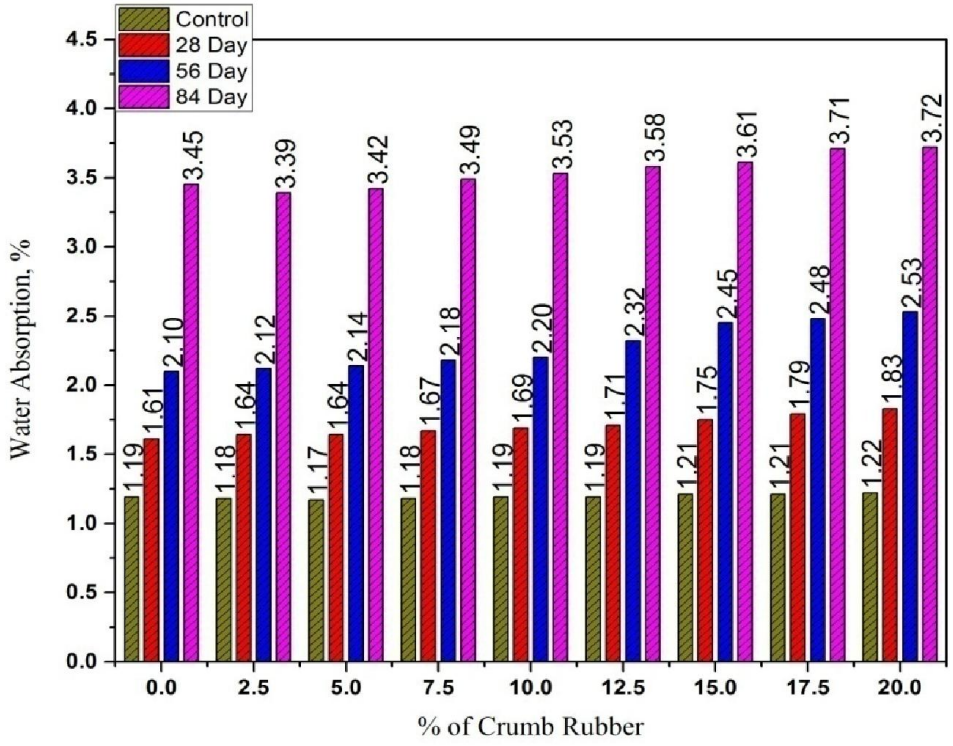


Figure 4.47: Water absorption (%) of acid attacked concrete specimens with w/c 0.5

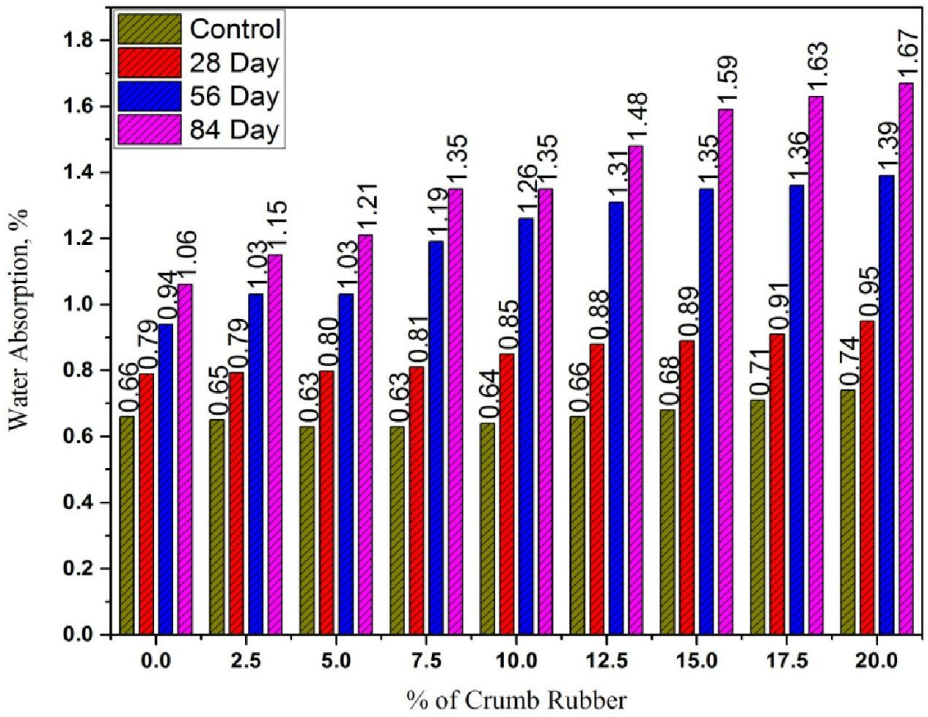


Figure 4.48: Water absorption (%) of acid attacked concrete specimens with w/c 0.3

In the case of concrete mixes with water-cement ratio 0.4; gradual increase in the amount of water absorption was noticed at 28 days in the mixes where the crumb rubber was replaced from 0% to 20% for fine aggregates. Similar trend was noticed at 56 days and 84 days of exposure. At 84 days, the amount of water absorption for control mix was 2.89%. It was 3.15% for the mix with 10% crumb rubber and was 3.32% for the mix with 20% crumb rubber. Similar pattern was observed for the series with water-cement ratios 0.45 and 0.50.

In the case of high strength concrete with water-cement ratio 0.3; the water absorption of the specimens with crumb rubber was higher than that of the control mix. The amount of water absorption gradually increased with the increasing percentage of crumb rubber in concrete. At 28 day, the amount of water absorption of the specimens with 0% crumb rubber was 0.79%. It was 0.85% for the specimens with 10% crumb rubber and maximum water absorption of 0.95% was observed for the specimens with 20% crumb rubber. At 84 day, the water absorption of control mix specimens was observed as minimum (1.06%), while the maximum amount of water absorption (1.67%) was observed for the specimens with 20% crumb rubber.

Water absorption of acid attacked specimens at 28, 56 and 84 days did not follow the trend of the control mix. When we observe Figure 4.40, we can observe that the top layer of the concrete specimens with 0% crumb rubber was completely removed (100%) by the action of sulphuric acid. In the case of the specimen with 20% crumb rubber, less than 100% top surface were affected by the action of acid. The rubber particles and the cementitious layer surrounding the rubber particles were unaffected by acid and have projected outwards by providing extra pockets to arrest the water. So the water absorption of rubberized concrete was higher than the control mix concrete.

4.3.11 Sulphate attack

The oven dried weight of the test specimens were taken after 28 days of water curing and then subjected to continuous soaking for 3 to 6 months in a solution containing 3% $MgSO_4$. Three different tests were done on the sulphate attacked specimens.

4.3.11.1 Variation in compressive strength of sulphate attacked specimens

The graphs showing the percentage of reduction in compressive strength of sulphate attacked specimen is shown in Figures 4.49-4.51. The photographs of the sulphate attacked concrete specimen are shown in Figures 4.52 and 4.53.

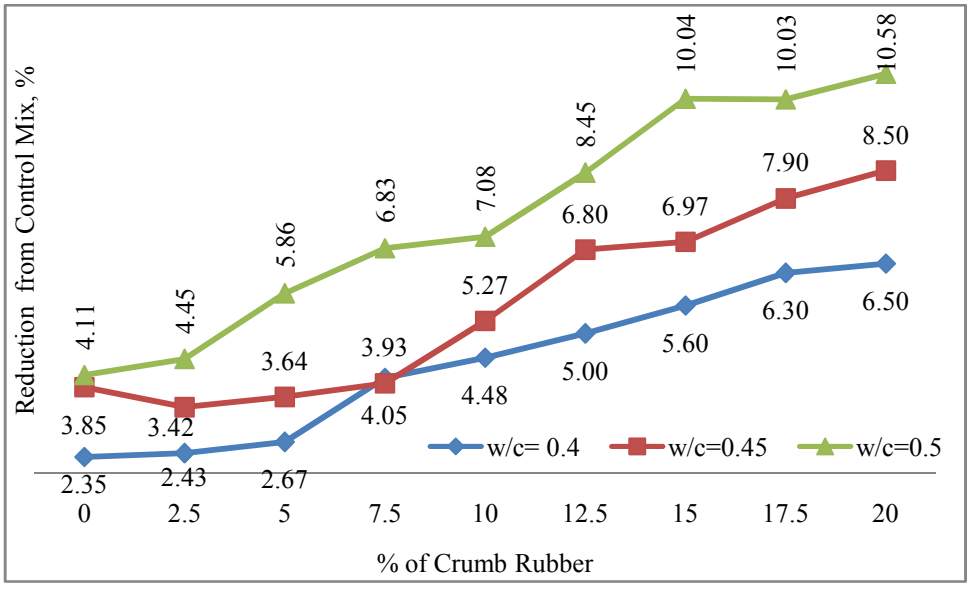


Figure 4.49: Reduction in compressive strength of concrete specimens at 91 days of sulphate attack

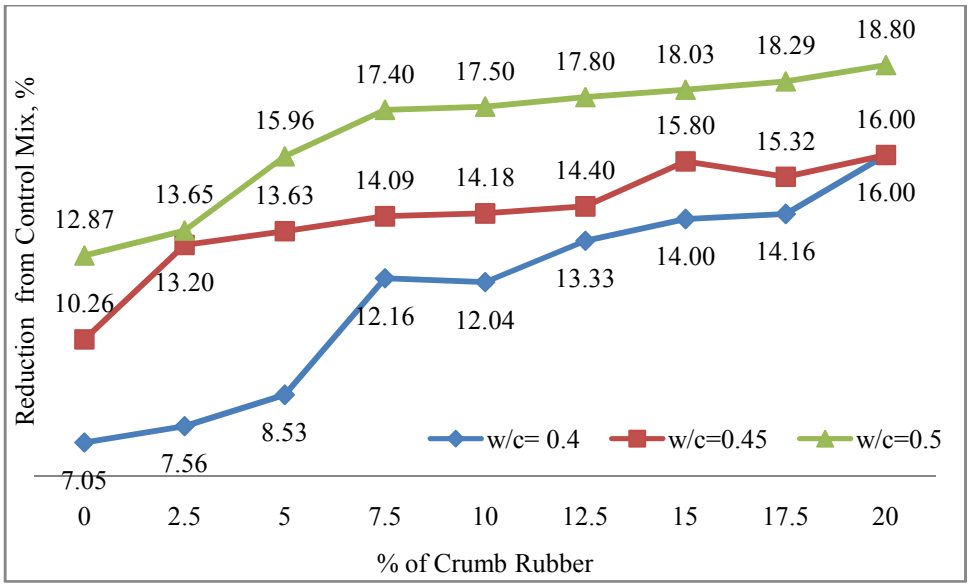


Figure 4.50: Reduction in compressive strength of concrete specimens at 182 days of sulphate attack

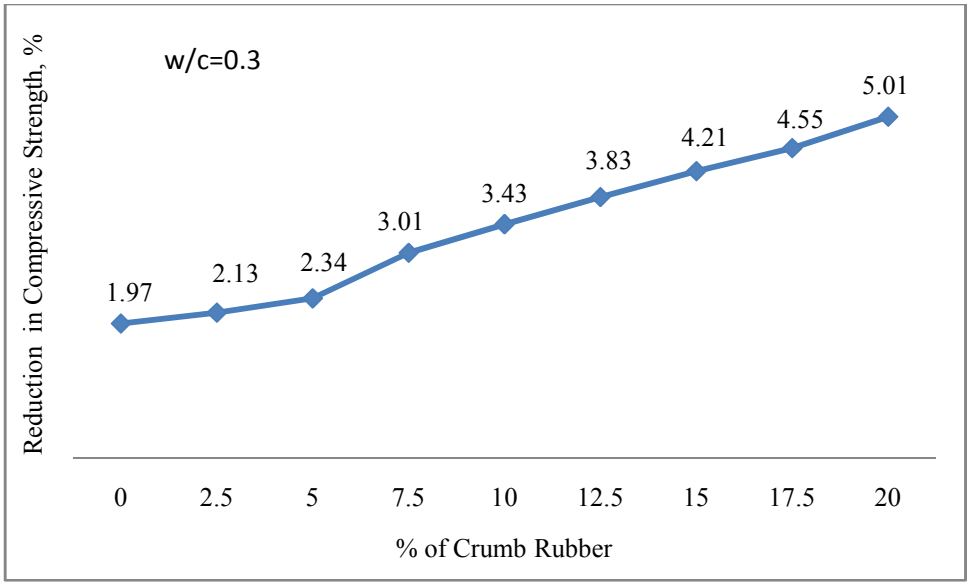


Figure 4.51: Reduction in compressive strength of high strength concrete specimens at 91 days of sulphate attack

Figure 4.52: Concrete specimens after 28 days of curing.

Figure 4.53: Control concrete specimens and rubberized specimen after 182 days of sulphate attack test

From the results it is clear that there was more reduction in the values of compressive strength of sulphate attacked concrete specimen with the increase in the percentage of crumb rubber and with the increase in water-cement ratio. In the series with water-cement ratio 0.4 the compressive strength loss at 91 days for the control mix specimens was 2.35% and it was 6.5% for the specimens with 20% crumb rubber. Similar trend was observed for the series with water-cement ratios 0.45 and 0.5. The loss in strength was very severe for the water-cement ratio 0.5. The specimens with 20% crumb rubber had recorded a loss of 10.58%. At 182 days, the trend similar to that of 91 days was observed. When the water-cement ratio was 0.4, the loss in compressive strength was 7.05% for control mix specimens and 16% for the specimens with 20% crumb rubber.

In the series with water-cement ratio 0.3, the compressive strength test for sulphate attacked specimen was observed for 91 days only. Gradual reduction in the compressive strength was noticed as the amount of crumb rubber was increased. The control mix specimens with 0% crumb rubber have exhibited the lowest reduction in compressive strength loss (1.97%). The loss was 3.43% for the specimens with 10% crumb rubber and it was 5.01% for the specimens with 20% crumb rubber.

At 182 days of exposure in sulphate solution, volume changes were observed in the concrete specimens. The volume of the specimens has increased even after some deterioration due to sulphate attack, irrespective of the quantity of rubber used. The dimension at the top and bottom of the specimens were more than the dimension at the middle of the specimens. It means that the top and bottom of the specimens had bulged out due to the sulphate attack and deterioration of the specimens initiated and progressed from top and bottom portion. More deterioration of concrete was observed in the specimens with more amount of crumb rubber as shown in Figure 4.53.

4.3.11.2 Variation in weight of sulphate attacked specimens

The results for the variation in weight of sulphate attacked specimens at 28, 91 and 182 days for the mixes with w/c 0.4, 0.45 and 0.5 are shown in Figures 4.54-4.56. For high strength concrete, the tests were performed up to 91 days and it is reported in Figure 4.57.

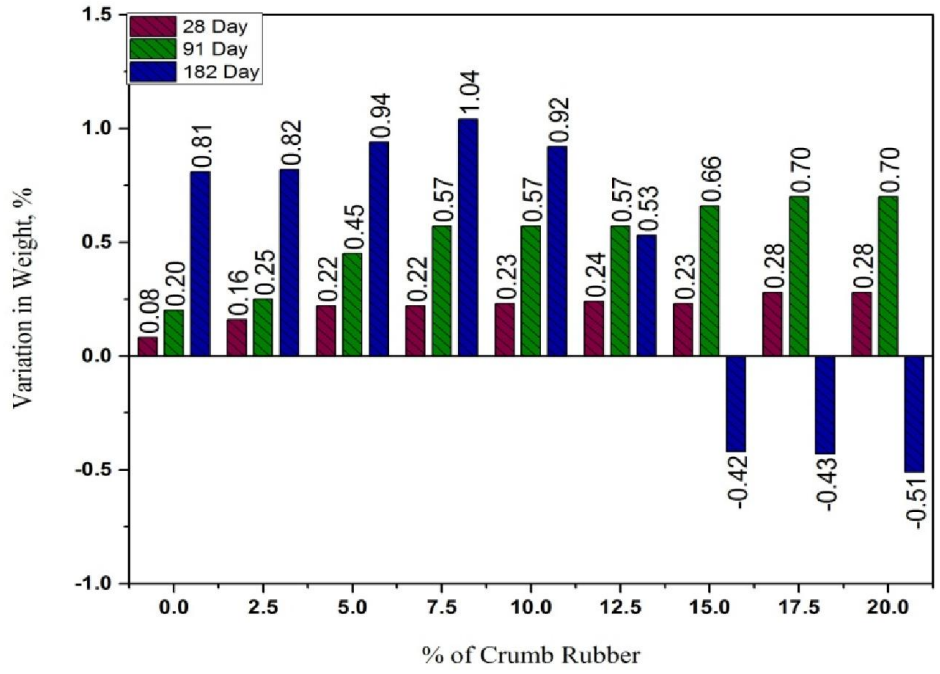


Figure 4.54: Variation in weight of sulphate attacked concrete specimen, w/c 0.4

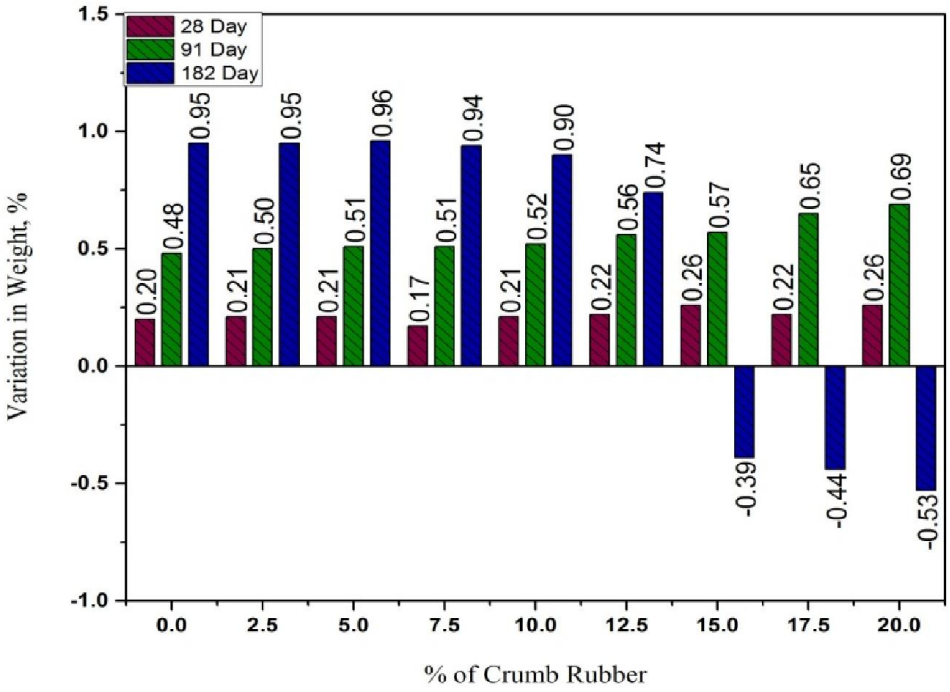


Figure 4.55: Variation in weight of sulphate attacked concrete specimen, w/c 0.45

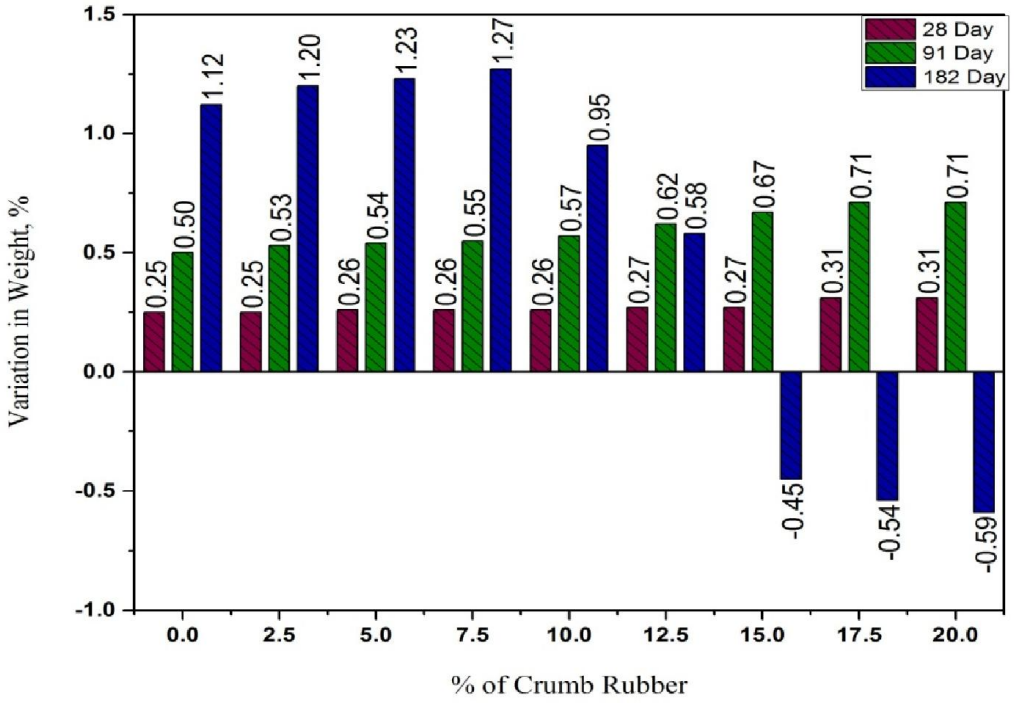


Figure 4.56: Variation in weight of sulphate attacked concrete specimen, w/c 0.5

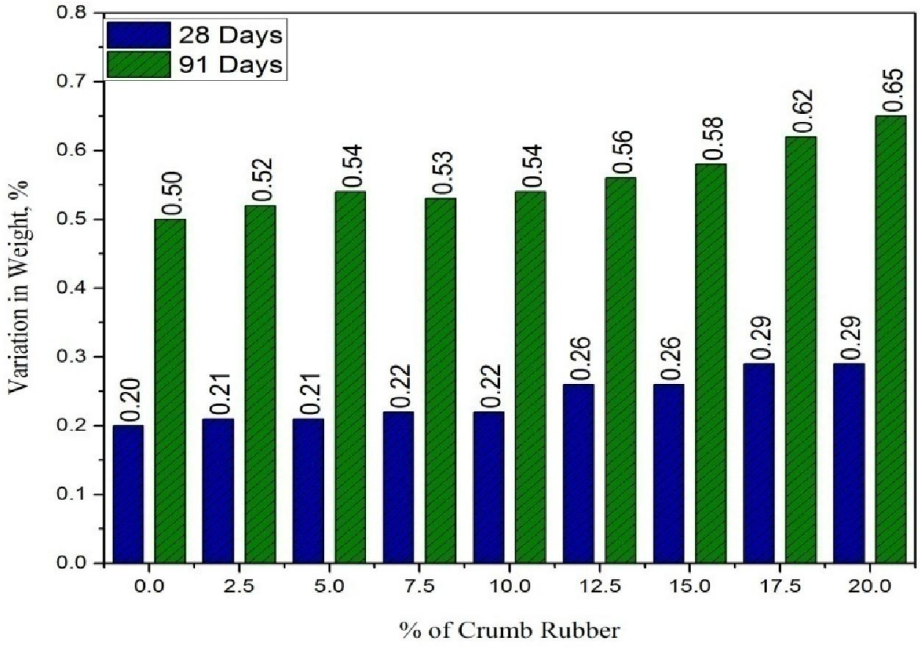


Figure 4.57: Variation in weight of sulphate attacked concrete specimen, w/c 0.3

From the results, it was observed that there was gradual variation in the weight of the specimens immersed in $MgSO_4$ solution for the sulphate attack test with respect to time of exposure and with respect to amount of crumb rubber. In the series with water-

cement ratio 0.4 (at 182 days), gradual increase in the weight of specimens were noticed from the specimens with 0% crumb rubber to the specimens containing 7.5% crumb rubber. Increase in weight of specimen was observed in the mixes with 0% to 12.5% crumb rubber. In the specimens with crumb rubber 15% and above, decrease in weight (from the initial weight) was noticed. Similar trend was noticed in the series with water-cement ratio 0.45 and 0.5. In the series with water-cement ratio 0.3, it was noticed that for all the specimens, there was gradual increase in the weight of the specimens from 28 to 91 days.

Weight loss was observed in certain mixes at 182 days because the process of disruption of concrete had started in these mixes. So from the results, we could conclude that the concrete with more amount of crumb rubber would be more affected by the action of sulphate attack.

4.3.11.3 Water absorption of sulphate attacked specimens

Water absorption test for the sulphate attacked specimens were performed at 91 and 182 days of immersion. The results are given in Figures 4.58-4.61.

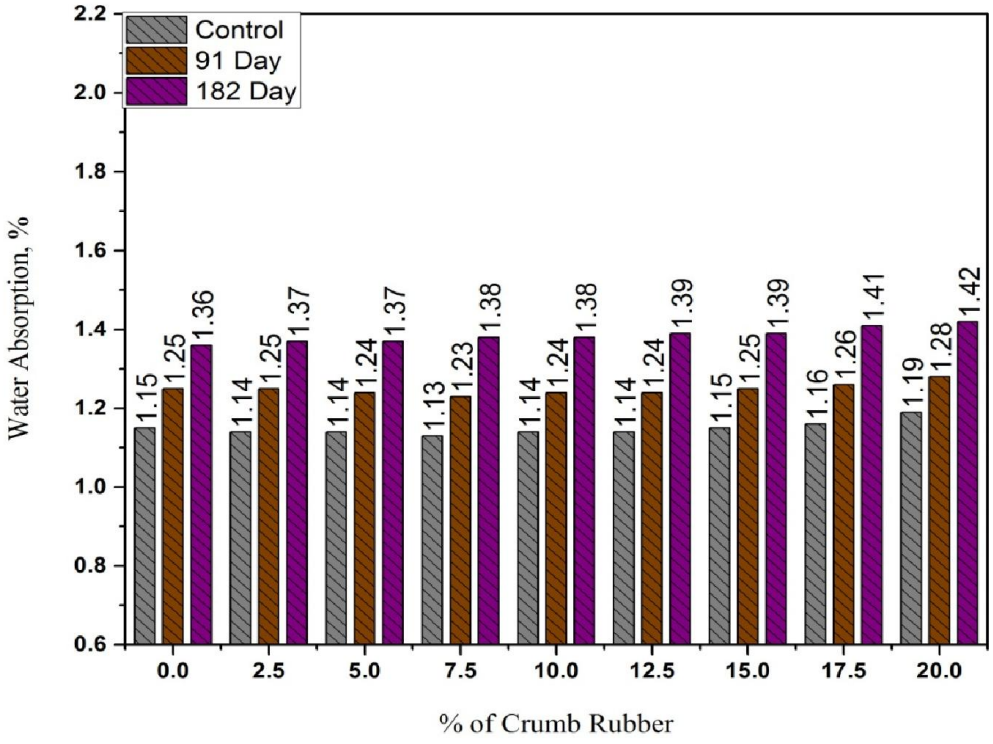


Figure 4.58: Water absorption of sulphate attacked concrete specimen, w/c 0.4

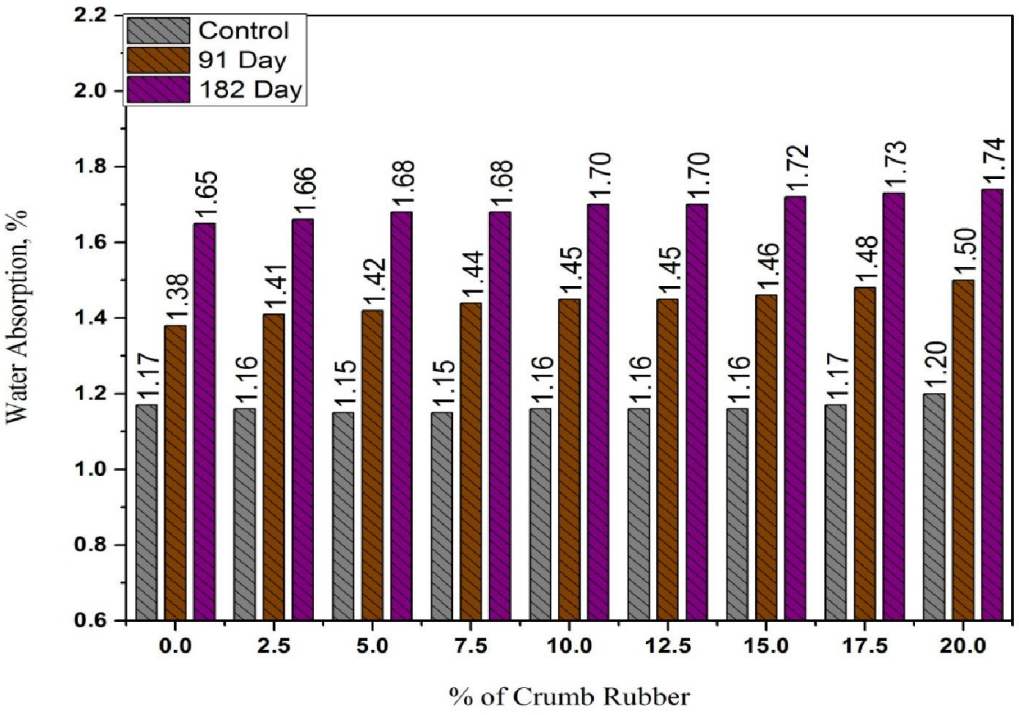


Figure 4.59: Water absorption of sulphate attacked concrete specimen, w/c 0.45

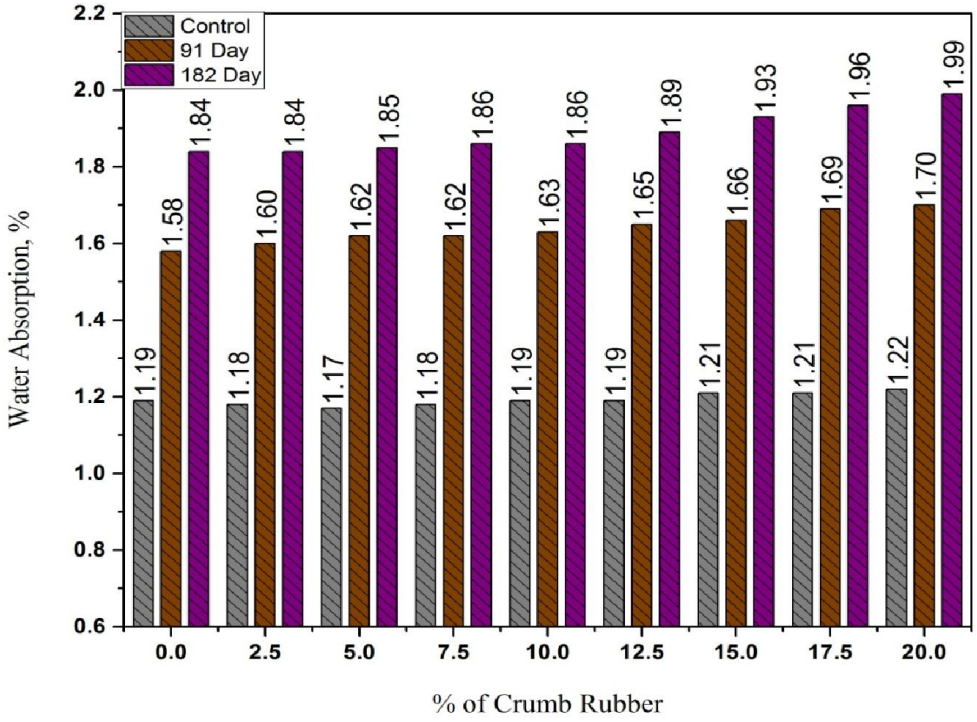


Figure 4.60: Water absorption of sulphate attacked concrete specimen, w/c 0.5

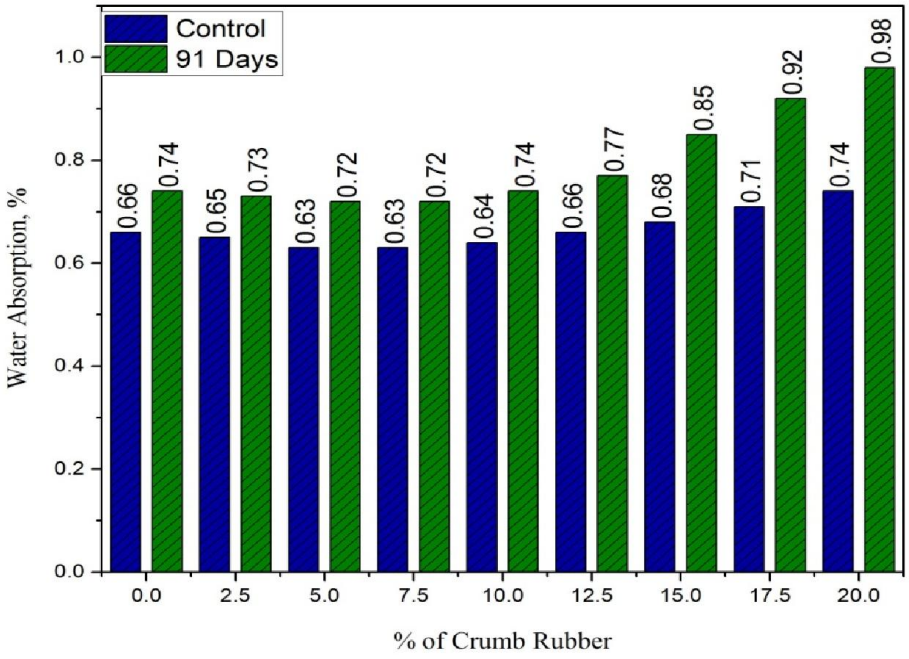


Figure 4.61: Water absorption of sulphate attacked concrete specimen, w/c 0.3

From the results it could be noticed that the water absorption had increased in all the samples with the increase in the duration of exposure to sulphate solution. Water absorption has increased from 0 to 91 days and from 91 to 181 days when compared to the values of the control mix. At 91 days of exposure for the specimens with water-cement ratio 0.4, the water absorption initially showed a decreasing trend with the increase in crumb rubber, and then it started to increase. An increasing trend in the amount of water absorption was observed at 182 days as the amount of crumb rubber was increased in concrete. The amount of water absorption for the control mix was 1.25% at 91 days and 1.36% at 182 days. At 91 days, lowest water absorption of 1.23% was observed in the specimen with 7.5% crumb rubber. In the case of the series with water-cement ratios 0.45 and 0.5, an increasing trend with the increase in the amount of crumb rubber was observed at 91 days and 182 days of exposure. The water absorption of the mixes with 20% crumb rubber was the maximum. It was 1.74% in the case of water-cement ratio 0.45 and 1.99% in the case of water-cement ratio 0.5.

In the case of high strength concrete with water-cement ratio 0.3, the amount of water absorption had shown a decreasing trend from the specimens with 0% crumb rubber to the specimens with 7.5% crumb rubber. The water absorption of the mix with 0% and 10% crumb rubber was 0.74%. Similar to the values obtained in the water absorption

test of the control specimen, an increase in the amount of water absorption was noticed from the mix with 10% crumb rubber to the mix with 20% crumb rubber. The water absorption of the specimen with 10% crumb rubber was 0.74% and that of the specimen with 20% crumb rubber was 0.98%.

In the concrete mixes with water-cement ratios 0.4 and 0.3, the water absorption followed the trend of the control mix specimens at the end of 91 days of sulphate attack. The amount of water absorbed by the specimens had increased in all the mixes when compared to the control mix. Comparing the water absorption of the control mix and that at 91 and 182 days of sulphate attack, it can be observed that the water absorption of specimens increases with time. At the end of 182 days, more destruction of the specimen took place with respect to the increase in the amount of crumb rubber. This might have caused the occurrence of micro voids around the surface of the specimen and have enabled more water absorption. Also, as the water-cement ratio increases to 0.45 and 0.5, the internal voids increases resulting in the increase in amount of water absorption for the increase in the rubber content at 91 days and at 182 days of exposure.

4.3.12 Corrosion of steel reinforcements

The macrocell current for various concrete mixes were calculated at initial day (0 day), 28 days, 56 days, 91 days and 182 days for the series with water-cement ratio 0.4, 0.45 and 0.5. In case of high strength concrete with water-cement ratio 0.3, the macrocell current was calculated up to 91 days. The results are given in Tables 4.7-4.10 and the variations are shown in Figures 4.62-4.65.

As per ASTM G 109-99a, a minimum value of 10 μA has been considered to ensure the presence of sufficient corrosion. A positive macrocell current indicates active corrosion in progress and vice versa.

Table 4.7: Results showing variation in macro cell corrosion of concrete mixes with w/c 0.4 (results are in terms of µA. Limit is 10 µA)

Crumb ⇨ Rubber / Days ⇩	0%	2.5%	5%	7.5%	10%	12.5%	15%	17.5%	20%
0	-2.31	-2.12	-2.32	-2.54	-2.02	-2.59	-2.41	-2.45	-2.59
28	-2.23	-2.30	-2.13	-2.00	-2.04	-2.09	-2.27	-2.35	-2.43
56	-1.38	-1.63	-2.12	-1.77	-1.38	-1.88	-2.27	-2.40	-1.92
91	-1.38	-1.59	-1.58	-1.21	-1.15	-1.46	-2.05	-2.20	-1.83
182	-1.27	-1.11	-1.13	-1.06	-1.02	-1.27	-1.57	-1.81	-1.67

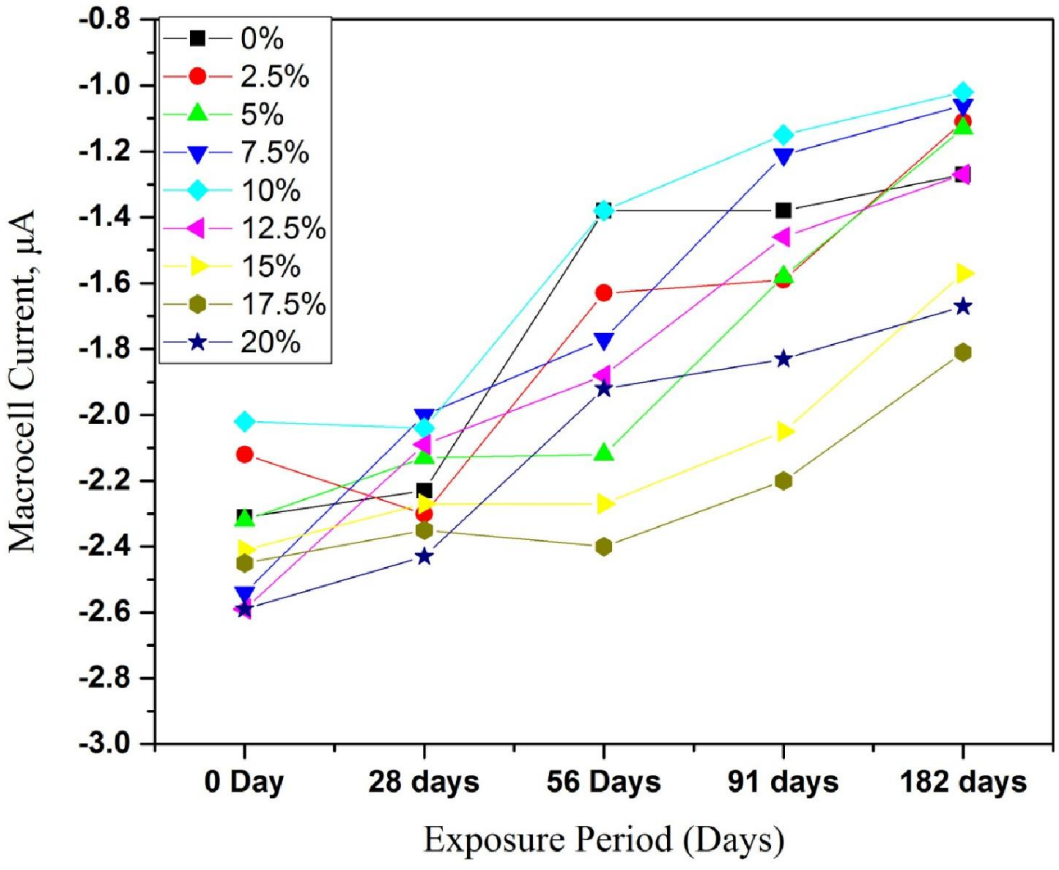


Figure 4.62: Macrocell current of specimens with water-cement ratio 0.4

Table 4.8: Results showing variation in macro cell corrosion of concrete mixes with w/c 0.45 (results are in terms of µA. Limit is 10 µA)

Crumb ⇨ Rubber / Days⇩	0%	2.5%	5%	7.5%	10%	12.5%	15%	17.5%	20%
0	-2.33	-2.27	-2.08	-2.38	-2.45	-1.63	-2.51	-1.93	-1.83
28	-2.05	-1.82	-1.84	-1.45	-1.89	-1.33	-2.49	-1.52	-1.56
56	-1.97	-1.45	-1.62	-1.31	-1.39	-1.37	-2.02	-1.46	-1.65
91	-1.82	-1.35	-1.59	-1.08	-1.19	-1.13	-1.87	-1.30	-1.30
182	-1.44	-1.11	-1.36	-1.00	-1.03	-1.04	-1.47	-1.18	-1.18

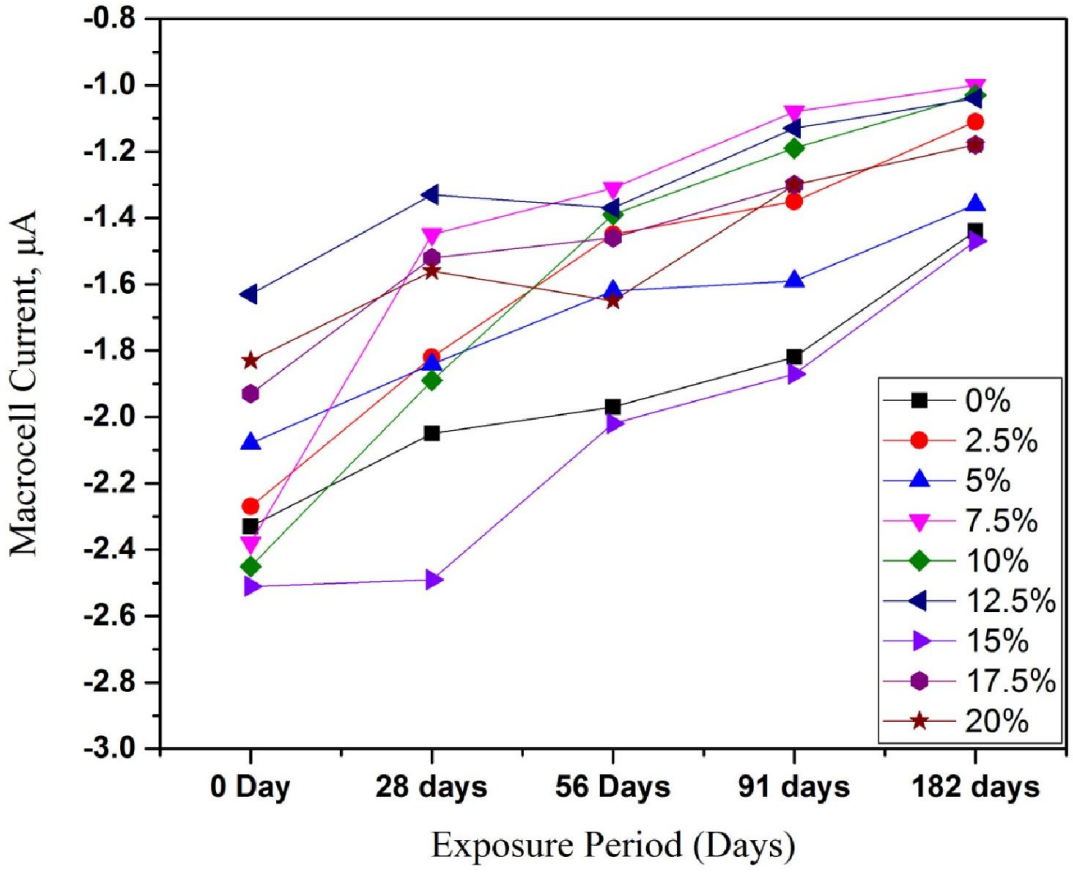


Figure 4.63: Macrocell current of specimens with water-cement ratio 0.45

Table 4.9: Results showing variation in macro cell corrosion of concrete mixes with w/c 0.5 (results are in terms of µA. Limit is 10 µA)

Crumb Rubber ⇨ / Days ⇩	0%	2.5%	5%	7.5%	10%	12.5%	15%	17.5%	20%
0	-1.88	-1.74	-1.86	-1.89	-1.91	-1.99	-2.45	-2.49	-2.55
28	-1.76	-1.72	-1.85	-1.60	-1.56	-2.27	-2.47	-2.44	-2.63
56	-1.43	-1.55	-1.74	-1.32	-1.53	-1.76	-2.09	-2.24	-2.56
91	-1.42	-1.32	-1.65	-1.44	-1.57	-1.54	-2.03	-2.29	-2.52
182	-1.11	-1.16	-1.17	-1.05	-1.20	-1.27	-1.55	-1.56	-2.05

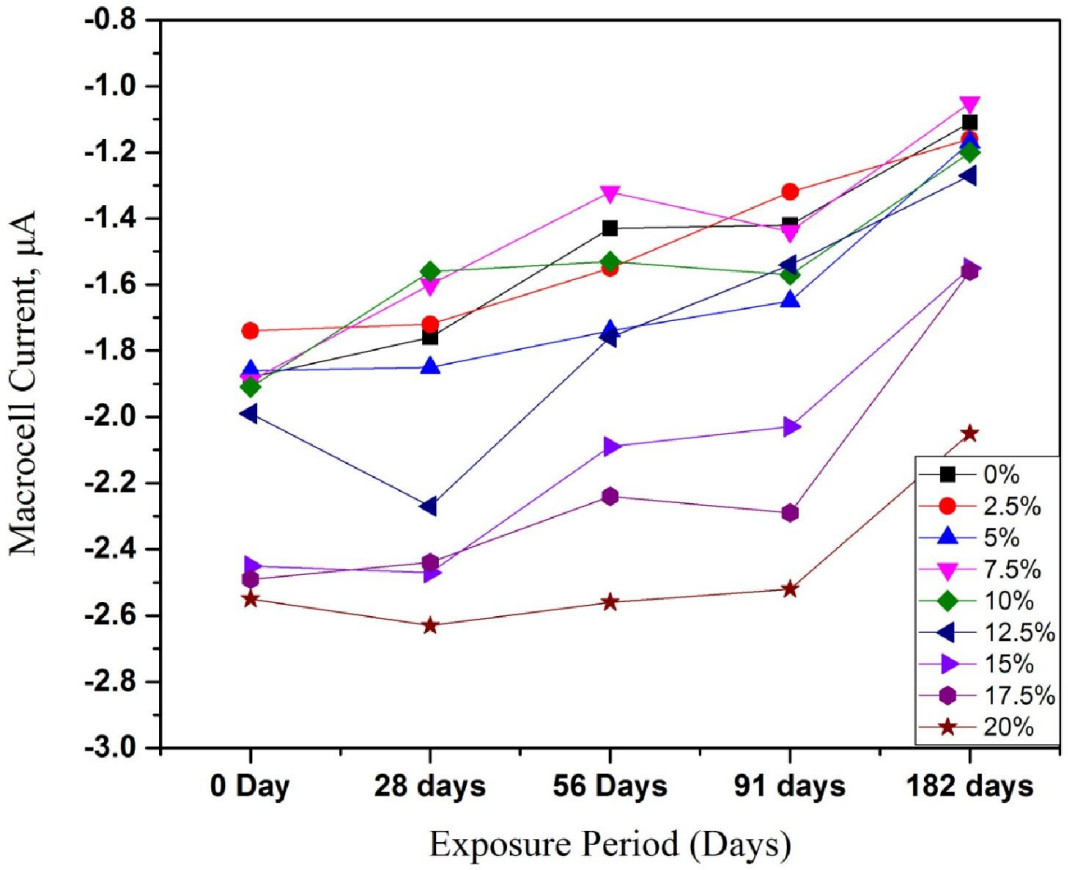


Figure 4.64: Macrocell current of specimens with water-cement ratio 0.5

Table 4.10: Results showing variation in macro cell corrosion of concrete mixes with w/c 0.3 (results are in terms of µA. Limit is 10 µA)

Crumb ⇨ Rubber / Days ⇩	0%	2.5%	5%	7.5%	10%	12.5%	15%	17.5%	20%
0	-1.57	-1.45	-1.42	-1.54	-1.48	-1.65	-1.62	-1.59	-1.69
28	-1.44	-1.33	-1.26	-1.46	-1.38	-1.41	-1.55	-1.31	-1.49
56	-1.35	-1.12	-1.11	-1.28	-1.35	-1.29	-1.41	-1.19	-1.28
91	-1.04	-1.05	-0.92	-1.04	-1.27	-1.15	-1.29	-1.01	-1.09

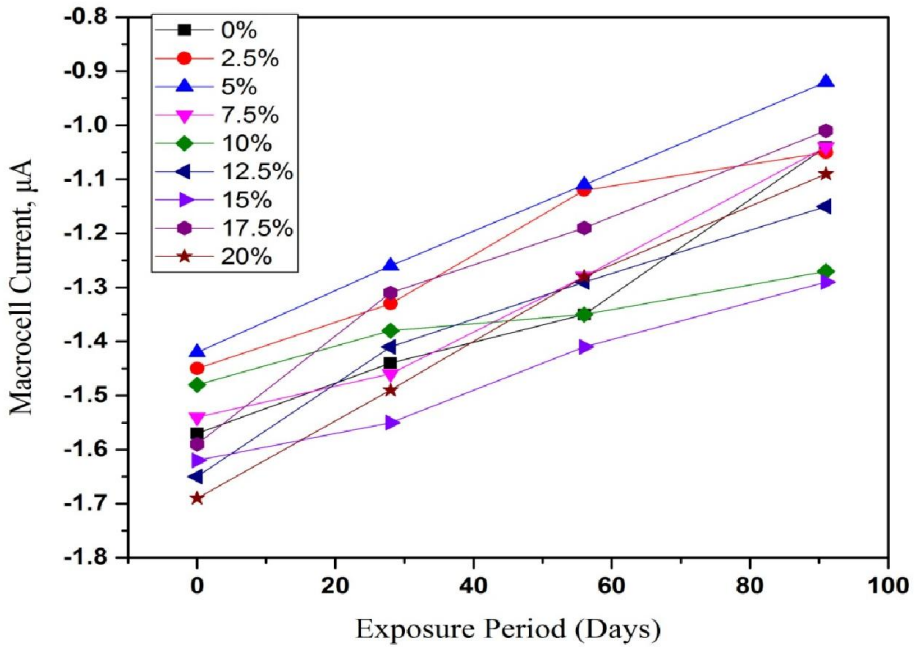


Figure 4.65: Macrocell current of concrete specimens with water-cement ratio 0.3

In the series with water-cement ratio 0.4, the initial readings of the control mix were -2.31and the readings at 182 days were -1.27 µA. For the concrete mix with 10% tire rubber, the readings were -2.02 µA and -1.02 µA respectively and in the concrete mix with 20% crumb rubber, it was -2.59 µA and -1.67 µA respectively. The readings were found to be gradually increasing from 0 day to 182 days. At the end of 182 days, the macrocell current of the mixes with crumb rubber from 0% to 12.5% was higher than that of the control mix while the macrocell current of the mixes with crumb rubber 15%, 17.5% and 20% was lesser than that of the control mix. At water-cement

ratio 0.45, the macrocell current of control mix was higher than all the other mixes except the mix with 15% crumb rubber. In the water-cement ratio 0.5, the macro cell current of control mix was higher than the values of all other mixes at 182 days. In the case of water-cement ratio 0.3, the macro cell current of the control mix at 91 days was -1.04 μA, while it was -1.09 μA for the mix with 20% crumb rubber.

It appears that the readings were showing the trend of changing from negative to positive for all the mixes. As all the readings obtained were less than 10 μA, we could conclude that there is no presence of sufficient corrosion in the specimens even at 182 days of ponding. The same conclusion can be drawn from the results of total corrosion calculated as per ASTM G 109-99a. The maximum value for total corrosion (38.18 C) was obtained at 182 days for the specimens with 20% crumb rubber with water-cement ratio 0.5 and minimum value (19.17 C) obtained for the specimens with 12.5% crumb rubber at water-cement ratio 0.45. As per ASTM G 109-99a the threshold value for total corrosion was 150 C. So we could conclude that there is no presence of sufficient corrosion for any of the specimens at 182 days.

4.3.13. Microstructure by SEM

Scanning Electron Microscopy tests were done on concrete specimens (taken as mentioned in the methodology) to study morphology and micro structural properties of the material. SEM images taken on the various constituent materials are given in a series on Figures: Image of cement in Figure 4.66, silica fume in Figure 4.67, crumb rubber and fine aggregate (river sand) passing through the 300 μm sieve were given in Figures 4.68 and 4.69, respectively. The SEM images of concrete with and without crumb rubber are given in Figures 4.70 to 4.74.

The SEM images of cement particles and silica fume show spherical appearance and small grain size, especially for the latter. In addition, silica fume exhibits rough surface, which further contributes to its high specific surface area and hence high reactivity.

When we observe the surfaces of crumb rubber and river sand, we find typically smooth and solid surfaces on river sand; while varied and irregular surface can be noted on the crumb rubber. Some parts are relatively smooth, with occasional spherical indentations, most likely as a result of the comminution process leaving

behind such typical clam shaped crevices. The bond between rubber particles and cement paste is not as good as with traditional rigid aggregates, which may also offer some infiltration of cement paste through their surface and even chemical reactions with it, which are unlikely to occur with rubber crumbs.

When we observe the images of concrete specimens given in 4.70-4.74 (images taken after 90 days of casting of concrete specimens), it appears that the cracks are running through cement stone (i.e. hydrated cement paste), not through aggregates. Crack formation through aggregate is generally observed with lightweight aggregate, where the strength of the aggregate is lower than that of hydrated cement. The clam shaped cavities suggest that crumb rubber delaminates from cement stone, so the bond between them is weak. Moreover, there are cracks and voids to note around rubber particles at the interface of the crumb rubber and cement paste, which reflects the weak bond between the crumb rubber and cement mortar leading to reduced compressive strength of concrete. The flexibility of rubber particles entails some degree of ductility to concrete, but ultimately weakens the matrix. From Figures 4.70 to 4.74, we can observe that there are more voids in the concrete as the amount of crumb rubber was increased. The images of concrete with 10% crumb rubber and that with 20% crumb rubber clearly shows that there was lack of internal packing in the concrete with 20% crumb rubber.

It could be understood that the difference between the two w/c ratio samples (0.4 and 0.3) are seen as less dense structure with more cracks for the higher water/cement ratio sample. This is explained by the fact that the stoichiometric water demand of cement paste is satisfied by adding as little water as that represented by 0.3 w/c ratio, with any excess only generating voids and space in concrete, and this could be one parameter for the lower density and strength. The images of control mixes with 0.4 and 0.3 w/c ratios (Figures 4.70 and 4.74) demonstrate this difference in the achieved density very well.

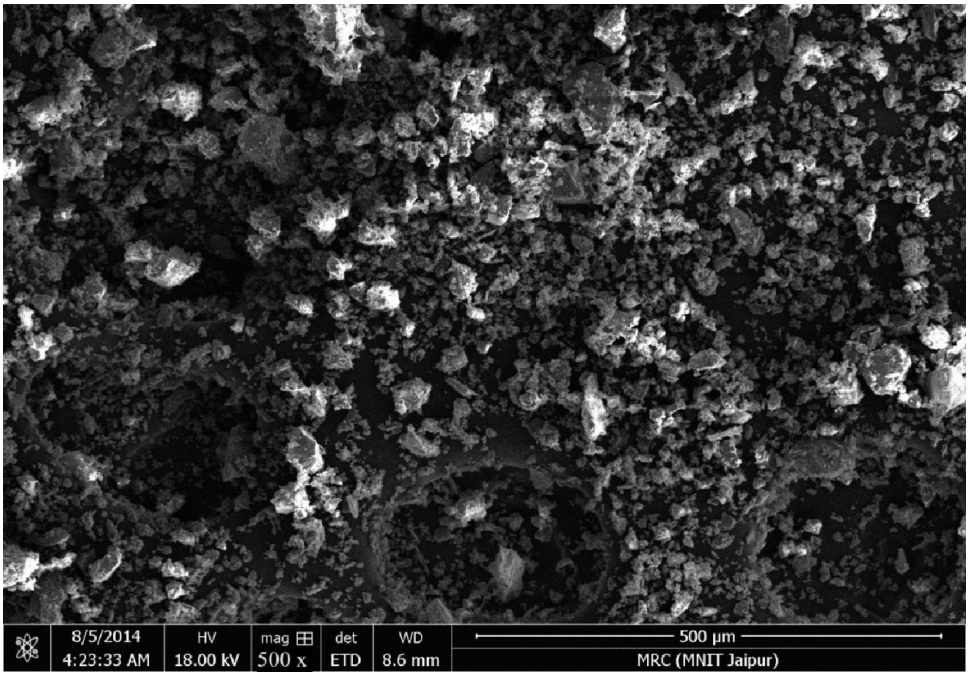


Figure 4.66: SEM image of cement

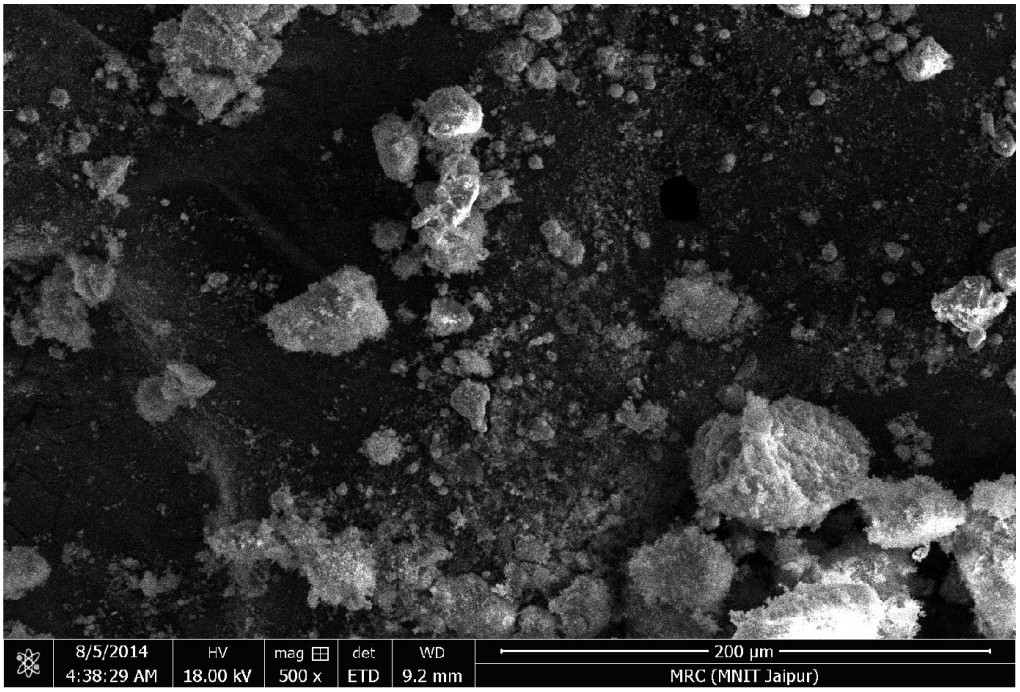


Figure 4.67: SEM image of silica fume

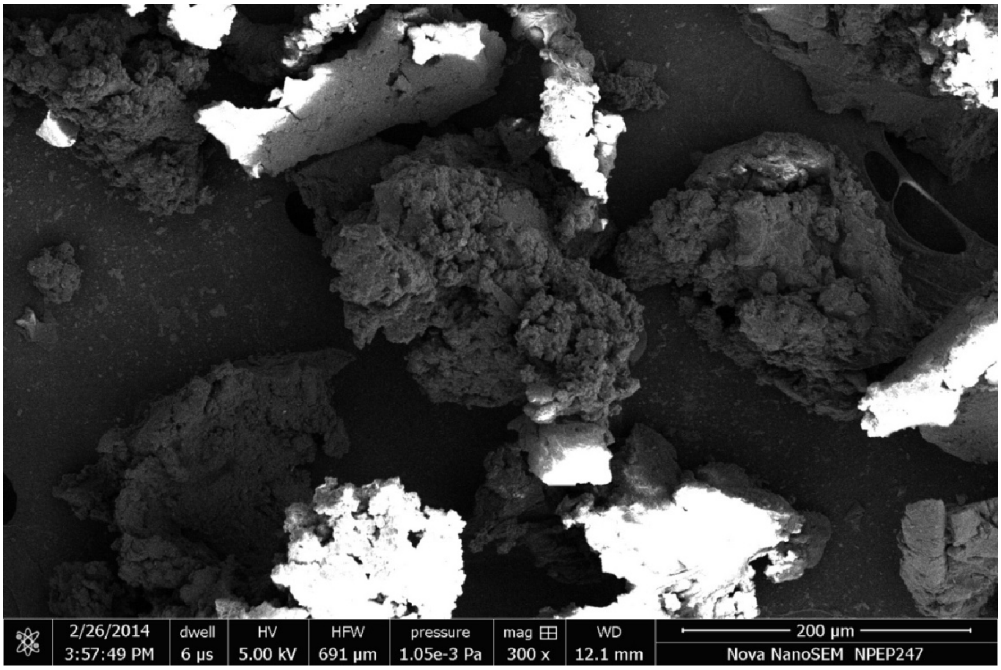


Figure 4.68: SEM image of crumb rubber passing through 300 µ sieve

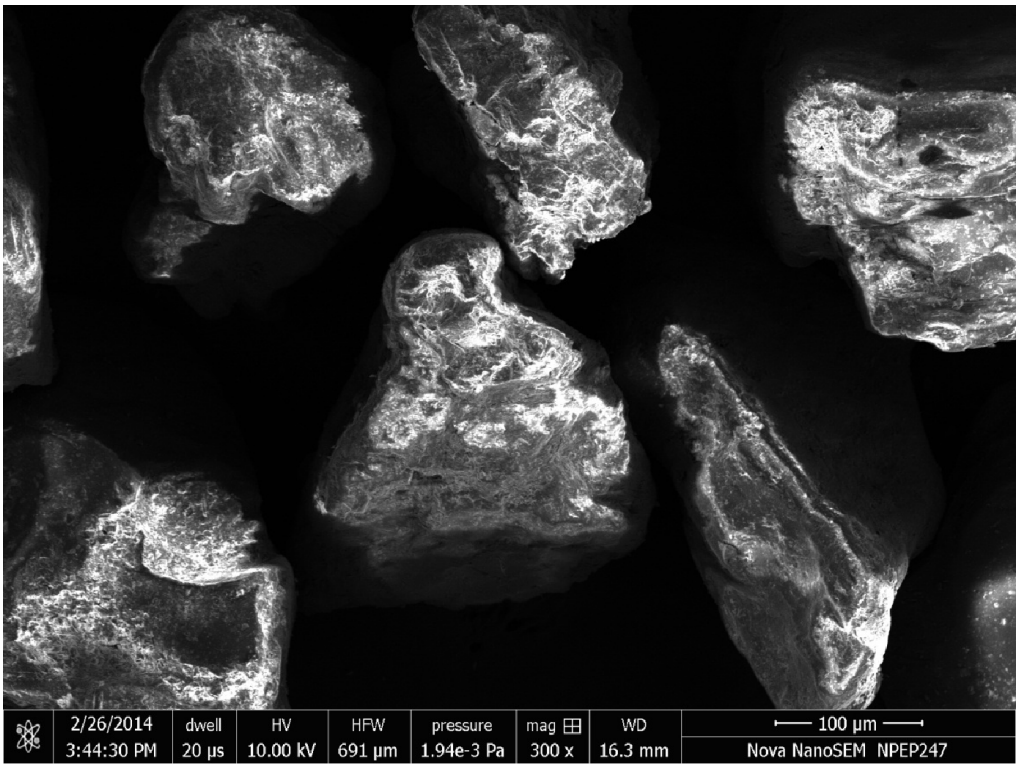


Figure 4.69: SEM image of sand passing through 300 µ sieve

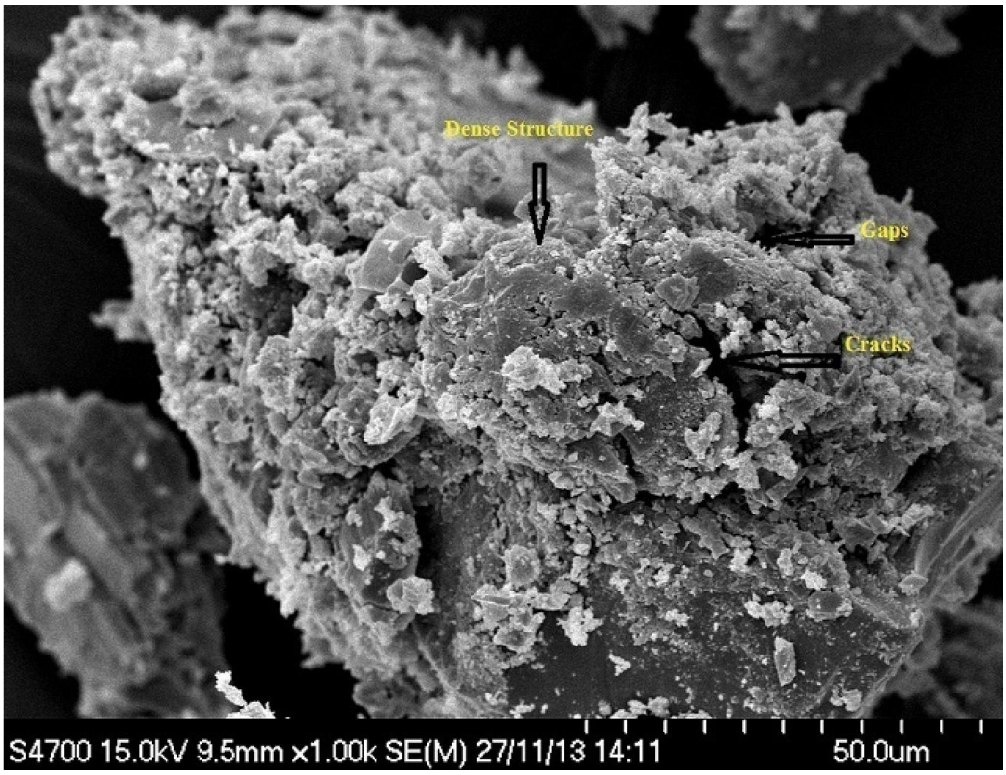


Figure 4.70: SEM image of control mix concrete with w/c 0.4

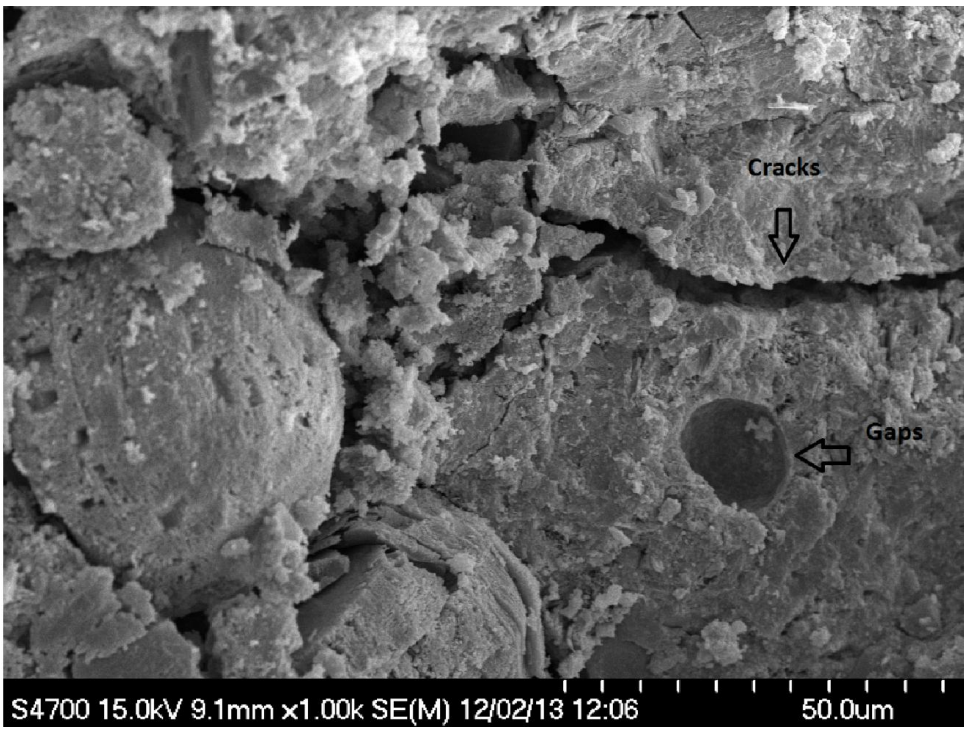


Figure 4.71: SEM of concrete with 10% crumb rubber (w/c 0.4)

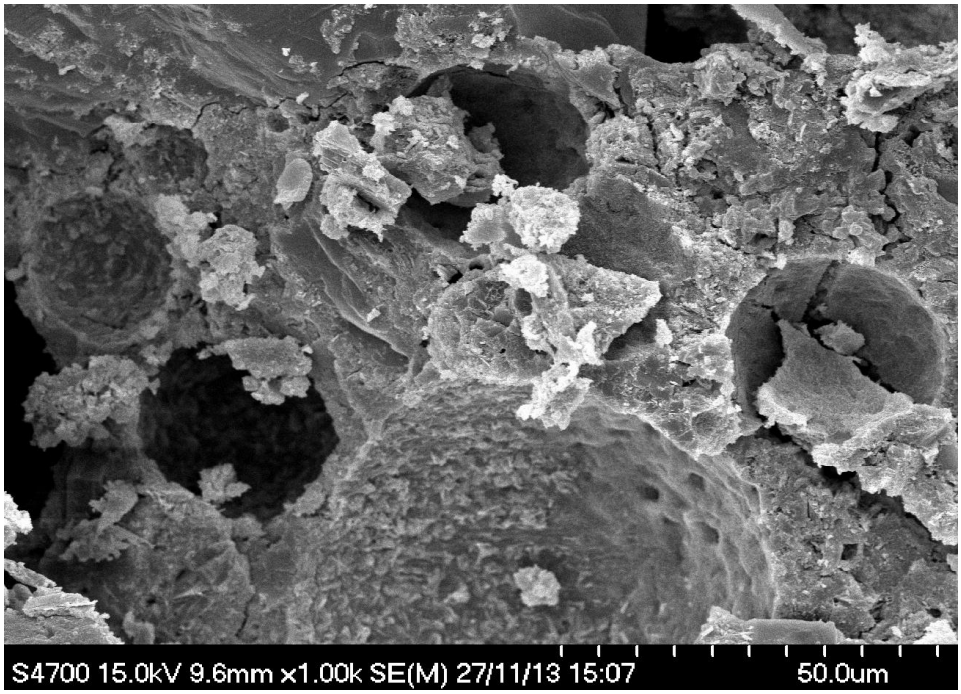


Figure 4.72 (A): SEM of concrete with 20% crumb rubber (w/c 0.4)

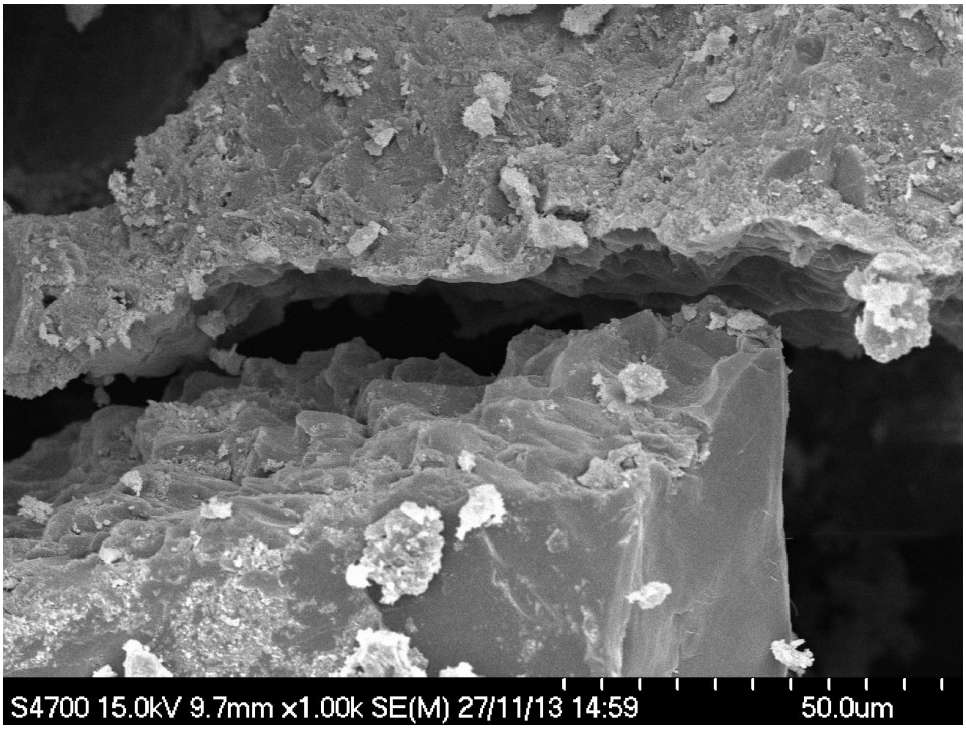


Figure 4.72 (B): SEM of concrete with 20% crumb rubber (w/c 0.4)

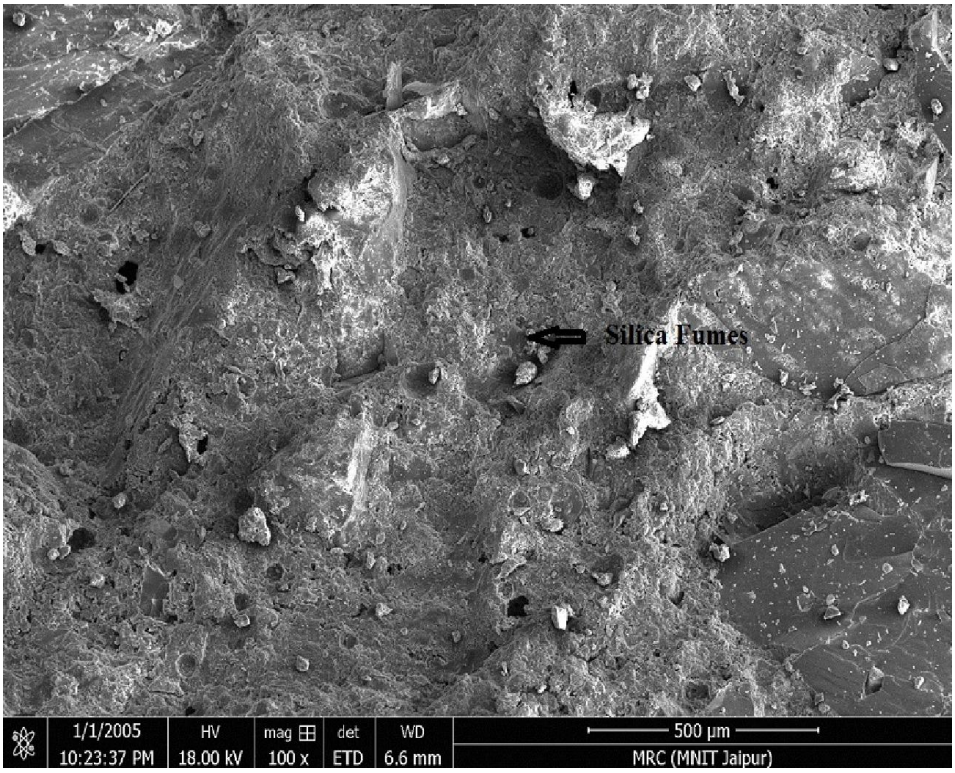


Figure 4.73: SEM image of control mix concrete (w/c 0.3)

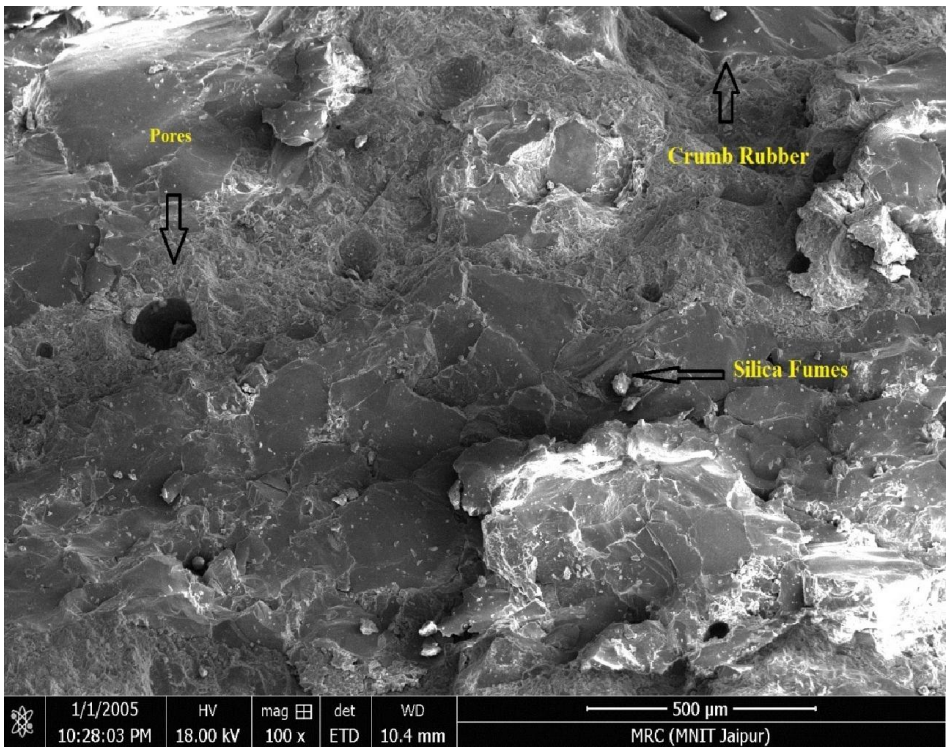


Figure 4.74: SEM image of concrete with 20% crumb rubber (w/c 0.3)

CHAPTER-5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Introduction

This experimental study was based on the utilization of waste tire rubber as a partial substitute for natural fine aggregates in cement concrete. In this research work, four series of concrete were casted. M30 grade of concrete was prepared in the first series with a water-cement ratio of 0.4. Crumb rubber (waste tire rubber mechanically grinded into rubber crumbs) was partially substituted for fine aggregates from 0% to 20% in multiples of 2.5%. The properties of concrete with water-cement ratios of 0.45 and 0.50 were also studied as the second and third series to determine the variation in different properties. In the fourth series, M60 grade concrete with a water-cement ratio of 0.30 was studied. The properties of concrete such as compressive strength, flexural tensile strength, abrasion resistance, pull-off strength, water permeability, water absorption, resistance to acid attack and sulphate attack, carbonation, depth of chloride penetration and corrosion of steel reinforcements were tested. SEM test was performed to study the micro structure.

5.2 On the basis of the results and discussions from this study, the following conclusions may be drawn:

5.2.1. From the compacting factor test conducted on the concrete with and without crumb rubber, it was observed that all the values were in the range of 0.94 to 0.98. Addition of crumb rubber did not affect the workability of concrete. There was no need to increase or decrease the quantity of the super plasticizer as the crumb rubber was added to the concrete.

5.2.2. In the compressive, flexural tensile and pull-off strength tests, gradual decrease in strength was noticed as the amount of crumb rubber was increased in concrete. The compressive and pull-off strength of the mix with 20% crumb rubber reduced by more than 50% compared to the control mix. The reduction in flexural strength for the same mix was only 25-27% when compared to the control mix.

5.2.3. The bulk density of the concrete decreased with the increase in the percentage of crumb rubber. The highest density was observed in the control mix concrete (with 0% crumb rubber) and gradual decrease in the density was noticed as the amount of crumb rubber was increased. The reason for this decrease in density of concrete may be due to the usage of crumb rubber which has a much lower specific gravity than river sand.

5.2.4. From the abrasion test, it was observed that the rubberized concrete specimens showed better resistance to abrasion when compared to the control mix specimens. During the abrasion test, the crumb rubber particles present in the rubberized concrete had projected beyond the smooth surface of the concrete and acted like a brush limiting the grinding/rubbing. This minimized the action of abrasive powder on the surface of concrete and hence the rubberized concrete was more resistant to abrasion compared to the control mix.

5.2.5. From the water penetration test of concrete, gradual increase in the depth of penetration was noticed, as the amount of crumb rubber was increased from 0% to 20%. All the concrete mixes with water-cement ratios of 0.4, 0.45 and 0.5 exhibited low to medium permeability, while those with a water-cement ratio of 0.3 exhibited low permeability.

5.2.6. From the water absorption test, it was clear that the control mix specimens absorbed more water than the rubberized concrete up to 7.5% substitution with crumb rubber for the series with water-cement ratios of 0.3, 0.4 and 0.45. A minimal amount of water absorption was noticed for the mixes with 7.5% crumb rubber. Beyond 12.5% substitution, the amount of water absorption was slightly higher when compared to the control mix concrete specimens. Similar results were obtained from the chloride ion penetration test.

5.2.7. From the carbonation test, it was noticed that the depth of carbonation of the concrete mixes in which crumb rubber was substituted from 2.5% to 12.5% were lower than or equal to that of control mix concrete in the case of water-cement ratios of 0.4 and 0.3. Minimal depth of carbonation was observed in the specimens with 7.5% - 10% crumb rubber. But in the case of water-cement ratio of 0.45 and 0.5, there was gradual increase in the depth of carbonation as the amount of crumb rubber is increased.

5.2.8. From the acid attack test, it was noticed that the loss in compressive strength and weight of concrete specimens were higher in the control mix and was minimum for the mixes with 20% crumb rubber. The crumb rubber particles prevented the separation of constituent particles of concrete by tightly holding it. So the concrete with more crumb rubber were more resistant to the loss in both compressive strength and weight. The water absorption of acid attacked rubberized concrete was higher than that of the control mix at 28, 56 and 84 days.

5.2.9. From the sulphate attack test, compressive strength was observed to be inversely proportional to the percentage of crumb rubber and water-cement ratio. Loss in weight up to 0.59% was observed for sulphate attacked specimens with higher amounts of crumb rubber after 182 days of immersion.

5.2.10. From the results of corrosion test, as all the readings obtained in the macrocell corrosion test were less than 10 μA, we could conclude that there is no evidence of significant corrosion in the specimens even at 182 days of ponding.

5.2.11. From the SEM analysis, a smooth, hard surface was observed on the river sand; while a rough, irregular surface was noticed on the crumb rubber. In the analysis of concrete, it was observed that the bond between rubber particles and cement paste was not as good as with traditional rigid aggregates. More voids were observed in the concrete as the amount of crumb rubber was increased.

5.2.12. **Applications and benefits to society may be as follows**

- If we can use tire rubber as a partial substitute for aggregates in concrete, the Environmental pollution caused by the discarded tire rubber can be prevented to a great extent.
- A lot of natural fine aggregates can be saved due to the substitution with the waste tire rubber in concrete.
- This could be an effective method to dispose the discarded tire rubber.
- The cost of construction projects can be reduced by reducing the use of the costlier natural fine aggregates.
- The waste accumulation that destroys the beauty of nature can be prevented to a great extent.

When we consider the concrete mixes with water cement ratios of 0.3, 0.4, 0.45 and 0.5, we could conclude that the compressive strength, flexural tensile strength, pull-off strength, water penetration and resistance to sulphate attack decreases with the increase in the amount of crumb rubber in concrete. Resistance to abrasion and acid attack increases with the increase in the amount of crumb rubber. Water absorption and carbonation resistance of rubberized concrete were found to be better than the control mix, up to a certain percentage of substitution. There was no evidence of significant corrosion in the specimens even at 182 days of ponding.

When we consider the grade of concrete, crumb rubber may be utilized for the partial replacement of natural fine aggregates in cement concrete up to 12.5%, for obtaining the compressive strength above 30 MPa in case of M30 grade concrete (with w/c 0.4) and above 60 MPa in case of M60 grade concrete (with w/c 0.3). To achieve the target strength, the recommended amount of crumb rubber is up to 5% for M30 grade concrete and up to 10% for M60 grade concrete. Rubberized concrete with up to 20% crumb rubber may be utilized (in situations where compressive strength is not very important) in areas where there is a risk of acid attacks. The tire rubber particles can improve the abrasion resistance of concrete, and this can help its application in pavements, floors and concrete highways, or in places where there are abrasive forces between surfaces and moving objects.

5.3 Recommendations for future work

5.3.1. The concrete with waste tire rubber as a fibre may be tested to study the strength and durability properties.

5.3.2. In our study, experiments were performed with the use of Ordinary Portland Cement (OPC) as a binder in concrete. Tests may be conducted with Portland Pozzolana Cement (PPC) as a binder instead.

5.3.3. The carbon black powder generated from the pyrolysis process of waste tire rubber may be utilized as filler or as a partial replacement for binder in concrete.

5.3.4. The tests like Mercury Intrusion Porosimetry (MIP), X-Ray Diffraction (XRD), X-Ray Fluorescence (XRF), Thermal Gravimetric Analysis (TGA), shrinkage, fire resistance, micro cell corrosion and half cell potentials may be performed for deeper study.

5.3.5. The level of accuracy in this study could be improved by better quality control.

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Annexure-1

Concrete Mix design

In the first series, M30 grade concrete was designed with water-cement ratio 0.40. For the second series and third series, water-cement ratio was increased to 0.45 and 0.50 respectively in the above mix design, without changing any other ingredients other than super plasticizer. For the fourth series, M60 grade concrete with water-cement ratio 0.30 was designed. The design steps for M60 grade concrete is shown as below.

1) $F'_{ck} = F_{ck} + 1.65S$

$= 60 + 1.65 \times 5$

$= 68.25\ N/mm^2$

2) Water-cement ratio = 0.3

3) Maximum water content = 186 Litres. Super plasticizer can reduce it up to 25%. So, water content = 186x0.75= 140 litres

4) Cement content= (140/0.3)=467 Kg/m^3. Maximum cement content is 450 Kg/m^3.

5) Volume of Coarse aggregate and Fine aggregate. From table 3 of IS 10262, for Zone II, Coarse aggregate is 0.62 and Fine aggregate is 0.38.

6) Cementitious materials. Adding silica fumes, 6% by weight of cement. It will come as 27 Kg/m^3. Total cementitious materials are 477 Kg/m^3. Water-cement ratio is 0.294 (140/477)

7) Corrected volume of aggregates. For water-binder ratio of 0.3, Coarse aggregate is 0.64 and fine aggregate is 0.36.

Mix Calculations

a) Volume of concrete – $1m^3$

b) Volume of cement = (450/3.15) (1/1000)= 0.143

c) Volume of water= 0.140

d) Volume of silica fumes=0.00852

e) Super plasticizer = 0.00303

f) d+e= 0.001155

g) All in aggregates. 1-(0.143+0.140+0.001155)= 0.7055

h) Mass of Coarse aggregate

20 mm (70% of total C.A. Specific gravity 2.68)= 0.4942x0.64x2.68x 1000 = 848 Kg

10 mm (30% of total C.A. Specific gravity 2.62)= 0.212x0.64x2.64x1000 = 355 Kg

i) Mass of fine aggregate= 0.706x0.36x2.62x1000= 666 Kg

Final mix proportions

a) Cement = 450 Kg/m^3

b) Silica fumes= 27 Kg/m^3

c) Total cementitious content = 477 Kg/m^3

d) Water = 140 Kg/m^3

e) Fine aggregate = 666 Kg/m^3

f) Coarse aggregate, 20 mm= 848 Kg/m^3

g) Coarse aggregate, 10 mm = 355 Kg/m^3

Annexure-2

Concrete mix proportions

Table 1: Mixture proportions of fresh concrete M60 grade, water-cement ratio 0.3

ID	FB 20	FB 21	FB 22	FB 23	FB 24	FB 25	FB 26	FB 27	FB 28
% of Rubber	0	2.5	5	7.5	10	12.5	15	15.5	20
Cement, kg/m^3	450.000	450.000	450.000	450.000	450.000	450.000	450.000	450.000	450.000
Silica Fumes kg/m^3	27.000	27.000	27.000	27.000	27.000	27.000	27.000	27.000	27.000
Water, kg/m^3	140.000	140.000	140.000	140.000	140.000	140.000	140.000	140.000	140.000
10mm CA, kg/m^3	355.000	355.000	355.000	355.000	355.000	355.000	355.000	355.000	355.000
20mm CA, kg/m^3	848.000	848.000	848.000	848.000	848.000	848.000	848.000	848.000	848.000
FA, kg/m^3	666.000	649.350	632.700	616.000	599.400	582.750	566.100	549.450	532.800
Crumb - Rubber, kg/m^3	0	6.68	13.35	20.05	26.71	33.38	40.06	46.74	53.41
Admixture %	2	2	2	2	2	2	2	2	2

Table 2: Mixture proportions of fresh concrete M30 grade, water-cement ratio 0.4

ID	FB 20	FB 21	FB 22	FB 23	FB 24	FB 25	FB 26	FB 27	FB 28
% of Rubber	0	2.5	5	7.5	10	12.5	15	15.5	20
Cement, kg/m^3	388.000	388.000	388.000	388.000	388.000	388.000	388.000	388.000	388.000
Water, kg/m^3	155.200	155.200	155.200	155.200	155.200	155.200	155.200	155.200	155.200
10mm CA, kg/m^3	465.600	465.600	465.600	465.600	465.600	465.600	465.600	465.600	465.600
20mm CA, kg/m^3	737.200	737.200	737.200	737.200	737.200	737.200	737.200	737.200	737.200
FA, kg/m^3	698.400	680.940	663.480	646.020	628.560	611.100	593.640	576.180	558.720
Crumb - Rubber, kg/m^3	0	7.370	14.730	22.110	29.470	36.840	44.220	51.580	58.950
Admixture %	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65

Table 3: Mixture proportions of fresh concrete M30 grade, water-cement ratio 0.45

ID	FB 30	FB 31	FB 32	FB 33	FB 34	FB 35	FB 36	FB 37	FB 38
% of Rubber	0	2.5	5	7.5	10	12.5	15	15.5	20
Cement, kg/m^3	388.000	388.000	388.000	388.000	388.000	388.000	388.000	388.000	388.000
Water, kg/m^3	174.600	174.600	174.600	174.600	174.600	174.600	174.600	174.600	174.600
10mm CA, kg/m^3	465.600	465.600	465.600	465.600	465.600	465.600	465.600	465.600	465.600
20mm CA, kg/m^3	737.200	737.200	737.200	737.200	737.200	737.200	737.200	737.200	737.200
FA, kg/m^3	698.400	680.940	663.480	646.020	628.560	611.100	593.640	576.180	558.720
Crumb - Rubber, kg/m^3	0	7.370	14.730	22.110	29.470	36.840	44.220	51.580	58.950
Admixture %	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30

Table 4: Mixture proportions of fresh concrete M30 grade, water-cement ratio 0.5

ID	FB 10	FB 11	FB 12	FB 13	FB 14	FB 15	FB 16	FB 17	FB 18
% of Rubber	0	2.5	5	7.5	10	12.5	15	15.5	20
Cement, kg/m^3	388.000	388.000	388.000	388.000	388.000	388.000	388.000	388.000	388.000
Water, kg/m^3	194.000	194.000	194.000	194.000	194.000	194.000	194.000	194.000	194.000
10mm CA, kg/m^3	465.600	465.600	465.600	465.600	465.600	465.600	465.600	465.600	465.600
20mm CA, kg/m^3	737.200	737.200	737.200	737.200	737.200	737.200	737.200	737.200	737.200
FA, kg/m^3	698.400	680.940	663.480	646.020	628.560	611.100	593.640	576.180	558.720
Crumb-Rubber, kg/m^3	0	7.370	14.730	22.110	29.470	36.840	44.220	51.580	58.950
Admixture %	0	0	0	0	0	0	0	0	0

Annexure-3

Economic analysis of the investigation

In this research work, investigation was done on the strength and durability characteristics of cement concrete in which the natural fine aggregates were partially replaced with crumb rubber. Replacement was done up to 20% and the results thus obtained were presented in detail in the previous chapters. This chapter deals with the economic analysis of using such a concrete.

1) Cost of river sand- as per the retail rate in 2014, it is **Rs 4-6/kg** (http://www.business-standard.com/article/current-affairs/sand-prices-rise-over-2-fold-in-vizag-builders-blame-faulty-policy-114111701772_1.html)

2) Cost of Crumb rubber- **Rs 2-4** (The cost given is inclusive of the cost of waste material, collection from streets and grinding the tire rubber in the form of crumbs or powder). This detail was collected from S&J Granulate solutions, Maharashtra.

3) To produce one cubic metre concrete, the amount of fine aggregate is 666.00 Kg/m^3. (This is as per the concrete mix design given in Annexure 2)

4) If 20% (133.2 Kg/m^3) of fine aggregate is to be replaced by crumb rubber, it requires only 53.380 Kg/m^3 of crumb rubber due to the lower specific gravity of crumb rubber. Natural fine aggregate is taken by weight and crumb rubber was replaced by volume. It was done for volumetric equalization. Thus, the cost for Fine aggregate (river sand) will be Rs 800/- and that of the crumb rubber will be Rs 214/-.

5) There will be a saving of Rs 586/- for one cubic metre of concrete mixture considered. But as revealed in the research work reported in the previous chapters, there can be loss in compressive strength up to 50% when there is 20% replacement with crumb rubber.

6) The huge benefit of waste minimization and pollution control can be the highest achievement if this is implemented.

Annexure-4

Range of Water Permeability according to Eshmaiel Ganjien et al., 2009 (Ref:45)

Permeability range according to DIN 1048	low	medium	high
Permeability depth in 4 days, in cm	Less than 3	3-6	Greater than 6

When the depth of water penetration is less than 3 cm, it can be called as low permeability. If it is between 3 cm to 6 cm, it is called medium permeability and if it is greater than 6 cm, it is called high permeability.

Annexure- 5

Acid attack of rubberized concrete

A) Water absorption of acid attacked concrete at 84 days of exposure

% of CR / w/c Ratio	0	2.5	5	7.5	10	12.5	15	17.5	20
0.3	1.06	1.15	1.21	1.35	1.35	1.48	1.59	1.63	1.67
0.4	2.81	2.91	3.05	3.12	3.15	3.21	3.23	3.24	3.32
0.45	3.05	3.01	3.11	3.18	3.23	3.26	3.41	3.52	3.49
0.5	3.45	3.39	3.42	3.49	3.53	3.58	3.61	3.71	3.72

B) Variation in weight of acid attacked concrete at 84 days of exposure (% loss)

% of CR / w/c Ratio	0	2.5	5	7.5	10	12.5	15	17.5	20
0.3	8.22	8.23	8.16	7.77	7.57	7.25	7.08	6.81	6.49
0.4	8.50	8.27	8.33	7.84	7.61	7.52	7.53	7.49	7.24
0.45	8.48	8.57	8.47	8.44	8.32	7.95	7.67	7.56	7.45
0.5	9.10	9.04	8.95	8.75	8.62	7.68	7.64	7.56	7.46

C) Compressive strength of acid attacked concrete at 84 days of exposure (% loss)

% of CR / w/c Ratio	0	2.5	5	7.5	10	12.5	15	17.5	20
0.3	71.8	71.6	68.8	66.2	62.4	59.8	57.8	49.1	47.3
0.4	77.65	76.59	73.33	72.97	65.67	62.67	58.00	59.23	56.00
0.45	76.93	76.05	73.63	71.45	67.64	63.20	60.13	59.07	56.00
0.5	79.45	78.19	75.67	74.40	66.67	62.44	59.02	57.71	56.47

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4. **List of Publications**

[1]. Blessen Skariah Thomas, Ramesh Chandra Gupta. A Comprehensive review on the applications of waste tire rubber in cement concrete. Renewable and Sustainable Energy Reviews 2016, 54: 1323-1333.

[2]. Blessen Skariah Thomas, Ramesh Chandra Gupta. Properties of High Strength concrete containing scrap tire rubber. Journal of Cleaner Production 2016, 113: 86-92.

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