DEVELOPMENT OF LIGHT WEIGHT, THERMAL RESISTANT CONCRETE UTILIZING RECYCLED PLASTIC AGGREGATES

BY

SHAIK INAYATH BASHA

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DEANSHIP OF GRADUATE STUDIES

This thesis, written by **SHAIK INAYATH BASHA** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN CIVIL ENGINEERING.**

Dr. Salah U. Al-Dulaijan
(Advisor)

Dr. Salah U. Al-Dulaijan
Department Chairman

Dr. Mohammad Maslehuddin
(Co-Advisor)

Dr. Salam A. Zummo
Dean of Graduate Studies

Dr. Shamsad Ahmad
(Member)

7/6/17

Date

عمادة الدراسات العليا
DEANSHIP OF GRADUATE STUDIES

Dr. Mohammed Al-Osta
(Member)

Dr. Jobin Jose
(Member)

Dedicated to

My Beloved Parents and family members

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ABSTRACT

Full Name : SHAIK INAYATH BASHA

Thesis Title : Development of Lightweight, Thermal Resistant Concrete Utilizing Recycled Plastic Aggregates

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The concrete industry needs millions of tons of aggregate, comprising natural sands and gravel, each year. A similar notion can be stated in case of ‘plastic’ as majority of the contemporary products and equipment in our daily life are made using plastic. Another resemblance of these two materials is their non-biodegradable character, and this raises plenty of questions to scientists and environmentalists. The utilization of recycled plastic during the preparation of concrete, as a partial replacement of natural aggregates, resolves the issues of safe disposal of waste plastic, reduces landfill anxiety over environmental protection and conserves our natural resources for the future.

The aim of the proposed research was to assess the possibility of utilizing recycled waste plastic, as a partial/full replacement of natural aggregates. The concrete specimens prepared utilizing recycled plastics were tested to evaluate their mechanical properties and durability properties.

From the experimental data, it is concluded that the mechanical properties decreased with the increase in the plastic content, the poor bond between the plastic and the cement paste is the reason for poor mechanical properties of the concrete. The durability of the concrete was marginally affected due to the incorporation of plastic aggregates. Due to

the low unit weight and thermal conductivity values of recycled plastic aggregate concrete, there is a potential of using this concrete in construction applications.

ملخص الرسالة

الاسم الكامل: شيخ عناية باشه

عنوان الرسالة: تطوير خرسانة خفيفة الوزن ومقاومة للحرارة باستخدام البلاستيك المعاد تدويره كرمل

التخصص: ماجستير العلوم في الهندسة المدنية

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تحتاج صناعة الخرسانة كل عام إلى ملايين الأطنان من الركام، بما في ذلك الرمال الطبيعية والحصى. ويمكن ذكر فكرة مماثلة في حالة "البلاستيك" حيث يتم تصنيع معظم المنتجات والمعدات المعاصرة في حياتنا اليومية باستخدام البلاستيك.

تشابه آخر لهاتين المادتين هو طابعها غير قابل للتحلل، وهذا يثير الكثير من الأسئلة للعلماء والبيئيين. إن استخدام البلاستيك المعاد تدويره أثناء تحضير الخرسانة، كبديل جزئي للركام الطبيعي، يحل قضايا التخلص الآمن من النفايات البلاستيكية، ويقلل من قلق المدافن على حماية البيئة ويحافظ على مواردنا الطبيعية للمستقبل.

وكان الهدف من البحث المقترح هو تقييم إمكانية استخدام البلاستيك المعاد تدويره من النفايات، كبديل جزئي / كامل للركام الطبيعي. تم اختبار العينات الخرسانية المعدة باستخدام البلاستيك المعاد تدويره لتقييم خواصها الميكانيكية وخصائص المتانة.

من البيانات التجريبية، استنتج أن الخواص الميكانيكية انخفضت مع الزيادة في محتوى البلاستيك، الترابط السيئ بين البلاستيك ومعجون الاسمنت هو السبب في الخواص الميكانيكية الضعيفة للخرسانة. وقد تأثرت متانة الخرسانة بشكل طفيف بسبب استخدام الركام البلاستيكي. ونظرا لانخفاض وحدة الوزن وقيم التوصيل الحراري للخرسانة الكلية للبلاستيك المعاد تدويره، هناك إمكانية لاستخدام هذا الخرسانة في تطبيقات البناء.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The global consumption of plastics is over 300 million metric tons per year and the annual growth over the last five years is estimated at 3.4% [1]. A large portion of plastics, especially commodity plastics, is produced in the Middle East. Plastics have been used in an enormous number of applications, such as packaging, furniture, medical devices, automotive and industrial components, oil/water treatment industries, land/soil conservation and flood prevention, traffic lane equipment, electronic materials, aircraft components and other applications. The accumulation of huge volumes of commodity waste plastics derived from municipal solid waste and other household items has become a major waste management issue over the past two decades. The threat of plastic waste seems to be always growing as it contains several toxic chemicals that pollute soil, air and water. In the plastic waste stream, polyethylene (HDPE and LDPE) forms the largest fraction, followed by PET, PP and PS. The earlier trends, such as landfill and incineration of these non-biodegradable materials creates a lot of pollution and smoke and in the long-run a worldwide threat to the environment and humanity itself.

Recently, government organizations and various environmental activists are paying a lot of interest and efforts to recycle polymeric waste materials and exploit them in a manner that resolves any concern related to the environmental pollution. Recycling offers the advantages of preservation of available natural resources, reduced labor and riddance of environmental pollution starting from the petroleum industry until the final disposal of the product after the use [2].

Research on concrete mixes with reinforced plastics started in the 1990s like plastic fibers, plastic resins and very recently plastic aggregates [3]. Recently, concrete has been identified as an excellent disposal means of several industrial wastes, such as fly ash, silica fume, oil ash, ground granulated blast furnace slag (GGBS) and marble powder with some improved properties and slight compromise in strength has gained a lot of attention among researchers and industrialists [4]. There are also few studies in which raw plastic materials, mostly in the form of granules, were added to make lightweight concrete for specific applications [5]. The incorporation of plastics in concrete can have significant effects in two stages; the first one is during the concrete manufacturing in which plastic as aggregates affects the workability. Irregular and porous type plastic aggregates limit the concrete workability while spherical and smooth aggregates are likely to improve the workability.

In the second stage, the effects of plastic aggregates on the performance of concrete with respect to its compressive strength, split tensile strength and the ductility was studied. It was reported that there is a considerable loss in bond strength between the plastic aggregate and the binding paste and there is a weak affinity between hydrophobic plastic and the cementitious matrix that is hydrophilic in nature. The presence of low modulus plastic material also influences the overall strength of the concrete. However, there is improved abrasion and wear resistance due to the presence of better abrasion resistant plastic material. The important advantages of plastic based concrete are better energy efficiency, thermal comfort, and the ductile material capable of absorbing vibrations or deformations without losing the integrity. This ductile behavior is a significant advantage to prevent the crack formation and propagation to some extent. The failure mode of plastic aggregates filled concrete shows the pull out of plastic components rather than split apart of the natural aggregates. The breakdown of a concrete specimen with plastic aggregates on compressive loading displays a steady failure instead of the classic brittle failure that is noted with the natural aggregates.

Due to the increasing problem of disposal of waste plastics to explore the possibility of utilizing them in concrete. This study was conducted to explore the possibility of utilizing recycled plastic aggregates generated from commodity waste plastics, in concrete.

1.2 NEED FOR THE RESEARCH

The disposal of plastic waste is a huge challenge since there is a lack of recycling culture. One of the avenues of utilizing the plastic waste is to utilize it in concrete. Such usage is expected to solve the disposal and environmental problems associated with these materials. In the proposed study plastic from consumer solid waste was utilized in concrete. It is expected that the developed plastic concrete will be lighter and have better thermal insulation properties compared to the conventional concrete. These two attributes will lead to considerable energy saving and also solve the disposal problem of the plastics.

The advantages of recycling plastics are reduced labor cost, continuation of existing culture of reuse, recycle and reduce to save the natural resources for the future, create opportunities for small business, fewer laws and regulations for the quality of the recycled material and lower cost of transportation and processing.

The garbage in Saudi Arabia, collected through individuals and community bins is disposed of in landfills or dumpsites. The waste management system in Saudi Arabia is characterized by the lack of waste disposal facilities and absence of tipping fees.

Figure 1 Figure showing waste in KSA.

It is expected that most of the landfills would reach their capacities within the next 10 years. Although the concern is increasing towards this scenario, the recycling, reuse and energy recovery is still at an early stage. [1]

Therefore, a considerable effort is required in improving the waste management scenario in the Kingdom. Introduction of modern waste management techniques like material recovery facilities, waste-to-energy systems, recycling infrastructure and using the waste in construction can significantly improve waste management scenario and can also generate good business opportunities

1.3 OBJECTIVES

The overall objective of this research was to utilize recycled plastics as a partial substitution of natural aggregates in Portland cement concrete. The specific objectives of the proposed research were the following:

I. Study the effect of the incorporation of recycled plastics as a replacement of natural aggregates, on the properties of concrete,
II. Determine the optimum plastic content with regard to concrete properties,
III. Evaluate the effect of surface characteristics of recycled plastics on the properties of concrete, and
IV. Identify avenues for the utilization of the developed concrete.

1.4 THESIS ORGANISATION

This thesis is organized in a total of 5 chapters. The content of each of these chapters is explained below.

Chapter 1: In this chapter background, the need of this research and objectives of the research study are included.

Chapter 2: This chapter provides an overview of the previous studies, the Literature review related to the subject of this research work.

Chapter 3: This chapter includes the experimental methodology, materials properties, mix preparation, tests employed, the equipment and procedure for carrying out these tests.

Chapter 4: This chapter describes the results and discussions of the test program.

Chapter 5: This chapter has been dedicated to the conclusions and recommendations based on the discussion from the previous chapters.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Plastics are polymers, a very large molecule made up of smaller units called monomers which are joined together in a chain by a process called polymerization. The polymers generally contain carbon and hydrogen with, sometimes, other elements such as oxygen, nitrogen, chlorine or fluorine [6].

A substantial increase in the production and consumption of plastic all over the globe has led to huge amount of plastic waste. The mechanical recycling of this plastic waste and its utilization in concrete or mortar preparation appears as one of the ideal solution for disposing the used plastics, because of economic and ecological benefits. Even though, plastic recycling is universally accepted and promoted, most of the recycled products cannot be used for the same application due to health issues and sustainability. Hence, the most efficient and safest way to meet this challenge is to utilize them in products useful for construction industry. The exponential growth in population, urbanization, and trade and industry in the Middle East isnot only accelerating the consumption rates but also increasing the production rate of all classes of waste. Saudi Arabia along with other Middle Eastern countries comes in the top-ten worldwide in terms of per capita solid waste generation (15 million tons of solid waste in a year). For more than 50 years, global production of plastic has continued to rise. Some 299 million tons of plastics were produced in 2013, representing a 4% increase over 2012. Recovery and recycling, however, remain insufficient, and millions of tons of plastics end up in landfills and oceans each year [7].

Approximately 10–20 million tons of plastic end up in the oceans each year. A recent study conservatively estimated that 5.25 trillion plastic particles weighing a total of 268,940 tons are currently floating in the world's oceans. This plastic debris results in an estimated $13 billion a year in losses from damage to marine ecosystems, including financial losses to fisheries and tourism as well as time spent cleaning beaches. Animals such as seabirds, whales, and dolphins can become entangled in plastic matter, and floating plastic items—such as discarded nets, docks, and boats—can transport microbes, algae, invertebrates, and fish into non-native regions, affecting the local ecosystems. Businesses and consumers could increase their participation in the collection in order to move plastic waste toward a recovery supply chain, and companies could switch to greater use of recycled plastics. Governments must regulate the plastic supply chain to encourage and monitor recycling. The mechanical recycling of this plastic waste and its utilization in concrete or mortar preparation appears as one of the ideal solutions for disposing of the used plastics, because of economic and ecological benefits. Even though plastic recycling is universally accepted and promoted, most of the recycled products cannot be used for the same application due to health issues and sustainability. Hence, the most efficient and safest way to meet this challenge is to utilize them in products useful for the construction industry. The exponential growth in population, urbanization, and trade and industry in the Middle East is not only accelerating the consumption rates but also increasing the production rate of all classes of waste. Saudi Arabia along with other Middle Eastern countries comes in the top-ten worldwide in terms of per capita solid waste generation (15 million tons of solid waste in a year).

2.2 TYPES AND USES OF PLASTICS

Plastics are classified according to the basis of the polymer, from which they are made. The types of plastics that are most commonly reprocessed are polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), and polyvinyl chloride (PVC). Table 1 details the types and uses of plastic and recycled plastic.

Table 1: Types and uses of plastics and recycled plastics, [6]

Type of plastic	Description	Some uses for virgin plastic	Some uses for recycled plastic
Polyethylene terephthalate (PET)	Clear tough plastic, may be used as a fiber	Soft drink and mineral water bottles	Clear film for packaging, carpet fibers, fleecy jackets
Low-density polyethylene (LDPE)	Soft, flexible plastic, milky white, unless a pigment is added	Lids of ice-cream containers, garbage bags, and garbage bins	Film for builders, industry, packaging and plant nurseries
High-density polyethylene (HDPE)	Very common plastic, usually white or colored	Crinkly shopping bags, freezer bags, and milk	Compost bins, detergent bottles, crates, and mobile rubbish bins

Unplasticised Polyvinyl chloride (UPVC)	Hard rigid plastic, may be clear	Clear cordial, juice bottles, plumbing pipes and fittings	Detergent bottles, tiles, and plumbing pipe fittings
Plasticized Polyvinyl chloride (PPVC)	Flexible, clear, elastic Plastic	Garden hose, shoe soles, blood bags and tubing	Hose inner core, and industrial flooring
Polypropylene (PP)	Hard, but flexible plastic	Ice-cream containers, potato crisp bags, stools and chairs	Compost bins, kerb side recycling crates, and worm factories
Polystyrene (PS)	Rigid, brittle plastic. May be clear, glassy	cheap, transparent kitchen ware, light fittings, bottles, toys, and food containers	Clothes pegs, coat hangers, and video/CD boxes
Polyester (EPS)	Foamed, lightweight, energy absorbing, and thermal insulation	Hot drink cups, and takeaway food containers	spools, rulers, and video/CD boxes
Polyamides (PA)	Nylons	fibers, toothbrush bristles, and fishing lines	

2.3 PREVIOUS STUDIES RELATED TO USING RECYCLED PLASTIC AS AGGREGATE

The plastic aggregates of the waste plastic used in many studies were obtained from various sources, such as plastic bottles ground in the laboratory by using a grinding machine and then sieved to get the suitable size fraction [8] or collecting the plastic aggregates from the commercial industries which manufactures the plastic products by recycling the used plastic.

The utilization of plastic waste from various commodities in the concrete manufacturing sector is an attractive and safe mode of disposal that can resolve the majority of environmental issues caused by polymers [9-11].

The partial replacement of natural aggregates using recycled thermoplastic wastes reduces the weight of the concrete due to very low specific gravity of recycled plastics in comparison with the natural aggregates. The advantages of lightweight concrete include: the reduction in foundation size, greater design flexibility, reduced dead load of the structure, improved dynamic loading response, longer and thinner sections, smaller size structural components, less reinforcing steel and fewer construction costs. Another major change that occurs in the concrete due to the addition of waste plastic is the enhanced thermal insulation that seems to be the prime criteria for energy saving in building construction [12]. However, the corrosion resistance of concrete is hardly changed due to the presence of plastic waste even under aggressive environment [13].

The introduction of plastic waste as a replacement of fine aggregate also proved to be an effective approach to arrest the propagation of micro cracks generated in concrete [14]. However, it is noted that the workability has been decreased to some extent. The thermosetting plastic waste that cannot be processed by thermal recycling may be used as admixture in the concrete formulation that meets most of the requirements for non-load-bearing lightweight concrete applications [15].

There are few studies to understand the effect of polymer waste material in the concrete or construction material, either as a binder or as a reinforcing/non-reinforcing filler [16].

Saikia and de Brito [17] published a detailed review article on the use of plastic waste as an alternate for natural aggregates in concrete. It was reported that the size and shape of plastic aggregates significantly affected the workability of concrete and the density of the whole concrete decreased when the plastic content was increased. The incorporation of plastic aggregates in the concrete usually reduced the compressive strength while the flexural and tensile splitting strength were little affected. They reported that concrete may have improved ductility and the tendency to generate crack under mechanical loading [17]. The lower thermal conductivity of the plastic waste aggregate significantly reduced the heat energy consumption of the building with less heat loss during the winter and less heat gain during summer [17]. The same research group evaluated the effect of waste plastic on the mechanical properties of concrete under different curing conditions [18]. It was reported that increasing the quantity and size of the plastic decreased the strength properties (compressive and splitting tensile) and modulus of elasticity of concrete. However, they reported enhanced wear resistance against abrasion of concrete with plastic.

Mahdi et al. [19] used depolymerized PET plastic waste as a binder instead of OPC to prepare polymer mortar and polymer concrete and the presence of a suitable initiator in the mixture led to crosslinking and hence strong polymer concrete. The recycled plastics (commodity plastics like PE, PP and PVC), when used as lightweight coarse aggregates, as a replacement for natural coarse aggregates, alter the thermal properties of the buildings.

Almost a decade ago, Elzafraney et al. [20] conducted energy saving analysis of a house built of recycled mixed plastic waste as aggregates in concrete. They observed that the building made of recycled plastic incorporated concrete exhibited higher levels of energy saving and comfort compared with the standard concrete building. The presence of recycled plastic in concrete lowered the heating and cooling effects largely. However, the loading levels of these inert aggregates in the concrete mix were limited for the partial replacement of aggregates due to a substantial reduction in the compressive strength [20-21].

Ghernouti and Rabehi [22] investigated the strength properties of mortars incorporating plastic bag wastes as fine aggregates. They reported that the replacement of fine sand with granules of plastic bag wastes in mortar slows down the penetration of chloride ions and improves the behavior of mortars in acidic medium and sensitivity to cracking.

Recycled plastic waste particles obtained from PET bottles were successfully used as a replacement of natural aggregates in concrete without suffering much reduction in strength characteristics and several studies were carried out on polymer concrete based on waste PET as an aggregate replacement [23].

Rebeiz [24] reported about the preparation and characterization of reinforced and unreinforced recycled PET waste-based polymer concrete. It was reported that low viscosity and good wetting property of the resin with the aggregates were crucial factors for the workability of concrete. It was reported that the developed polymer concrete could be utilized for precast purposes, such as utility components, machine bases, building components and transporting components.

Fraternali et al. [25] reported about the mechanical properties of recycled PET fiber reinforced concrete and its durability in an aggressive seawater environment. It was reported that in comparison with the air-cured concrete with PET fiber reinforcement, the seawater cured specimens demonstrated slightly improved compressive strength and delayed the first-crack strength, whereas there was marked reduction in the energy absorption capacity.

Correia et al. [26] investigated the performance of concrete prepared using PET plastic waste as aggregates when subjected to high temperature, in terms of thermal response and residual mechanical properties. The replacement of natural aggregates with plastic waste was fixed between 7.5 and 15.0 wt. %. The thermal treatment of the concrete up to 800°C caused higher temperature development in plastic waste based concrete compared to normal concrete. It was observed that the thermal decomposition of the organic plastic waste material produced additional heat and the degradation of plastic in the concrete mix created a highly porous structure.

Iucolano et al. [27] optimized the plastic waste substitution in the mortar composition and analyzed the overall performance in terms of physical, mechanical and thermal properties. The experimental mortars demonstrated a strong potential as a base of green building material, adding to the typical qualities of a natural hydraulic lime, a low cost and widely available material with excellent characteristics. More importantly, these composite mortars have exhibited a thermal conductivity of less than 50% compared to that of traditional mortar. As a continuation of the above study.

Liguori et al. [28] investigated the interaction mechanism between recycled plastic aggregates and lime matrix in composite mortars by means of thermal, morphological and Fourier Transform Infrared Spectroscopy (FTIR) analyses. Plastic aggregates made of polyolefin and polyethylene terephthalate (PET), acquired from an industrial waste through recycling process were incorporated to prepare the concrete. The composite mortar specimens were prepared by substituting the silica powder with 10-20% of recycled plastic powder. They reported a superior chemical interaction between the plastic aggregate and mortar, involving a reduction of the negative effects on characteristic properties of the mortar composites, such as thermal degradation and fire retardant even without any chemical modification. All the specimens showed a scarce sensitivity to 'flashover', and hence can be classified as low risk materials for structural applications.

Alessandro et al. [29] studied the properties of lightweight concrete containing small sized granules of waste plastics of electrical wires. The incorporation of polymeric wastes in the concrete mix showed promising acoustic and thermal (lower thermal conductivity) performances. The structural properties suggested that these lightweight concretes could be easily used in flooring. The partial replacement of sand aggregates by glass fiber reinforced polymer waste material into polyester based mortars improved the flexural and compressive strength [30]. The optimum amount of the waste aggregates in the mortars for the maximum mechanical properties varied with respect to the size of the aggregates. Disposal of waste rubber tire in the surroundings is a serious environmental problem that needs to be tackled effectively by utilizing them in concrete sector specifically for non-structural applications [31].

Sadek and El-Attar [32] developed solid cement bricks using recycled scrap tire rubber as aggregates (0-100% and 0-50%; coarse and fine aggregates, respectively) and evaluated their structural behavior in masonry walls under compression. It was reported that the size and the content of rubber have a significant impact on the properties of the bricks and subsequently on the structural behavior of the masonry walls.

A recent study by Youssef et al. [33] demonstrated the effective utilization of crumb rubber in concrete prepared with the addition of fiber-reinforced polymer (FRP). The addition of FRP could compensate the reduction in compressive strength considerably, while the ductile character imparted by crumb rubber was well retained. These types of concretes are well suited for structural applications that are subjected to seismic loads where ductility, damping ratio and energy dissipation demands are more critical than strength. The abrasive wear of concrete in hydraulic structures can be efficiently prevented by using modifying the concrete using rubber particle as aggregates (granulated rubber concrete). Partial replacement of fine river aggregates with rubber granules (5 wt.%) improved the hydro-abrasive resistance. There was an increase in the ductility even though there was a reduction in the compressive and flexural strength and modulus of elasticity [34]. The surface coating of the rubber crumb using limestone powder and the concrete formulation using a small percentage of silica fume as partial replacement of the binder made a mechanically strong concrete, otherwise a low strength concrete due to the introduction of soft and weakly interacted rubber crumb. The surface resistivity and the resistance against chloride penetration are also improved for the modified concrete [35].

The incorporation of super plasticizer (2 wt.%) to the concrete mix containing glass fiber reinforced polymer waste powder (15 wt.%) as filler was able to increase the strength properties (compressive and split tensile strength). The optimum dosage and characteristics properties of the waste powder have a considerable effect on the final properties of concrete. The environmental viability of such concrete needs to be studied further to analyze its durability and stability under different environment [36]. In addition, the introduction of a super plasticizer significantly improved the workability (10-15%) of the concrete that was otherwise reduced due to partial replacement of fine sand aggregates with waste plastic flakes [37].

Laukaitis et al. [38] prepared lightweight thermo-insulating concrete containing crushed polystyrene (PS) waste and spherical blown PS waste. They used a 0.2% sulfonyl and 0.03% glue hydro solution in order to enhance the adhesion between the PS granules and the cement paste. It was reported that the compressive strength of the concrete in the range of 150–170 kg/cm^2 while the coefficient of thermal conductivity between 0.06 and 0.0.64 W/m K.

Mounanga et al. [39] reported that concrete containing polyurethane (PU) wastes (a low thermal conductive material) from insulation panels showed very low compressive strength because of the weak and porous PU particles as aggregates. The drying shrinkage also increases with increasing polymeric waste content in the concrete mix. The use of pre-soaked polyurethane wastes and a high water/cement ratio (> 0.5) was accountable for the high porosity causing a significant reduction in the compressive strength [40]. This can be overcome by using a low w/c ratio.

Cheng et al. [41] studied the role of expanded polystyrene content on the failure mode, stress-strain relationship and modulus of elasticity of lightweight concrete (900 kg/m^3) under uniaxial loading. The lightweight concrete exhibited good compressibility in the compression failure. In addition, oblique cracks appear in the case of uniaxial compression specimens; the lower the density was, the smaller the tilt angle of oblique cracks. The stress-strain curve of the concrete with a density of more than 422 kg/m^3 maintained a straight-line relationship on ascending segment but varied with the density on the descending segment. The elastic modulus was proportional to 5.85 times the index of relative density.

Sevigné-Itoiz'[42] in his publication 'Plastic waste recovery Contribution to greenhouse gas (GHG) savings in Spain', the environmental consequences of different alternatives were quantified to evaluate opportunities and limitations for selecting the best and most feasible plastic waste recovery option to minimize the GHG emissions. The study focused on Spain as a representative country for Europe. He concluded that the waste management is dependent on the quality of the recovered plastic in improving the resource efficiency and avoiding more GHG emissions.

Alqahtani'[43] in his recent investigation on Lightweight Concrete Containing Recycled Plastic Aggregates, where he incorporated Concrete with Recycled Plastic Aggregate as Coarse aggregate with red sand as a filler, found that 100% replacement of conventional Lightweight aggregate (LWA) with recycled plastic aggregate (RPA) showed about 13% reduction in chloride penetration. Compressive strength was reduced; however, the achieved strength was between 12 and 15 MPa which is useful for non-structural elements, such as pavements, low side building work, cementitious backfill, and others.

Corinaldesi'[44] in a recent study on Lightweight plasters containing plastic waste, with 100% replacement of raw materials namely natural sand and limestone by waste particles such as polyethylene terephthalate (PET) and pulverized Glass Fiber Reinforced Plastic (GFRP). Additionally, waste particles like PET and wood waste (WW) were combined to enhance the functional properties of plasters by adding silica fume, which is a further an industrial by-product. Further, even cement was replaced fully in some mixtures by a combination of lime and hydraulic lime to further enhance the carbon footprint of these plasters. Finally, in the optimization process, environmentally-friendly plasters were obtained with 100% replacement of raw materials by waste particles, which proved to be energy efficient.

Sharma'[45] published a detailed review article on the use of different forms of waste plastic in concrete. It was reported that the direct inclusion of plastic in concrete does not effectively improve the strength of concrete. However, it is useful to treat plastic surfaces with reactive materials, such as iron slag, silica fume, and metakaolin. In this case, the treated surface will react with the matrix and produce additional pozzolanic reactions. It was also found that Workability of concrete containing waste plastic begins to decrease as the amount of waste plastic increases. Addition of plastics in concrete, compressive strength of the concrete decreases. However, by using suitable mineral admixtures [46] and chemically treated plastic such as alkaline bleach treatment (bleach of NaOH) the performance of plastic fiber reinforced concrete can improve. Moreover, addition of limited percentages of plastic in concrete has resulted in small improvements in the tensile strength of concrete. The increments of tensile strength improvement result from the bridging actions of the fibers in the concrete.

Further, it was reported that the flexural strength of concrete improves with the addition of plastic fibers in concrete. The plastic in concrete works like a crack arrester during the propagation of the crack. Hence, improvements in ductility are also observed in concrete that is reinforced with plastic fiber relative to conventional concrete. The modulus of elasticity of plastic fiber reinforced concrete decreases as the plastic content increases in any form [47]. It was Concluded that mixing fibers in concrete is one major problem in the production of fiber reinforced concrete. The properties of concrete vary as the plastic fiber content in concrete varies. Thus, future research should focus on establishing a method for mixing plastic fiber in concrete, the shape of plastic fibers, the specified aspect ratios of plastic fibers, and the surface properties of plastic fibers so that the fibers adhered to the concrete mix. Plastic fiber reinforced concrete can be used for structures that are not subjected to heavy loads, such as park benches and stone curb. This can lead to reduce the amount of waste plastic.

Even though some research, discussed earlier, has been conducted on the use of properties of concrete incorporating plastics, much work needs to be done in this direction. In particular, the use of waste plastics to develop lightweight thermal resistant concrete needs to be studied. Development of lightweight concrete will result in economic and environmental benefits.

CHAPTER 3

METHODOLOGY OF RESEARCH

3.1 INTRODUCTION

This Chapter includes the experimental program and the constituent materials used to investigate the potential usefulness of using recycled plastic waste as a partial/ full replacement of coarse aggregate in the concrete.

The effects of recycled plastic waste on different properties of concrete were studied in the experimental program by the addition of different types of recycled plastic with various mix proportions of the concrete.

The laboratory study consisted of tests for both mechanical and durability properties. The tests for mechanical properties included: density (unit weight), compressive strength, flexural strength, modulus of elasticity, bond strength, thermal conductivity, shear and flexural behavior of the reinforced concrete with recycled plastic aggregates. The tests for the durability properties included: water absorption, rapid chloride permeability, reinforcement corrosion potential, wet/dry exposure, heat/cool exposure and drying shrinkage. The test procedures, details and equipment used to assess concrete properties are detailed in the following sections.

3.2 MATERIALS

The materials used in the test program include: ordinary portland cement, natural coarse aggregate, sand, water, superplasticizer and recycled plastic. Material properties are as follows:

3.2.1 CEMENT

Ordinary Portland cement conforming to ASTM C 150 Type I, with a specific gravity of 3.15 was used in all the concrete mixtures. The cement was obtained from local cement suppliers and kept in a dry location. The cement sample is shown in Figure 2

Figure 2: Cement used

3.2.2 WATER

Potable tap water, without any salts or chemicals was used in all the concrete mixtures and in the curing of specimens.

3.2.3 AGGREGATES

Two main categories of aggregate were used, coarse and fine aggregates, according to ASTM C33 for aggregate classification.

3.2.3.1 COARSE AGGREGATE

Locally available crushed limestone coarse aggregate was used in this study. The maximum nominal size of the coarse aggregate was 3/8 in, followed by 3/ 16 in (#4) and 3/ 32 in (# 8) size, with specific gravity of 2.6 and SSD water absorption of 1.1%. Figure 3, shows samples of various types of natural coarse aggregates that were used for preparing the concrete mixes.

(a) (b) (c)

Figure 3: Coarse Aggregates, (a) Size No. 3/8 (b) Size No. 4 (c) Size No. 8

3.2.3.2 FINE AGGREGATE

Locally available dune sand with a fineness modulus of 1.01, specific gravity of 2.56 and SSD water absorption of 0.6% was used as fine aggregate. Figure 4, shows the fine aggregates used in the study. The grading for this sand is given in Table 2.

Figure 4: Fine aggregate

Table 2: Fine aggregate grading.

Sieve Opening, mm	Cumulative % Retained
4.75	0
2.4	0
1.2	0
0.6	3.8
0.3	38.6
0.15	78.1
0.075	99.0

3.2.4 SUPERPLASTICIZER

Plasticizers are usually used to increase the workability of the concrete. Glenium 51, a polycarboxylic ether (PCE) was used to obtain the desired workability. This superplasticizer does not contain chlorides and complies with AS 1478.1 2000 Type HWR and ASTM C 494 Types A and F. The specific gravity of Glenium 51 was 1.095 kg/L with 65% water content by weight.

3.2.5 RECYCLED PLASTIC AGGREGATES

In this study, the recycled waste plastic aggregates were collected from a local recycling industry. The processing of the waste plastic in the industry includes collection of the waste plastic, separation based on their nature and type then they are melted to form large solid blocks, which are again crushed into small pieces by using different cutting blades. These small shaped particles in the range of 5- 10 mm size are further processed to prepare the flat plastic sheets. The plastics used in this research include: the collection of crushed plastic particles of different shapes and types. They were classified as white granules, fiber, black flakes and white flakes. The recycled plastic waste has a specific gravity of 0.95 and SSD water absorption is 0%. Figure 5, shows the various types of recycle plastic aggregates used in the study.

(a) Granules shape Recycled plastic **(b) Fiber shape Recycled plastic**

(c) Black Flakes shape Recycled plastic **(d) White Flakes Shape Recycled plastic**

(e) Rough Flakes Shape Recycled plastic

Figure 5:Different types of Recycled plastic aggregates

3.3 MIX PREPARATION

The mix proportions were prepared according to ACI 211.1. As a part of trial, several different mixes were prepared with variables such as cement content, water/ cement ratio, CA/ TA ratio, FA/ TA ratio, plastic proportions and admixture, as shown below:

Cement content(kg/m^3): 350, 370, 400

Water/ cement ratio: 0.45, 0.4

CA/ TA: 0.6, 0.5, 0.55, 0.4

Recycled plastic type: Granules, Fibers, Flakes

Recycled plastic content: 25%, 50%, 75%, 100%.

Admixture: 0.8%, 1.0%, 1.6%, 2.0%

A total of 50 different mixes were prepared to study the behavior of recycled plastic waste. The trial mixes were prepared to determine the optimum plastic content, coarse aggregate to fine aggregate ratio, optimum admixture content to obtain a workable mix with desirable strength and other parameters of the lightweight concrete. After conducting several trials some specific mixes were selected based on the workability, filling ability, unit weight and compressive strength. Finally, 18 mixes were selected for the detailed study which included replacing three types of recycled plastic waste at different plastic content based upon their workability criteria and six reinforced concrete beams were prepared to study the shear and flexure behavior considering only one type of recycled plastic, i.e. flakes with one mix design and at three different replacement levels.

A single mix consisted of three samples for compressive strength test, three samples for unit weight, three samples for modulus of elasticity test, three samples for bond strength test, three samples for water absorption test, three samples for chloride permeability test, three samples for flexural strength test, three samples for reinforcement corrosion monitoring, six samples for wet/dry exposure test(three for 3 months and three for 6 months), three sample for thermal conductivity and three samples for drying shrinkage test.

A conventional blade-type concrete mixture was used for the preparation of the mix, according to ASTM C 192.

The mixing procedure adopted is as follows:

- All the raw materials were weighted according to the mix design, the total water was divided into two parts, one part was mixed with the admixture and the other half was kept unaltered.
- First coarse aggregate was added to the mixture, then recycled plastic aggregate and fine aggregates were added and the mixture was allowed to mix uniformly.
- Then cement was added and the mixer was allowed to rotate for two minutes and then water was added, then the mixture was rotated for a while and then the remaining water with admixture was added and concrete was mixed for 5 minutes.

3.4 MIX PROPORTIONS

A total of 18 concrete mixes (M1, M2, M3, M4, M5, M6…..M18) containing four percentages of the recycled plastic aggregates with two different concrete mix designs were prepared in this study. The details of the concrete mixes are shown in the Table 3.

Table 3: weights of ingredients in the mixture investigated.

Mix	Cement (kg/m^3)	W/C	C.A/T. A	Super P.	Recycled plastic type	Plastic %
M1	350	0.45	0.4	1.6	Granules	25
M2	370	0.4	0.4	1.6	Granules	25

M3	350	0.45	0.4	1.6	Granules	50
M4	370	0.4	0.4	1.6	Granules	50
M5	350	0.45	0.4	1.6	Granules	75
M6	370	0.4	0.4	1.6	Granules	75
M7	350	0.45	0.4	1.6	Granules	100
M8	370	0.4	0.4	1.6	Granules	100
M9	350	0.45	0.4	1.6	Fibers	25
M10	370	0.4	0.4	1.6	Fibers	25
M11	350	0.45	0.4	1.6	Fibers	50
M12	370	0.4	0.4	1.6	Fibers	50
M13	350	0.45	0.4	1.6	Flakes	25
M14	370	0.4	0.4	1.6	Flakes	25
M15	350	0.45	0.4	1.6	Flakes	50
M16	370	0.4	0.4	1.6	Flakes	50
M17	350	0.45	0.4	1.6	Flakes	75
M18	370	0.4	0.4	1.6	Flakes	75

The composition of the various constituents in the concrete are summarized in Table 4:

Table 4: Composition of different ingredients in the concrete.

Mix	Cement (kg)	Water (liters)	Coarse agg. (kg)	Recycled plastic agg. (kg)	Fine aggregates (kg)	Admixture (ml)
M1	14.98	7.21	20.64	6.88	41.27	200
M2	15.83	6.81	20.72	6.91	41.45	211
M3	12.62	5.97	10.11	10.11	30.32	168.3
M4	15.83	6.68	12.05	12.05	36.14	211
M5	14.98	6.99	5.32	15.95	31.90	200
M6	14.04	5.84	4.73	14.20	28.40	187
M7	14.06	6.49	0	17.93	26.89	187
M8	14.86	6.11	0	18.0	27.0	198
M9	14.06	6.77	19.37	6.46	38.73	187
M10	14.86	6.39	19.45	6.48	38.90	198
M11	14.06	6.65	11.26	11.26	33.77	187
M12	14.86	6.27	11.31	11.31	33.92	198
M13	14.06	6.77	19.37	6.46	38.73	187
M14	14.86	6.39	19.45	6.48	38.90	198
M15	14.06	6.65	11.26	11.26	33.77	187
M16	14.86	6.27	11.31	11.31	33.92	198
M17	14.06	6.56	4.99	14.97	29.94	187
M18	14.86	6.18	5.01	15.03	30.07	198

3.5 EXPERIMENTAL PROGRAM

This study included the development of light weight and thermal resistant concrete with the use of recycled plastic as a partial/full substitution of coarse aggregate. The influence of recycled plastic on concrete properties was studied by preparing several concrete mixes involving different amount and shape of recycled PET plastic. In this work, three different sizes of recycled plastic were used in concrete mixes. These three sizes included granules, fibers and flakes.

For the testing program, a series of standard tests were conducted with variable amounts of recycled plastic aggregate as follow:

- To evaluate the effect of recycled plastic aggregate on compressive strength of concrete, a total of 54 (100x100x100 mm) concrete cubes were prepared.
- To see the effect of recycled plastic aggregate on flexural strength of concrete, a total of 54 (50 x 50 x 250mm) concrete prisms were prepared.
- A total of 54 (75 x 150 mm) cylinders were prepared to evaluate the modulus of elasticity of the concrete developed with the use of recycled plastic aggregate.
- To determine the bond strength of the concrete, a total of 54 (150 x 150x 150 mm) concrete cubes were prepared.
- To determine the chloride permeability of the concrete, a total of 18 (100 x 200 mm) concrete cylinders were prepared.
- To evaluate the reinforcement corrosion, a total of 54 (75 x 150 mm) concrete cylinders were prepared.

- To measure drying shrinkage, a total of 54 (50 x 50 x 250 mm) concrete prisms were prepared.
- To evaluate the unit weight, total of 54 (75 x 150 mm) concrete cylinders were prepared.
- To determine the water absorption of the concrete, total of 54 (75 x 150 mm) concrete cylinders were prepared.
- To measure the thermal conductivity, a total of 54 (50 x 20 mm) concrete cylindrical disks were prepared.
- To study the wet/dry exposure cycles, a total of 108 (50 x 50 x 50 mm) concrete cubes were prepared.
- To study the heat/cool exposure cycles, a total of 108 (50 x 50 x 50 mm) concrete cubes were prepared.

3.6 EQUIPMENT AND TESTING PROCEDURE

The laboratory testing included the mechanical and durability properties of the developed concrete. The tests for mechanical properties included compressive strength, flexural strength, modulus of elasticity, bond strength, unit weight and thermal conductivity. The durability properties included: water absorption, rapid chloride permeability, reinforcement corrosion, wet / dry exposure, heat / cool exposure and drying shrinkage.

3.6.1 MECHANICAL PROPERTIES

3.6.1.1 DENSITY (UNIT WEIGHT)

Concrete specimens 75 mm diameter and 150mm high were prepared for the determination of unit weight. A total of 54 concrete specimens were prepared with different plastic proportions and various types of recycled plastic. Each mix consists of three samples and the average of the three were considered as the unit weight of the mix.

3.6.1.2 COMPRESSIVE STRENGTH

Fifty-four cubic specimens (100 mm x 100 mm x 100 mm) were prepared for conducting the compressive strength, three for each plastic type (granules, fibers, flakes) with various proportions of recycled plastic (25%, 50%, 75% and 100%) and two different cement content (350 and 370 kg/m^3) and w/c ratio (0.45 and 0.4). The compressive strength was determined according to ASTM C109. The compressive strength of each mix was taken as the average strength of three cubes. A digital compression testing machine (MATEST) was used to test the specimens after 28 days of water curing. Figure 6, shows the 3000 KN capacity compression testing machine (MATEST) utilized to test the recycled plastic concrete specimens in compression.

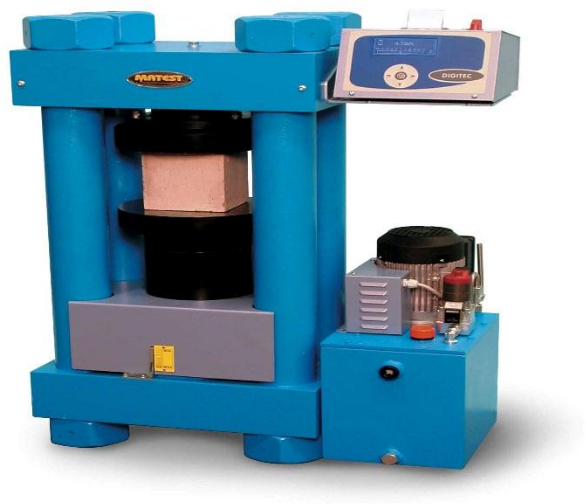


Figure 6: Compression testing machine for concrete samples

After 24 hours, cube specimens were retrieved from forms and stored in water (curing phase) up to the time of test. Before testing, they were air dried for one day. The compressive strength of the specimen, σ comp (in MPa), was calculated by dividing the maximum load carried by the cube specimen during the test by the cross-sectional area of the specimen.

3.6.1.3 MODULUS OF ELASTICITY

As specified in ASTM C 469 standard test method for static modulus of elasticity and poisson's ratio of concrete in compression, the elastic portion of the compressive stress strain curve up to 40 percent of the ultimate compressive strength ($0.4\ f_c^1$) was used to determine the modulus of elasticity. Three 75 mm x 150 mm concrete cylinders were utilized for each mix to determine the modulus of elasticity. The test setup includes a specially designed axial deformation gauge shown in Figure 7. The two parallel rings are both rigidly attached to the cylinder with a 3-in. gauge length between the attachment points.

Figure 7: Modulus of Elasticity test setup

The lower ring holds two LVDTs whose ends bear on the upper ring. Thus, the axial deformation of the cylinder can be accurately measured from initiation of loading through failure. The load and the output from the three LVDTs were digitally recorded throughout the test using a data logger. The setup is shown in the Figure 7. The testing of each cylinder was completed in a single constant load application from start to failure. In this test program, proper seating of the cylinder could be assured by monitoring the load deformation response during the test. The modulus of elasticity was calculated based on the average LVDT- based deformation measurements and the load reading. Figure 7, shows the cylindrical concrete specimens after their testing

3.6.1.4 FLEXURAL STRENGTH

The standard four-point flexural test to determine the modulus of rupture (MOR) according to ASTM C 78 is the most common method for obtaining flexural tensile strength. The flexural strength of concrete specimens was determined by the use of simple beam (50 x 50 x 250) mm. The test setup is shown in Figure 8.

The test method for conducting the test usually involves a specified test fixture on a universal testing machine. The specimen is placed on two supporting pins a set distance apart and two loading pins placed at an equal distance around the center. These two loadings are lowered from above at a constant rate until sample failure.

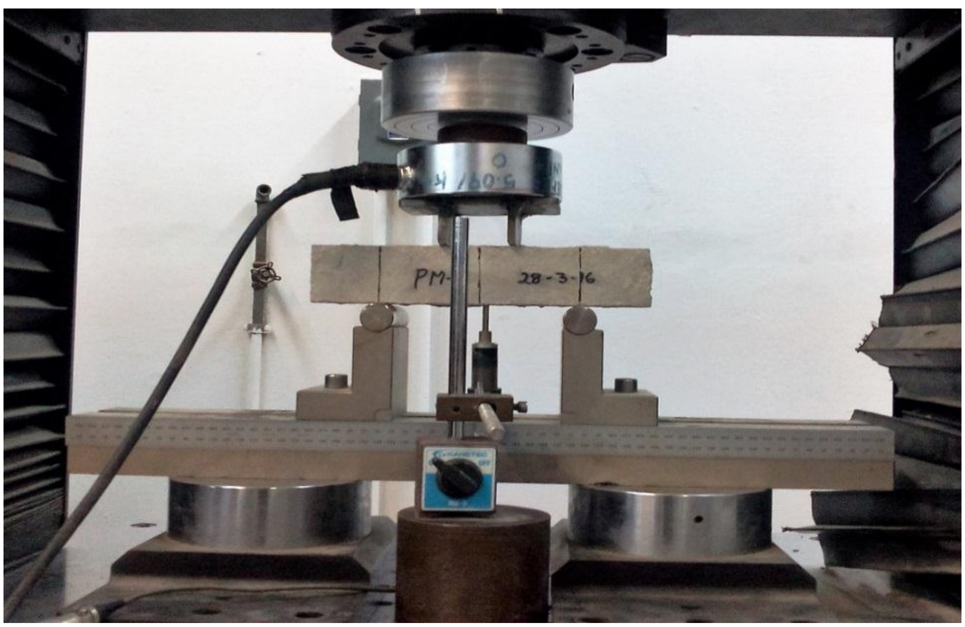


Figure 8: Flexural strength test setup

Figure 9: Data logger for recording the reading of the test

The flexural strength of the beam was calculated by using the following equation:

$$\text{Flexural Strength (MPa)} = \frac{FL}{bd^2}$$

Where:

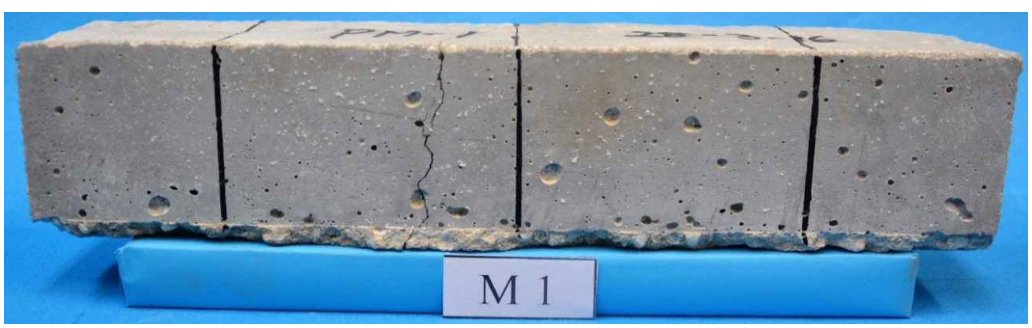
F: Maximum applied load (N);

L: Support span (mm);

b: Width of the tested beam (mm);

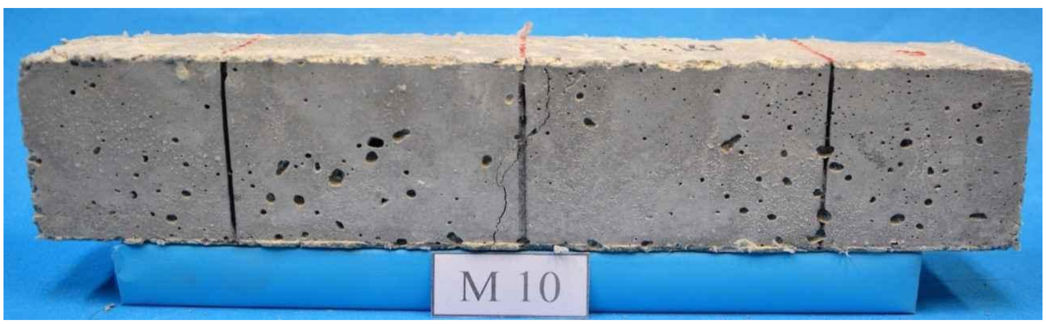
d: Depth of the tested beam (mm).

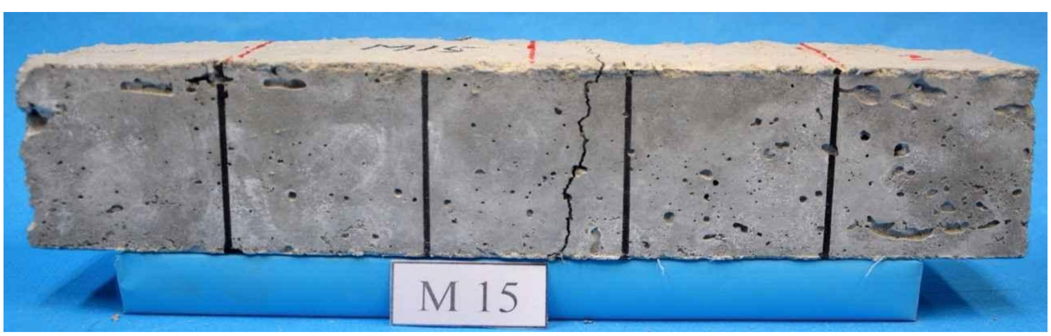
Typical failure images of the tested concrete prisms:




M 2


M3
M 3


M 10


M 15

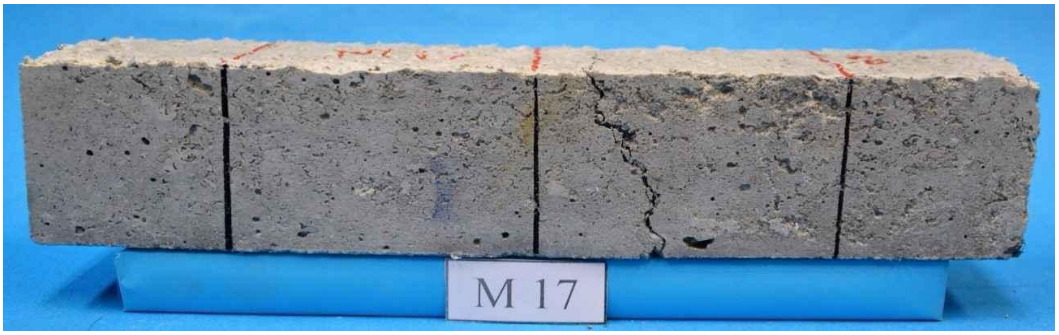


Figure 10: Typical images of the specimens tested in flexure

3.6.1.5 BOND STRENGTH

The bond strength is a measure of the effectiveness of the grip between concrete and steel and has no standard quantitative definition. In pull out tests on plain bars, the maximum load generally represents the bond strength that can be developed between concrete and steel. With plain bars the maximum load is not very different from the load at the first visible slip, but in the case of deformed bar, the maximum load may correspond to a large slip which may not be obtained in practice before other types of failure occur. It is preferable, therefore that when comparing plain and deformed bars to determine not only the maximum load but also the load at the arbitrary amount of slip and also plot the complete load slip curves for the plain and deformed bars under comparison. One such basis of comparison is the load at a relative movement (slip) between steel and concrete of 0.125 mm at the free end of the bar in a pull-out test. Figure 11, shows the specimens prepared for the bond strength, Figure 12, shows the experimental setup to determine the bond strength and Figure 13, shows the specimen preparation for the bond strength test.

Figure 11:Bond Strength specimens

The pull-out test was performed using a 100 KN universal testing machine. The test specimens were cured for 28 days. Reinforced concrete cubes of 150 mm x 150 mm x 150 mm were used for this test. Three LVDTs were attached one at the bottom of the cube fixed to the bottom of the steel bar and the other two were fixed on the surface of the concrete. A constant load was applied at an interval of 0.5 KN. The load and the output from the three LVDTs were recorded throughout the test using a data logger.

Figure 12: Bond test setup

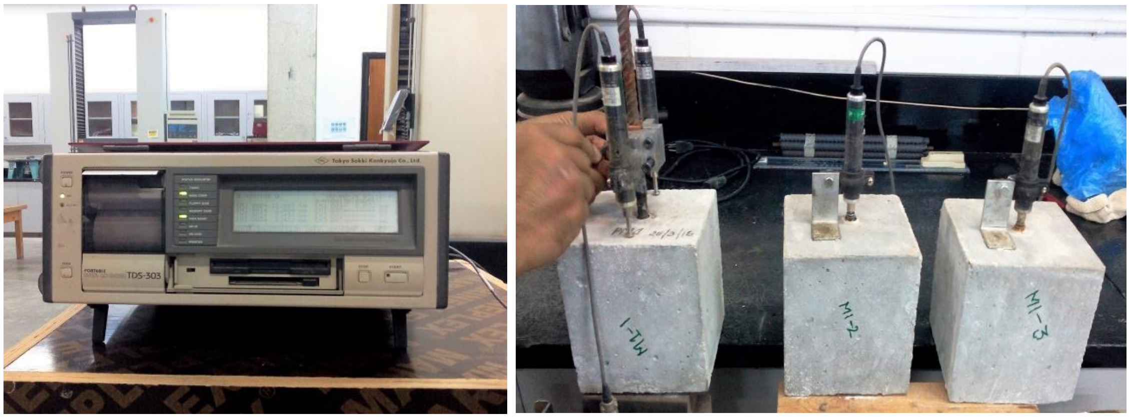


Figure 13: Specimen preparation for the bond strength.

3.6.1.6 THERMAL CONDUCTIVITY

Sixty cylindrical specimens measuring 50mm in diameter and 20mm high were prepared to conduct the thermal conductivity test. FOX 50 Heat Flow Meter instrument was used for measuring the thermal conductivity according to ASTM C518 and ISO 8301. The FOX 50 provides rapid results in a compact footprint. This equipment (Figure 14) is an ideal choice for measurements of medium-conductivity materials such as plastics, ceramics, glasses, composites, concrete and more.

Three samples from each mix were tested. Measurements were taken on the both faces of a specimen and average of the two readings was considered as the reading for one sample and average of three samples was considered as the reading per mix. Figure 15 shows a batch of specimens used to determine the thermal conductivity.

The instrument nearly takes an hour to maintain a stable temperature among the plates and directly gives the value of K (Lambda), the thermal conductivity.

Figure 14: Thermal conductivity testing machine

Figure 15: Concrete samples used to determine the thermal conductivity.

3.6.1.7 SHEAR AND FLEXURAL BEHAVIOR OF RCC BEAMS

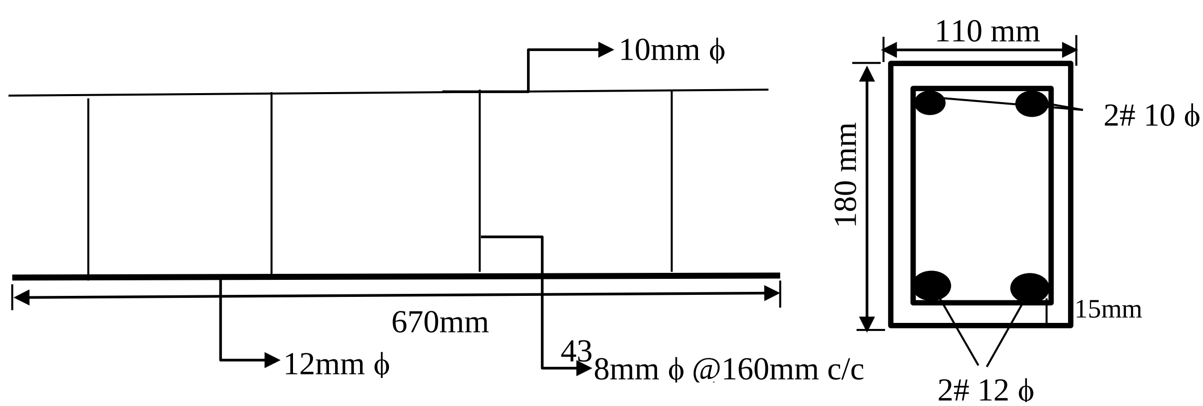
A total of six reinforced concrete beams were prepared with the recycled plastic aggregates, three designed to fail in shear and the other three designed for flexural failure. The specimens were prepared with 0%, 25% and 50% recycled plastic. A cement content of 370 kg/m^3 and water/cement ratio of 0.4 was considered for these specimens. The size of beam designed for shear failure was 110x180mm and the size for the flexural failure was 110x 130mm. Both the beams were of same length, i.e. 700 mm. The type of recycled plastic aggregate used was flakes and the beams were cured for a period of 14 days. Figure 16 shows the RCC beams prepared and Figure 17 shows the test setup.

Figure 16: RCC beams with recycled plastic aggregate

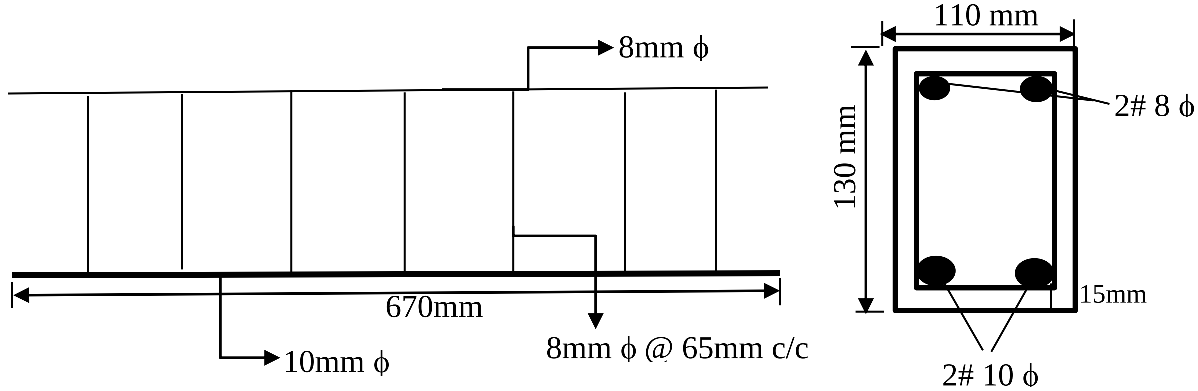
Figure 17: Setup for testing the RCC beams under shear and flexural

Reinforcement details:

Beam designed to fail in shear:



Beam designed to fail in flexure:



3.6.2 DURABILITY

3.6.2.1 WATER ABSORPTION

Water absorption test was conducted on concrete cylinders of 75mm x 150mm and the standard followed for conducting this test was ASTM C 642. A total of 54, concrete specimens with different plastic content and two different mix designs were prepared. The concrete specimens were first heated at 110°C to oven dry the samples for 24 hours and then the dry weight was determined, then they were immersed in water for a period of 48 hours, after removing the samples from water they were surface dried and the saturated weight was determined. Then using the formula, the water absorption of the concrete specimens was determined. Average of the three samples per mix was considered as the water absorption of the respective mix.

3.6.2.2 RAPID CHLORIDE PERMEABILITY

Corrosion of reinforcing steel due to chloride ingress is one of the most common environmental attacks that lead to the deterioration of concrete structures. Penetration of chlorides into the crack-free concrete occurs mainly due to capillary absorption, hydrostatic pressure, diffusion, and evaporative transport, while diffusion is more predominant. Chloride diffusion takes place when the concentration of chloride, on outside of the concrete member is greater than inside, resulting in the movement of chloride ions through the concrete to the level of the rebar. If there is an availability of moisture and presence of oxygen, then reinforcement corrosion takes place.

The internal pore structure plays a vital role in the chloride ion ingress into the concrete. The factors which influence the pore structure are the mix design, degree of hydration, curing conditions, use of supplementary cementitious materials, and construction practices. Therefore, wherever there is a potential risk of chloride induced corrosion, then concrete should be evaluated for chloride permeability.

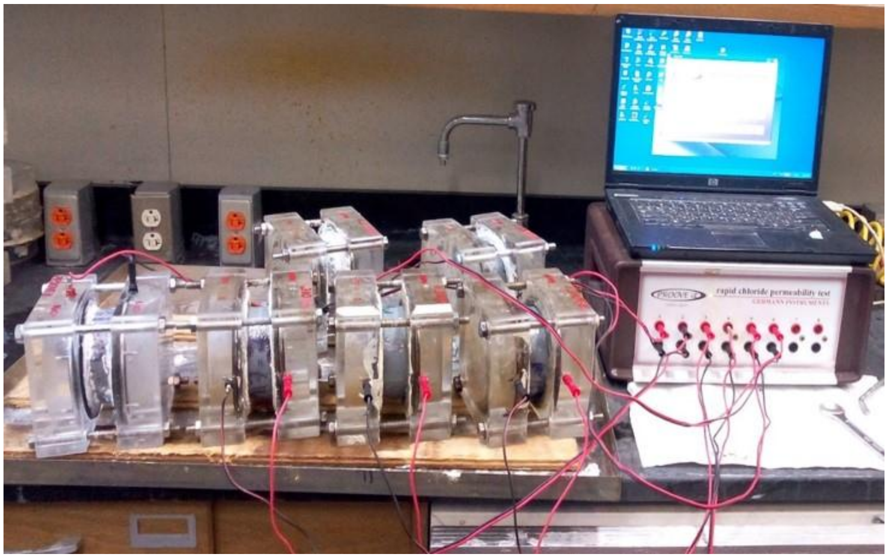


Figure 18: Setup to determine the Rapid chloride permeability

Figure 19: Specimens for rapid chloride permeability test

A total of 18 concrete cylinders of 100mm diameter and 200 mm length were prepared to determine the chloride permeability. The standard testing procedures are in AASHTO T 277 or ASTM C 1202. Figure 18 shows the setup to determine the rapid chloride permeability and Figure 19 shows the typical specimens of concrete. The test was conducted on 50mm thick and 100mm diameter concrete specimen by monitoring the amount of electrical current that passes through the specimen in 6 hours. The specimens are usually prepared by cutting a slice from the concrete cylinders. The setup consists of two lead wires, one is immersed in a 3 % NaCl solution and the other in a 0.3 M sodium hydroxide (NaOH) solution while maintaining a voltage of 60V DC across the ends of the sample throughout the test. Based on the charge that passes through the sample, a qualitative rating is made of the concrete's permeability, as shown in Table 4.

Table 5: Rating of chloride permeability of concrete according to the RCPT

Chloride permeability	Charge passing, coulombs
High	> 4000

Moderate	2000 to 4000
Low	1000 to 2000
Very low	100 to 1000
Negligible	< 100

3.6.2.3 FREE CORROSION POTENTIALS

To monitor the corrosion status of the concrete specimens containing recycled plastic aggregate, cylindrical specimens of size 75mm x 150 mm with a reinforced bar at the center were prepared. Fifty-four samples were prepared, three for each mix, hence average of the three samples per mix represents the reading of each mix. The samples were partially dipped in a 5% NaCl solution. The potentials were measured with a multimeter at regular intervals. The multimeter has two lead wires connected to it, the (-) lead (black) connected to the 'COM' port and the (+) lead (red) to the 'VΩmA' port of the multimeter. The other end of the black wire was connected to the reference electrode that was dipped into the solution whereas the other end of red wire was connected to the steel bar. Then the multimeter is switched on. The reading on the meter is the electrical potential difference between the electrically positive lead (red wire) and the electrically negative lead (black wire). Figure 20 shows a set of specimens used to measure corrosion potentials.

Figure 20: Samples for measuring corrosion potentials

3.6.2.4 DRYING SHRINKAGE

Shrinkage is the reduction in the volume of concrete caused mainly by the loss of water due to evaporation from a freshly hardened concrete exposed to air. Shrinkage may result in cracking of restrained concrete members. A total of 54 prisms of recycled plastic concrete specimens of 25 x 25 x 250 mm were prepared for determining the drying shrinkage according to ASTM C 356. Three specimens per mix were tested and their average values are reported. The setup consisting of a stand fitted with a LVDT connected to a data logger is shown in Figure 21 and 22.

Figure 21: Drying shrinkage samples

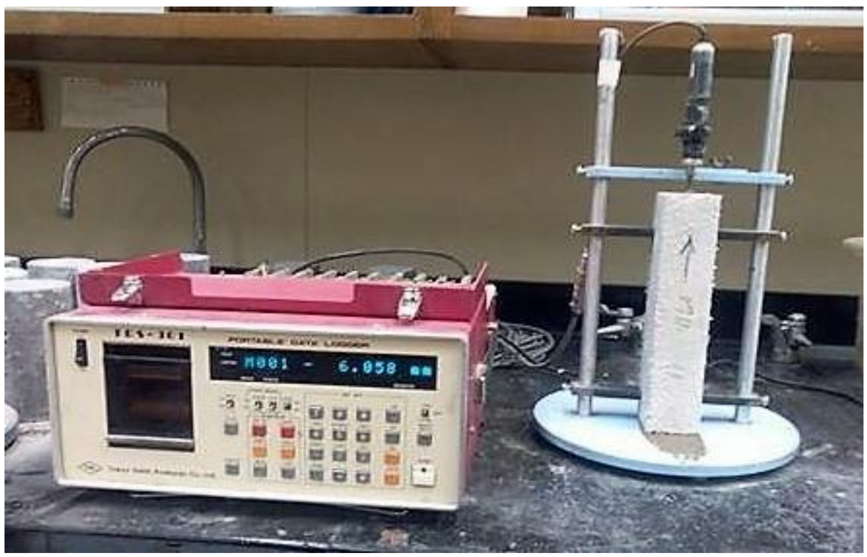


Figure 22: Setup for measurement of drying shrinkage.

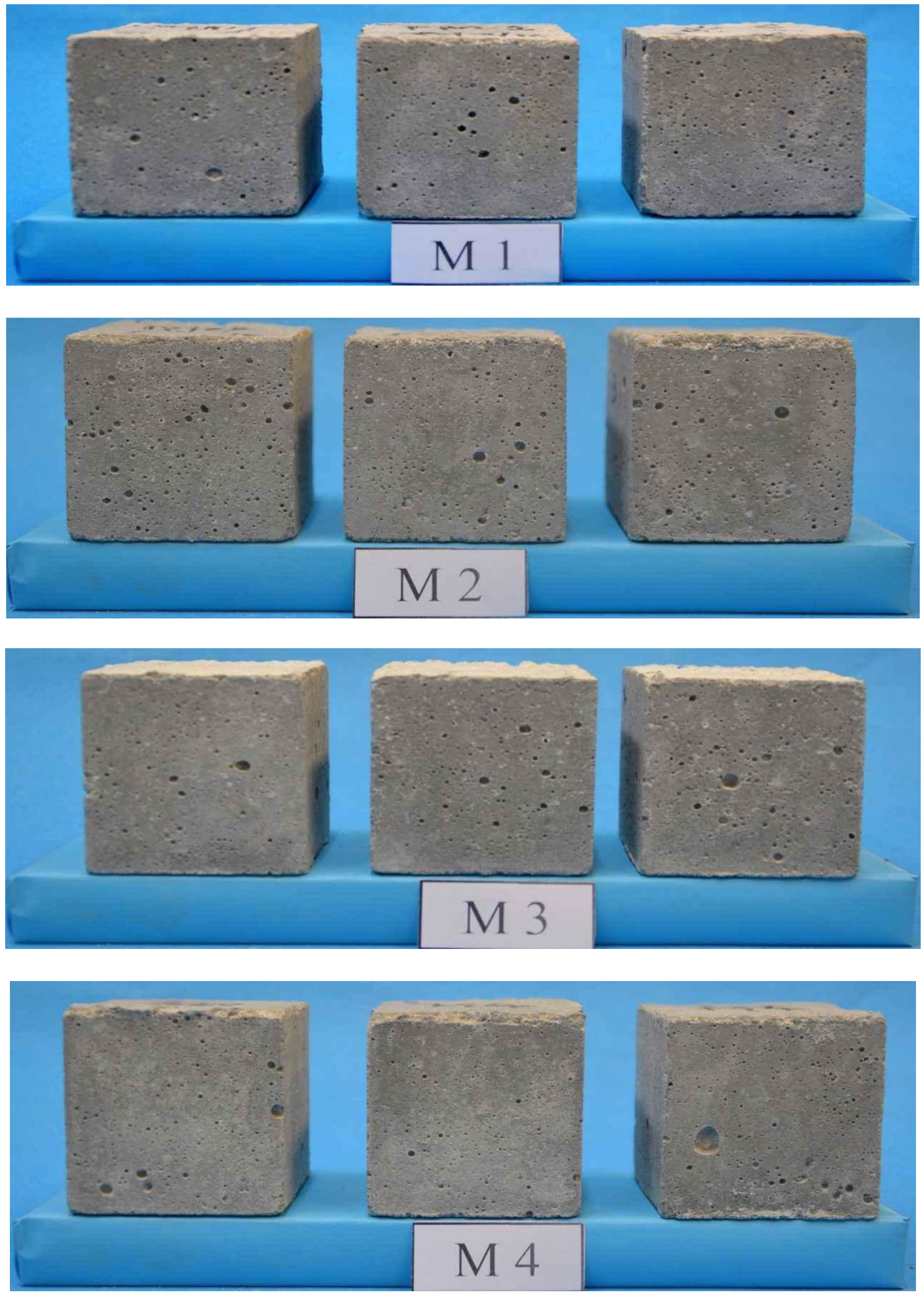
3.6.2.5 HEAT / COOL EXPOSURE CYCLES

The heat/cool exposure cycles test was conducted on concrete cubes of 50 mm size. Each mix has six representative samples and hence totally 108 samples were prepared to conduct the test. Two duration periods were considered to monitor the effect of the exposure cycles. Three samples for three months' exposure and remaining three samples for six months' exposure were assigned. The samples were heated at a temperature of 70^{o}C for about 24 hours in an oven then the oven was switched off for 24 hours for the samples to cool down. After three months' exposure, the samples were removed and difference in weight was calculated (initial weight before exposure – final weight after exposure), this is noted as weight loss. Similarly, the reduction in strength was also calculated by conducting compressive strength test before and after the exposure cycles. The difference gives the reduction in strength. Figure 23 and 24 shows the specimens and the oven used for the heat/cool evaluation.

Figure 23: Concrete samples for Heat/Cool exposure cycles

Figure 24: Oven used for heating and cooling the specimens

The concrete specimens after wet/dry exposure are shown in Figure 25.

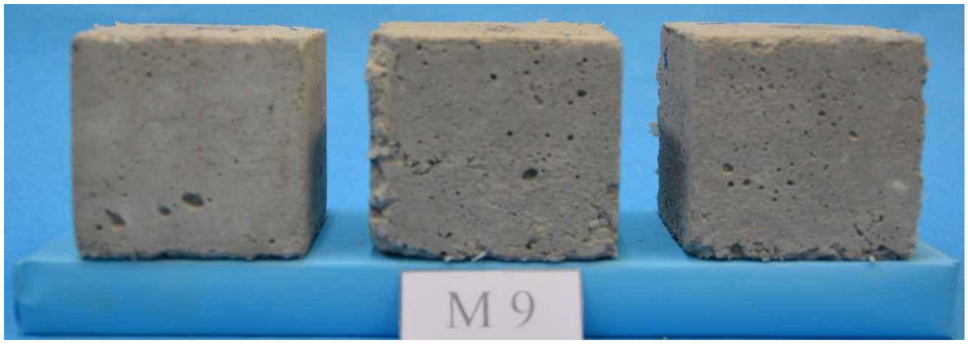


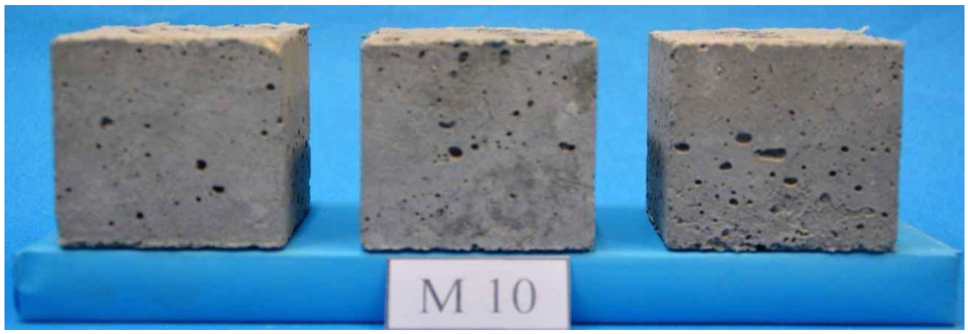

M 5

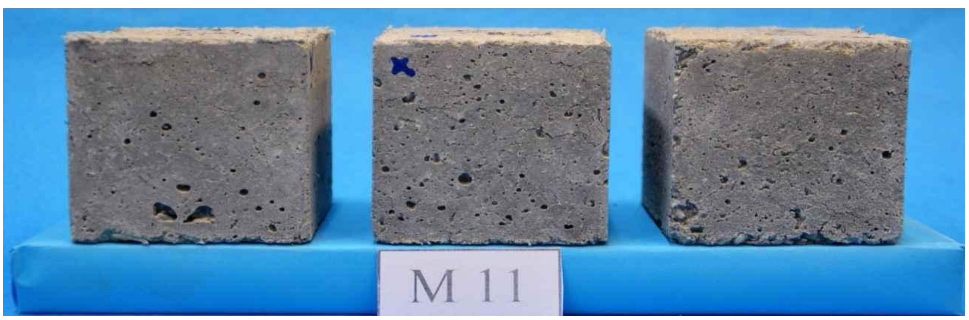

M 6


M7
M 7


M 8


M 9


M 10


M 11


M 12


M 13


M 14


M 15


M 16

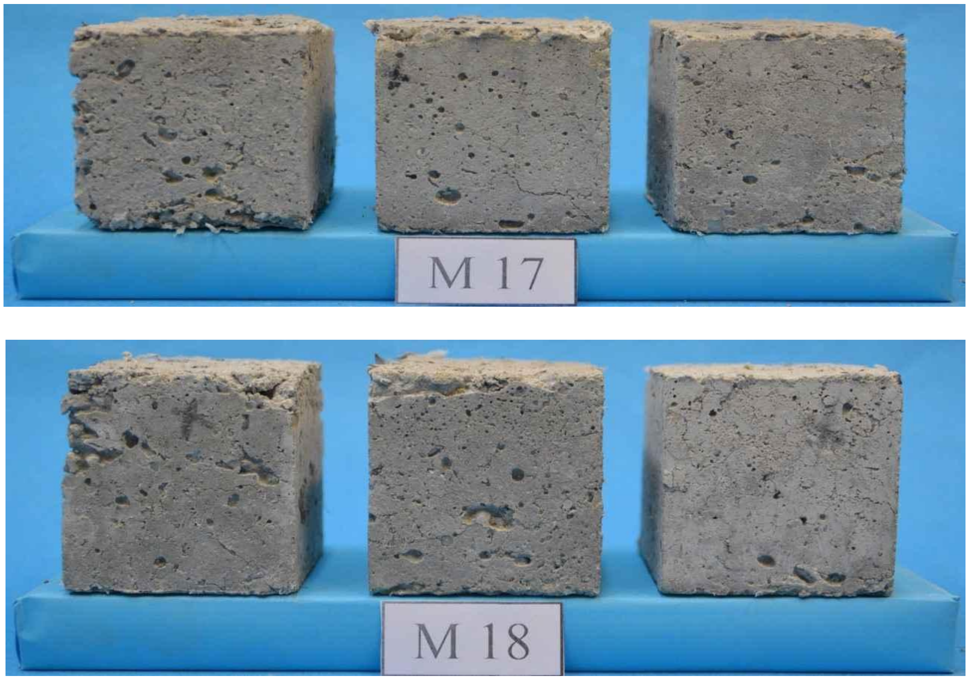


Figure 25: Heat/ Cool exposure samples after 3 months' exposure

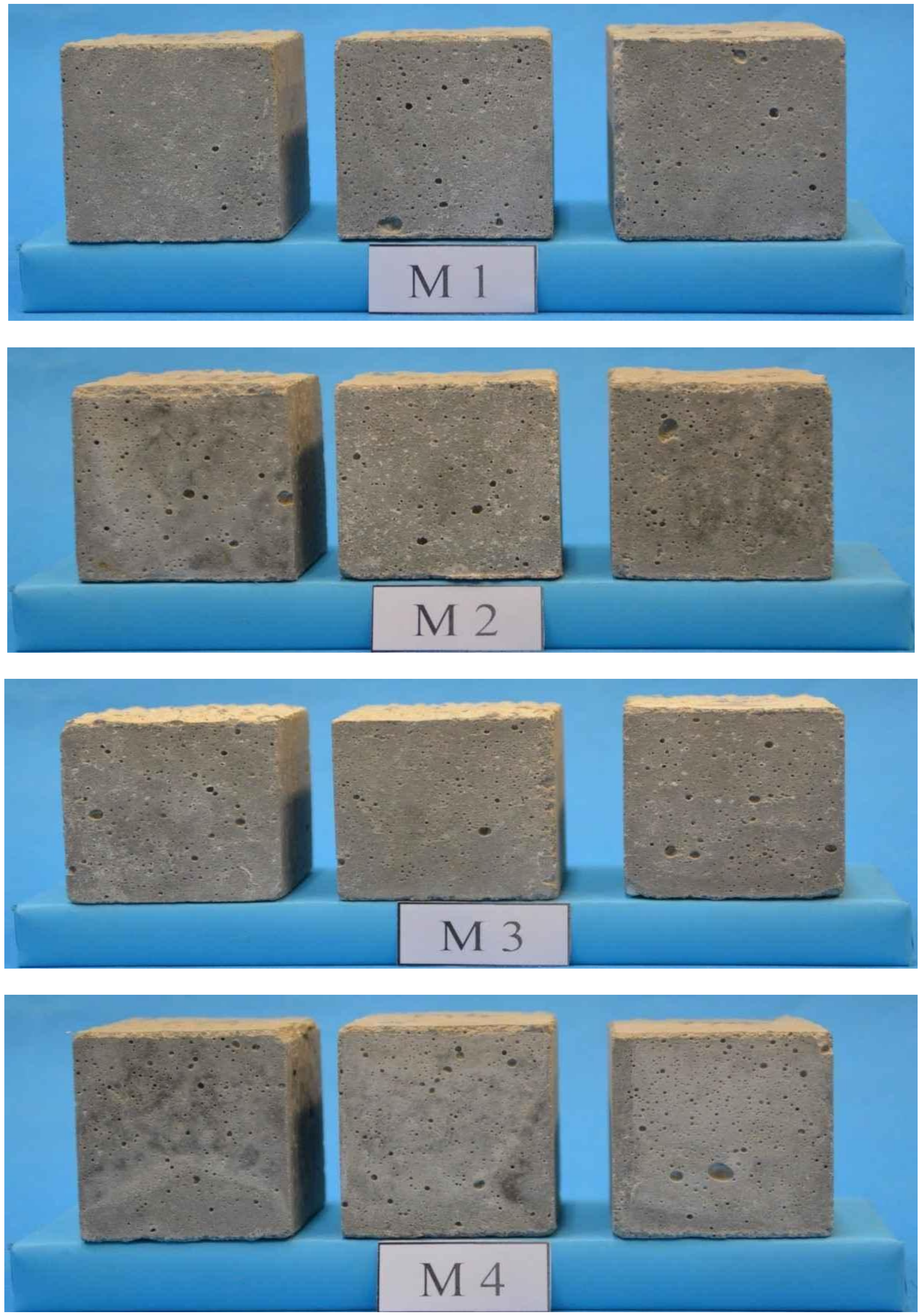
3.6.2.6 WET / DRY EXPOSURE CYCLES

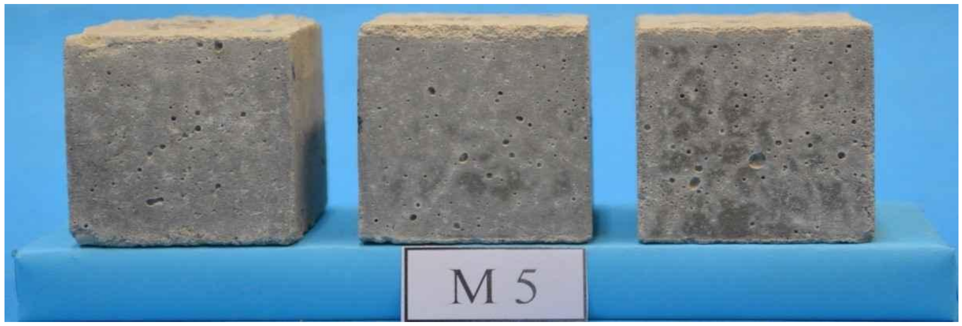
The wet/dry exposure cycles were conducted on concrete cubes of 50 mm size. Each mix has six representative samples and hence totally 108 samples were prepared to conduct the test. Two duration periods were considered to monitor the effect of the exposure cycles. Three samples for three months exposure and remaining three samples for six months' exposure were assigned. A special set-up was built for exposing the samples to wetting and drying. Two big rectangular tanks were filled with water and another two perforated tanks were used to keep the samples. The samples were kept under wet condition for about 24 hours and then drying for another 24 hours. During wetting the samples were immersed along with the perforated tanks in to the water tank and during drying the perforated containers were removed out of the water and kept outside for air drying. After three months' exposure, the samples were removed and difference in weight was calculated (initial weight before exposure – final weight after exposure), this was noted as weight loss. Similarly, the reduction in strength was also calculated by conducting compressive strength test before and after the exposure cycles. The difference gives the reduction in strength. Figure 26 and 27 shows the wetting and drying setup adopted during the wet/dry evaluation.

Figure 26: Concrete samples under Wet condition.

Figure 27: Concrete samples under Dry condition.

Concrete samples after wet/dry exposure are shown in Figure 28.




M 5


M 6


M 7


M 8

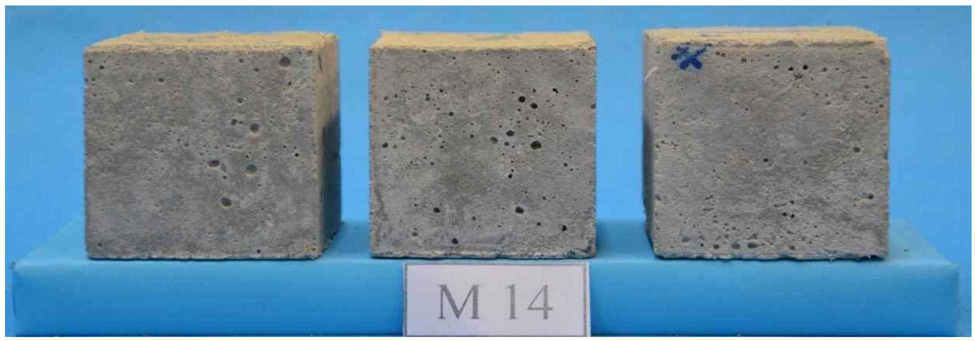

M 9

M 10

M 11

M 12


M 13


M 14


M 15


M 16

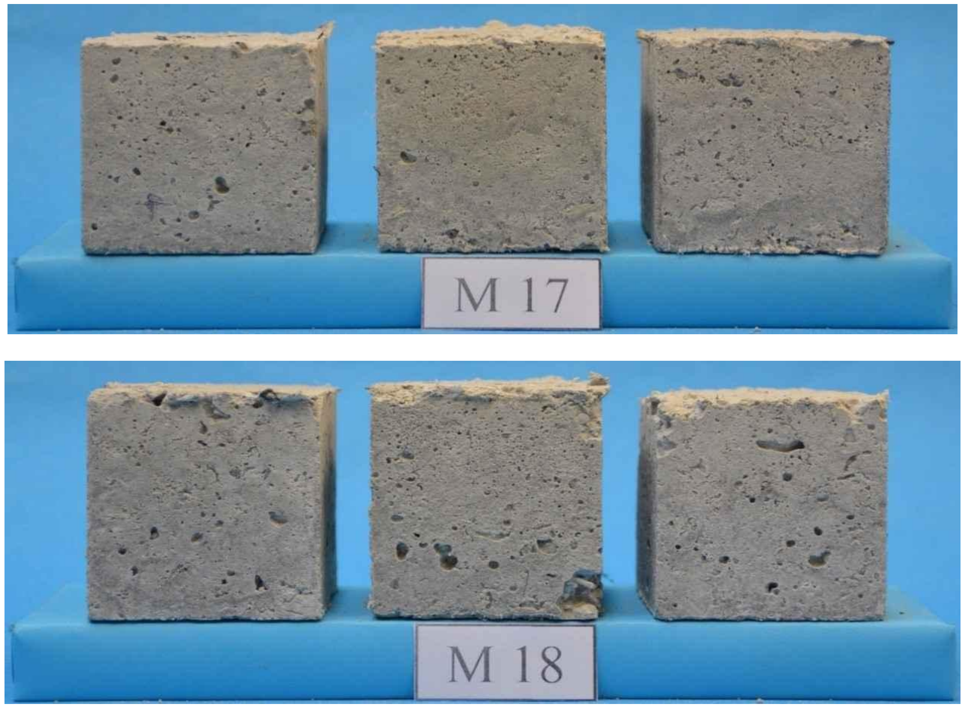


Figure 28: Wet/ Dry samples after 3 months.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

In this chapter, the results of the experimental program designed to study the mechanical and durability properties of the various recycled plastic aggregates concrete mixes is described. Density, compressive strength, flexural strength, modulus of elasticity, bond strength, water absorption, rapid chloride permeability, reinforcement corrosion, drying shrinkage, heat/cool exposure, wet/ dry exposure, thermal conductivity, shear and flexural behavior of concrete specimens was discussed to investigate the influence of recycled plastic aggregate on concrete properties.

The test results of this study, focus on the behavior of recycled plastic aggregate in concrete mixes. A total of 18 concrete mixes were prepared with 25%, 50%, 75% and 100% replacement of the recycled plastic aggregate with two different mix designs.

4.2 TRIAL MIXTURES

Several trial mixtures were prepared to optimize various constituents of the recycled plastic concrete. Firstly, the grading of coarse aggregate to fine aggregate ratio was optimized to obtain the maximum particle packing. To satisfy the flow criteria the dosage of plasticizer was optimized to meet the required flow. The optimization of other constituents, like water binder ratio, cement and plastic aggregate content was determined from the trial mixtures.

The different mix proportions include:

Cement content: $350\ kg/m^3$, $370\ kg/m^3$.

W/C ratio: 0.4, 0.45

CA/TA: 0.4, 0.5, 0.55, 0.6

FA/TA: 0.4, 0.5, 0.55, 0.6

Admixture: Glenium 51

Recycled Plastic type: Granules, Fibers, Black Flakes, White Flakes

Percentage replacement: 25%, 50%, 75%, 100%.

The mix nomenclature is shown in Table 5.

Table 6 : Mix proportions nomenclature

Mix Name	% of Plastic	CC (kg/m^3) - W/C	Plastic type
M 1	25 %	NT -1 (350 – 0.4)	K1- Granules
M 2	50 %	NT -2 (350 – 0.45)	K2- Fibers
M 3	75 %	NT -3 (370 – 0.4)	K3- Black Flakes
M 4	100 %	NT -4 (370 – 0.45)	K4- White Flakes

Summary of Trial mixes:

Based on the workability, filling ability, unit weight and compressive strength criteria the following mix designs were selected for the detail study.

Cement Content: 350 kg/m^3, 370 kg/m^3

water/cement: 0.4, 0.45

C.A / T.A: 0.4

Granules type: 25%, 50%, 75%, 100%

Fiber type: 25%, 50%

Flaky type: 25%, 50%, 75%, 100%

Plastic replacement

Typical Images of the broken samples for observing the plastic mixture are shown in Figure 29 through 33.

1) Conventional concrete:

Figure 29: Conventional concrete

2) Concrete with 25% plastic content:

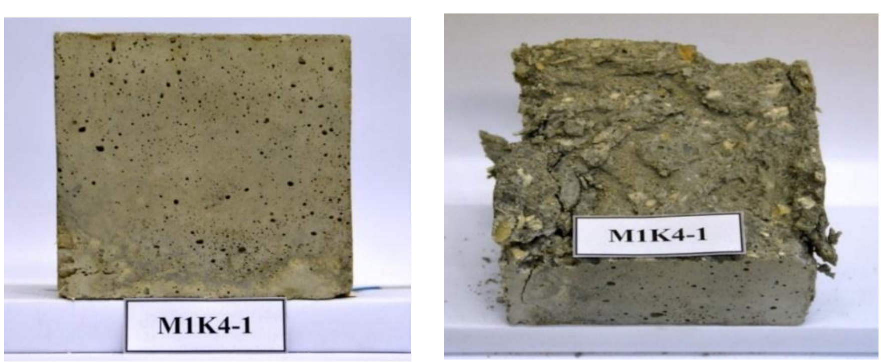


Figure 30:Concrete with 25% plastic content

3) Concrete with 50% plastic content:

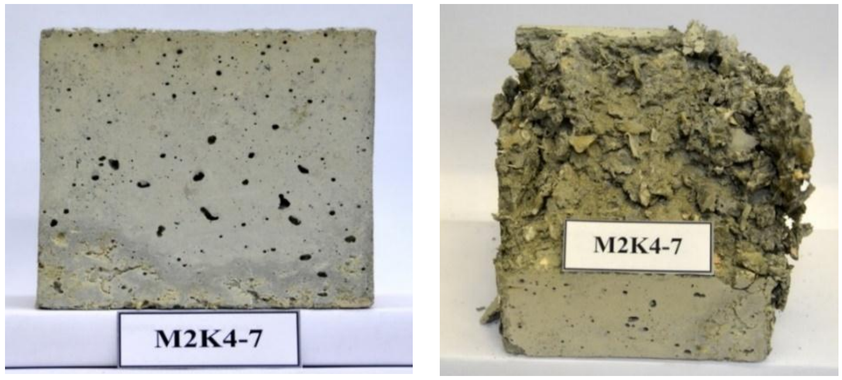


Figure 31: Concrete with 50% plastic content

4) Concrete with 75% plastic content:

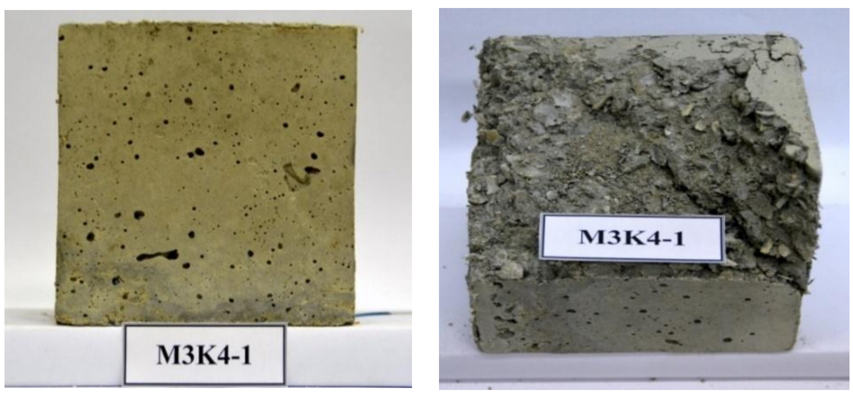


Figure 32:Concrete with 75% plastic content.

5) Concrete with 100% plastic content:

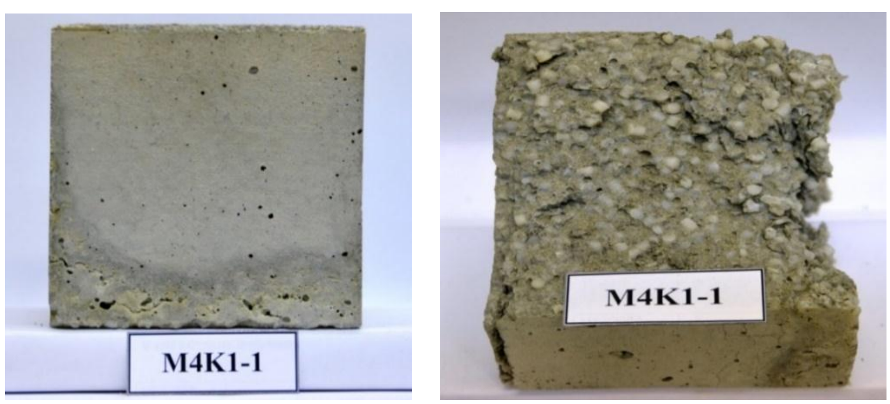


Figure 33: Concrete with 100% plastic content.

4.3 MECHANICAL PROPERTIES

4.3.1 DENSITY (UNIT WEIGHT)

Table 6, shows the unit weight of the concrete specimens containing various percentages of recycled plastic aggregate as a partial/ full substitution of the coarse aggregates with two mix designs. These data are depicted in Figures 34 and 35.

Table 7: Unit weight of concrete samples

Mix #	Sample #	Diameter, mm	Height, mm	Weight, gm	Volume, mm^3	Density, kg/m^3	Average Density, kg/m^3
M1	1	76.60	152.06	1430.80	700748.87	2042	2045
	2	76.05	152.11	1415.20	690949.15	2048	
	3	76.30	153.50	1442.20	701854.90	2055	
M2	1	76.90	152.22	1443.40	706991.64	2042	2049
	2	76.78	151.50	1441.80	701453.25	2055	
	3	78.04	151.30	1469.70	723707.93	2031	
M3	1	77.60	153.80	1276.50	727393.91	1755	1761
	2	77.30	153.20	1276.40	718964.81	1775	
	3	77.09	154.60	1265.00	721598.24	1753	
M4	1	77.96	152.09	1300.20	725995.96	1791	1784
	2	76.66	152.02	1276.20	701662.46	1819	
	3	76.34	151.08	1205.50	691514.31	1743	
M5	1	78.25	152.53	1216.00	733523.18	1658	1651
	2	76.45	154.54	1172.70	709391.15	1653	
	3	76.69	152.41	1155.10	704013.23	1641	

M6	1	76.80	151.90	1158.00	703671.72	1646	1656
	2	76.00	151.90	1148.30	689088.24	1666	
	3	77.30	151.70	1155.70	711925.34	1623	
M7	1	77.24	152.90	1061.40	716443.42	1481	1497
	2	76.34	152.40	1047.20	697556.13	1501	
	3	76.74	151.59	1057.30	701138.84	1508	
M8	1	77.24	152.90	1079.40	716443.42	1507	1518
	2	76.34	152.40	1095.50	697556.13	1570	
	3	76.70	151.50	1070.00	699992.27	1529	
M9	1	76.30	151.90	1409.00	694539.15	2029	2016
	2	76.50	151.50	1408.80	696346.48	2023	
	3	77.00	151.50	1408.50	705478.80	1997	
M10	1	77.65	151.02	1460.70	715166.67	2042	2063
	2	76.35	151.94	1435.30	695632.86	2063	
	3	75.92	152.32	1436.30	689539.60	2083	
M11	1	76.07	152.74	1304.80	694175.85	1880	1770
	2	76.72	151.75	1280.60	701513.07	1825	
	3	77.24	151.58	1257.50	710258.29	1770	
M12	1	77.21	151.67	1239.10	710128.06	1745	1774
	2	76.94	151.77	1252.80	705635.11	1775	
	3	76.58	151.93	1240.60	699784.22	1773	
M13	1	77.16	151.43	1412.10	708086.38	1994	2042
	2	76.4	151.76	1426.20	695719.08	2050	
	3	76.59	151.19	1449.20	696557.68	2081	

M14	1	76.85	151.56	1447.60	703011.16	2059	2061
	2	76.35	151.68	1435.70	694442.49	2067	
	3	76.93	151.60	1448.70	704661.51	2056	
M15	1	77.32	153.77	1309.10	722013.28	1813	1813
	2	76.81	152.87	1296.40	708349.64	1830	
	3	76.45	152.99	1272.90	702276.13	1813	
M16	1	76.89	152.89	1271.20	709918.81	1791	1817
	2	76.83	150.96	1271.60	699863.65	1817	
	3	77.20	152.33	1282.10	713033.48	1798	
M17	1	77.52	153.83	1187.30	726036.49	1635	1607
	2	77.51	154.87	1159.90	730756.44	1587	
	3	77.39	153.82	1155.50	723556.39	1597	
M18	1	76.66	154.05	1179.10	711032.11	1658	1627
	2	77.54	151.59	1147.90	715833.51	1604	
	3	77.46	153.93	1174.20	725384.27	1619	

The results indicate that unit weight of concrete containing recycled plastic aggregate decreased with increasing percentage of the plastic replacement.

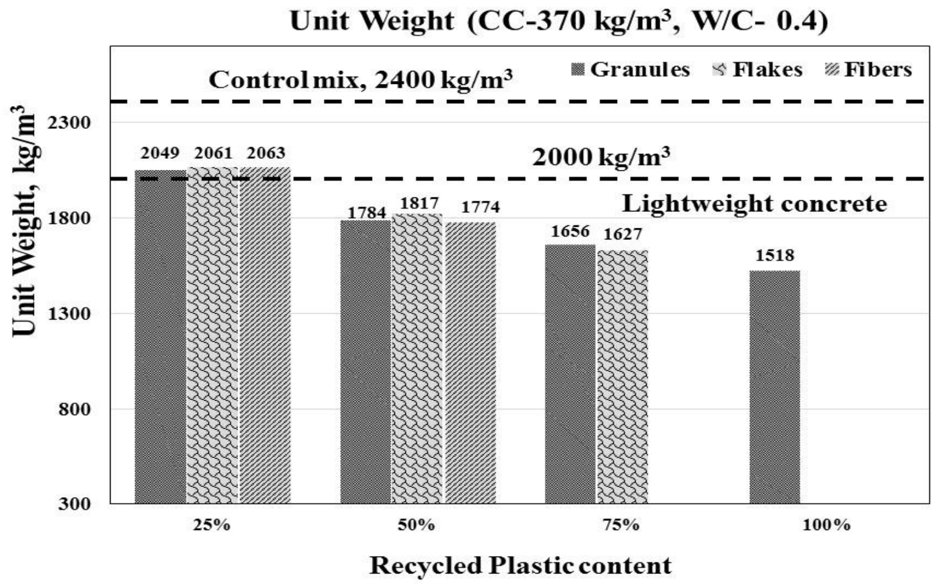


Figure 34: Unit weight at cement content- 370 kg.m^3, w/c- 0.4

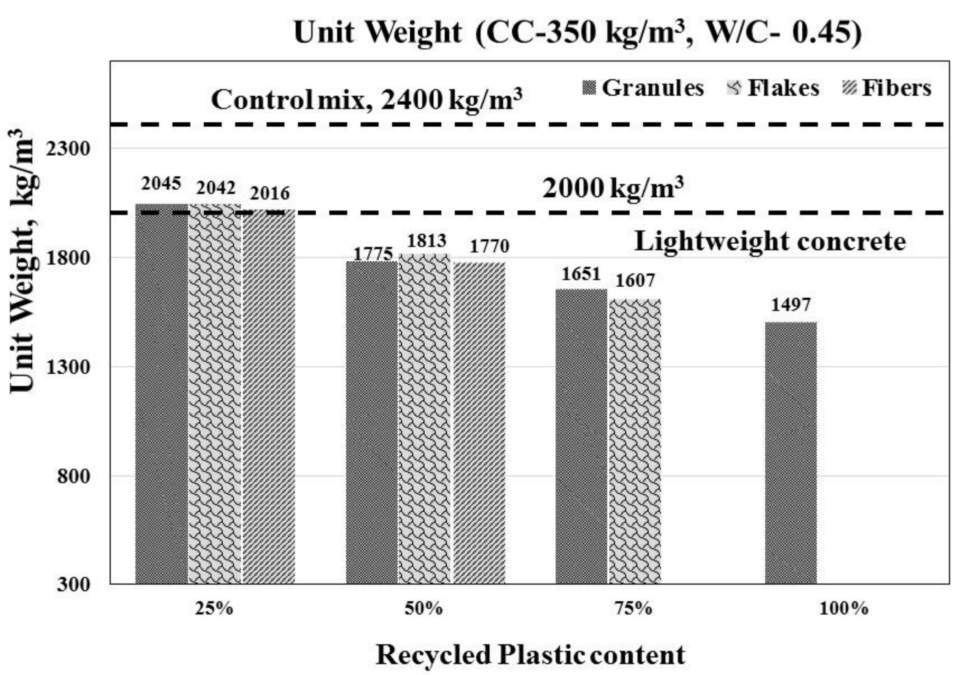


Figure 35: Unit weight at cement content- 350 kg.m^3, w/c- 0.45

4.3.2 COMPRESSIVE STRENGTH

Table 7 shows the compressive strength of concrete specimens containing various percentages of recycled plastic aggregate as a partial/ full substitution of the coarse aggregates with two mix designs. These data are depicted in Figures 36 and 37.

Table 8: Compressive strength of the concrete samples.

Mix #	Sample #	Length, mm	Width, mm	Load, KN	Area of C/S, mm^2	Compressive Strength, MPa	Average Compressive Strength, MPa
M1	1	100.60	102.00	266.40	10261.20	25.96	26.56
	2	100.20	102.00	261.90	10220.40	25.63	
	3	99.90	100.00	265.30	9990.00	26.56	
M2	1	101.15	103.20	377.40	10438.68	36.15	35.05
	2	100.83	102.90	362.70	10375.41	34.96	
	3	101.40	101.30	349.50	10271.82	34.03	
M3	1	100.89	102.30	188.40	10321.05	18.25	19.56
	2	101.10	102.90	203.50	10403.19	19.56	
	3	102.07	105.20	201.80	10737.76	18.79	
M4	1	101.04	101.38	242.30	10243.44	23.65	25.81
	2	100.70	101.71	264.10	10242.20	25.79	
	3	100.69	97.76	254.30	9843.45	25.83	
M5	1	102.17	102.07	194.40	10428.49	18.64	18.92
	2	96.97	102.19	190.00	9909.36	19.17	
	3	102.07	102.03	197.20	10414.20	18.94	
M6	1	100.43	102.55	201.70	10299.10	19.58	19.28

	2	102.20	102.50	203.60	10475.50	19.44	
	3	101.90	103.48	198.40	10544.61	18.82	
M7	1	99.40	101.49	164.10	10088.11	16.27	16.27
	2	99.62	101.23	166.20	10084.53	16.48	
	3	100.57	101.66	177.30	10223.95	17.34	
M8	1	102.62	102.30	174.70	10498.03	16.64	16.64
	2	104.53	102.37	172.40	10700.74	16.11	
	3	98.85	101.87	158.90	10069.85	15.78	
M9	1	100.48	101.68	216.70	10216.81	21.21	20.36
	2	101.29	102.01	205.00	10332.59	19.84	
	3	101.10	99.06	200.60	10014.97	20.03	
M10	1	101.37	100.17	224.10	10154.23	22.07	22.07
	2	101.38	100.54	224.80	10192.75	22.05	
	3	103.90	98.83	209.50	10268.44	20.40	
M11	1	101.86	101.42	155.40	10330.64	15.04	14.86
	2	98.92	101.15	141.40	10005.76	14.13	
	3	100.86	101.37	157.40	10224.18	15.39	
M12	1	98.87	102.84	180.00	10167.79	17.70	16.64
	2	100.88	102.26	158.40	10315.99	15.35	
	3	104.18	101.99	179.20	10625.32	16.87	
M13	1	104.40	101.76	241.10	10623.74	22.69	22.87
	2	99.74	105.62	240.50	10534.54	22.83	
	3	101.62	105.03	246.50	10673.15	23.10	
M14	1	100.55	102.86	296.20	10342.57	28.64	28.43

	2	101.28	102.06	282.70	10336.64	27.35	
	3	98.08	101.96	292.90	10000.24	29.29	
M15	1	102.20	103.48	204.80	10575.66	19.37	18.79
	2	104.71	102.85	212.40	10769.42	19.72	
	3	97.03	103.29	173.10	10022.23	17.27	
M16	1	101.78	101.21	207.80	10301.15	20.17	20.16
	2	100.94	101.54	215.70	10249.45	21.05	
	3	99.50	102.77	197.10	10225.62	19.28	
M17	1	99.27	103.20	135.70	10244.66	13.25	13.44
	2	101.63	103.59	132.90	10527.85	12.62	
	3	101.11	102.94	150.30	10408.26	14.44	
M18	1	101.39	102.90	158.80	10433.03	15.22	14.85
	2	100.19	103.20	145.50	10339.61	14.07	
	3	101.83	101.78	158.20	10364.26	15.26	

The data in Table 7 indicate that the compressive strength of concrete containing recycled plastic aggregate decreases with increasing quantity of plastic.

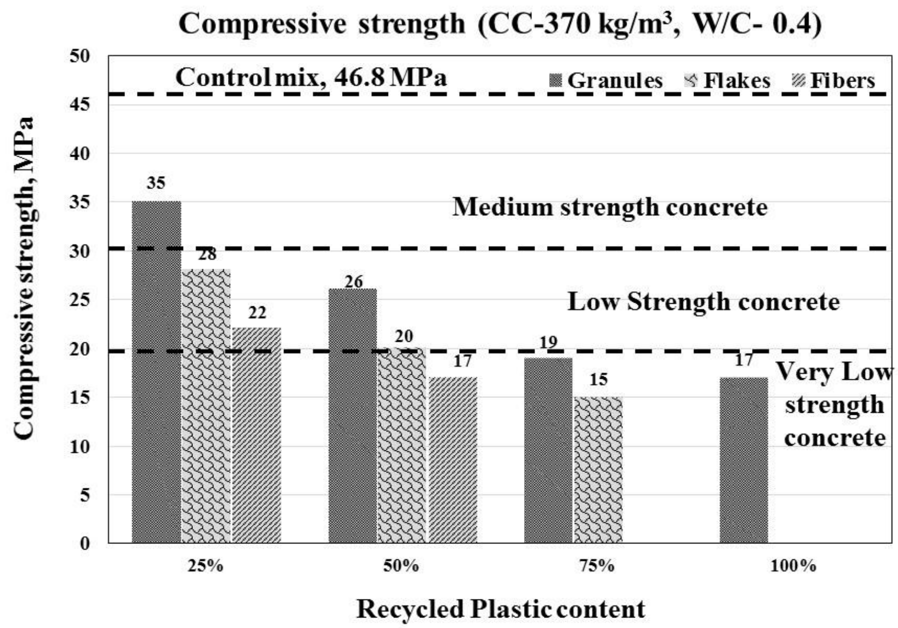


Figure 36: Compressive strength at cement content- 370 kg.m^3, w/c- 0.4

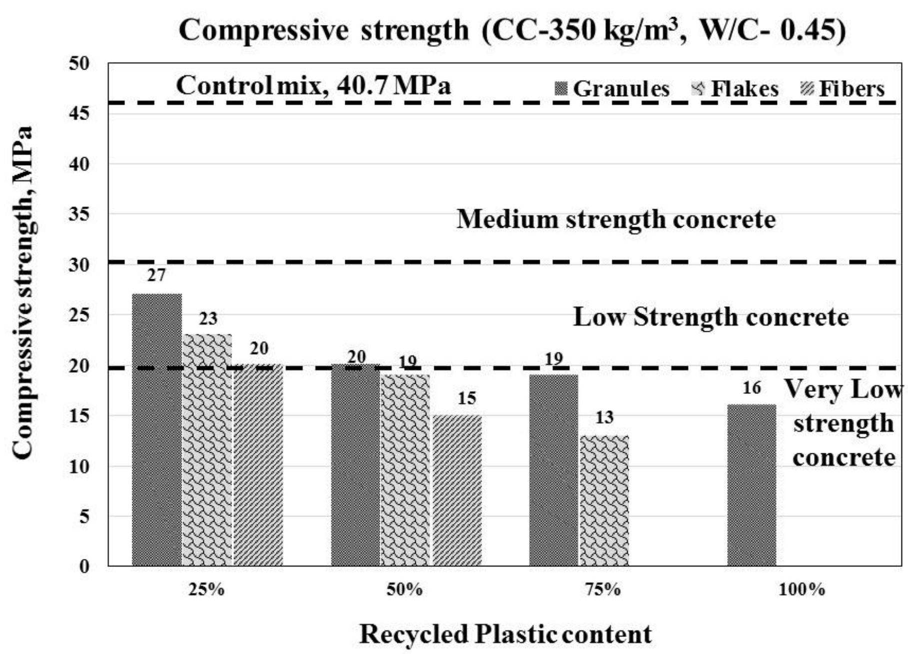


Figure 37: Compressive strength at cement content- 350 kg.m^3, w/c- 0.45

4.3.3 FLEXURAL STRENGTH

Table 8 shows the flexural strength of the concrete specimens containing various percentages of recycled plastic aggregate as a partial/ full substitution of the coarse aggregates with two mix designs. These data are depicted in Figures 38 and 39

Table 9: Flexural strength of the concrete samples

Mix #	Sample #	Failure Load, N	Deflection, mm	Flexural Strength, MPa	Average Flexural Strength, MPa
M1	1	2891.0	0.196	3.47	3.05
	2	1587.6	0.078	1.91	
	3	3136.0	0.078	3.76	
M2	1	3939.6	0.372	4.73	4.74
	2	4135.6	0.256	4.96	
	3	3782.8	0.076	4.54	
M3	1	2195.2	0.302	2.63	2.85
	2	2587.2	0.132	3.10	
	3	2342.2	0.082	2.81	
M4	1	3087.0	0.27	3.70	3.43
	2	2940.0	0.294	3.53	
	3	2538.2	0.104	3.05	
M5	1	2685.2	0.176	3.22	3.19
	2	2538.2	0.354	3.05	
	3	2744.0	0.154	3.29	
M6	1	2744.0	0.298	3.29	2.97
	2	2342.2	0.186	2.81	
	3	2342.2	0.086	2.81	

M7	1	2136.4	0.284	2.56	2.69
	2	2293.2	0.332	2.75	
	3	2293.2	0.368	2.75	
M8	1	1989.4	0.232	2.39	2.47
	2	2195.2	0.082	2.63	
	3	1989.4	0.08	2.39	
M9	1	3733.8	0.098	4.48	4.25
	2	3537.8	0.116	4.25	
	3	3341.8	0.298	4.01	
M10	1	3586.8	0.112	4.30	4.17
	2	3341.8	0.086	4.01	
	3	3488.8	0.064	4.19	
M11	1	2587.2	0.062	3.10	3.03
	2	2391.2	0.468	2.87	
	3	2587.2	0.232	3.10	
M12	1	2744	0.13	3.29	3.43
	2	2891	0.154	3.47	
	3	2940	0.4	3.53	
M13	1	3939.6	0.1	4.73	4.46
	2	3488.8	0.518	4.19	
	3	3733.8	0.072	4.48	
M14	1	3439.8	0.256	4.13	4.90
	2	4086.6	0.102	4.90	
	3	4733.4	0.256	5.68	
M15	1	3537.8	0.148	4.25	3.85
	2	3136	0.244	3.76	

	3	2940	0.236	3.53	
M16	1	3733.8	0.072	4.48	4.16
	2	3136	0.088	3.76	
	3	3537.8	0.176	4.25	
M17	1	2391.2	0.256	2.87	2.91
	2	2538.2	0.136	3.05	
	3	2342.2	0.162	2.81	
M18	1	3341.8	0.184	4.01	3.83
	2	3087	0.114	3.70	
	3	3136	0.234	3.76	

The results indicate that the flexural strength of concrete specimens containing recycled plastic aggregate decreases as the quantity of the plastic increases.

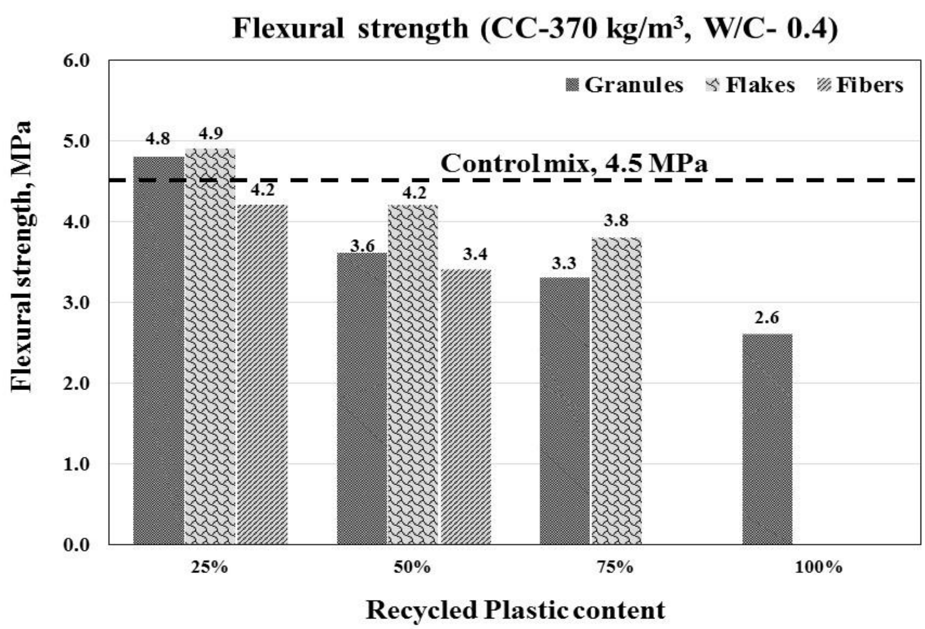


Figure 38: Flexural strength at cement content- 370 kg.m^3, w/c- 0.4

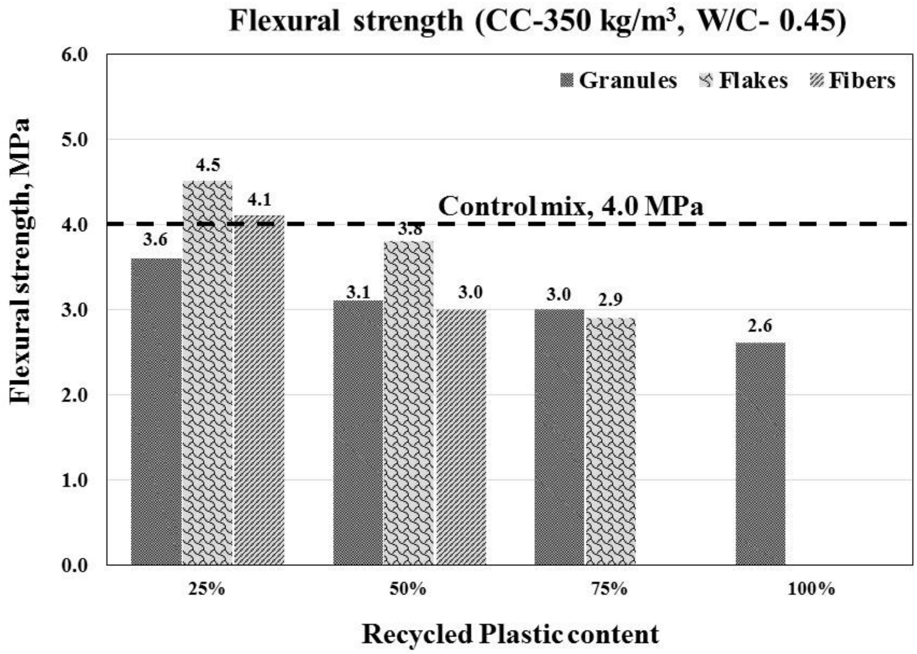


Figure 39: Flexural strength at cement content- 350 kg.m^3, w/c- 0.45

4.3.4 MODULUS OF ELASTICITY

Table 9 shows the modulus of elasticity of the concrete specimens containing various percentages of recycled plastic aggregate as a partial/ full substitution of the coarse aggregates with two mix designs. These data are depicted in Figures 40 and 41.

Table 10: Modulus of Elasticity of the concrete samples

Mix #	Sample #	Failure Load, KN	E (GPa)	Average E, (GPa)
M1	1	95.25	16.22	16.22
	2	102.24	19.28	
	3	92.14	46.86	
M2	1	104.12	9.45	16.98

	2	106.03	17.23	
	3	103.07	16.73	
M3	1	54.99	5.91	6.12
	2	55.99	7.16	
	3	54.03	5.29	
M4	1	91.29	12.02	12.32
	2	85.30	12.47	
	3	84.49	12.46	
M5	1	51.09	9.88	10.37
	2	59.98	10.85	
	3	58.98	13.17	
M6	1	57.07	8.97	8.16
	2	58.93	7.64	
	3	59.98	7.87	
M7	1	43.24	5.08	5.13
	2	49.09	5.18	
	3	57.98	11.35	
M8	1	48.09	5.66	6.37
	2	51.09	5.88	
	3	50.09	6.37	
M9	1	61.03	15.34	14.87
	2	62.08	16.28	
	3	62.27	13.00	
M10	1	62.18	16.15	18.75
	2	92.24	18.24	
	3	100.23	21.87	

M11	1	52.08	11.85	10.76
	2	52.03	10.51	
	3	55.99	9.92	
M12	1	50.98	9.00	14.44
	2	51.09	10.61	
	3	52.03	23.72	
M13	1	97.13	18.61	16.94
	2	86.30	15.26	
	3	89.39	11.78	
M14	1	95.24	19.28	18.75
	2	102.13	22.81	
	3	91.29	14.17	
M15	1	56.93	4.07	10.57
	2	56.98	9.58	
	3	63.92	11.56	
M16	1	61.87	11.20	11.05
	2	65.72	11.71	
	3	59.88	10.23	
M17	1	36.31	4.50	5.58
	2	39.30	5.58	
	3	37.30	4.05	
M18	1	47.36	6.53	6.86
	2	48.63	6.84	
	3	52.23	7.21	

The date in Table 9 indicate that the modulus of elasticity of concrete containing recycled plastic aggregate decreases with increasing quantity of plastic aggregates.

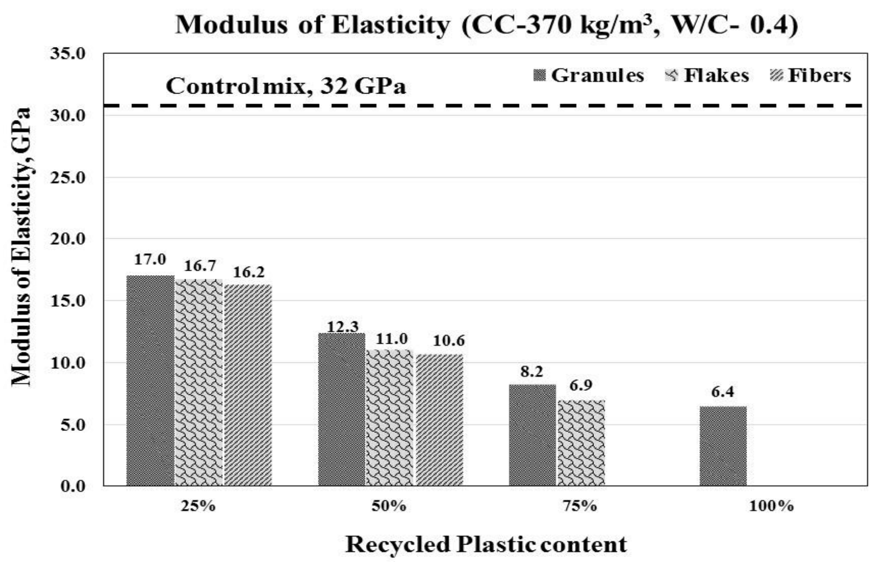


Figure 40: Modulus of elasticity at cement content- 370 kg.m^3, w/c- 0.4

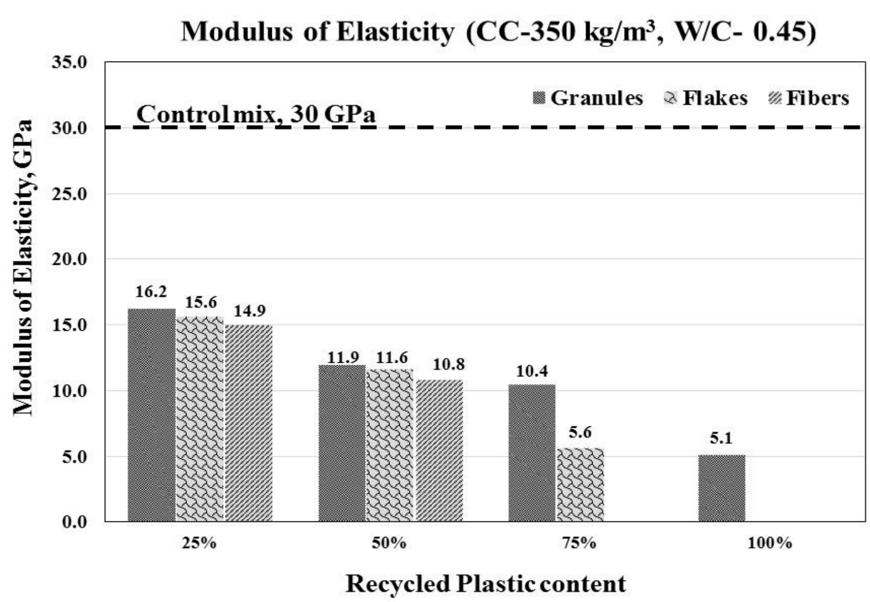


Figure 41: Modulus of elasticity at cement content- 350 kg.m^3, w/c- 0.45

4.3.5 BOND STRENGTH

Table 10 shows the bond strength of the concrete specimens containing various percentages of recycled plastic aggregate as a partial/ full substitution of the coarse aggregates with two mix designs. These data are depicted in Figures 42 and 43.

Table 11: Bond strength of the concrete samples

Mix #	Sample #	Bond Strength, MPa	Free end slip, mm	Loaded end slip, mm	Average Bond Strength, MPa	Average Free slip, mm	Average Loaded slip, mm
M1	1	16.17	0.56	0.64	15.20	0.67	0.70
	2	16.15	0.80	0.82			
	3	12.76	0.53	0.55			
M2	1	15.70	0.81	0.77	15.53	0.66	0.66
	2	15.60	0.58	0.52			
	3	15.28	0.56	0.69			
M3	1	8.48	0.68	0.69	11.74	0.70	0.64
	2	11.04	0.73	0.52			
	3	15.69	0.63	0.58			
M4	1	16.12	0.77	0.78	13.85	0.53	0.54
	2	14.40	0.61	0.62			
	3	11.03	0.27	0.28			
M5	1	8.46	0.46	0.47	9.62	0.37	0.31
	2	9.75	0.22	0.14			
	3	10.66	0.26	0.08			
M6	1	14.01	0.53	0.57	11.75	0.64	0.69
	2	8.07	0.28	0.24			
	3	13.17	0.86	0.99			

M7	1	11.05	0.89	0.95	9.90	0.61	0.83
	2	9.74	0.13	0.15			
	3	8.92	0.69	1.45			
M8	1	11.03	0.74	0.76	11.04	0.46	0.40
	2	10.64	0.37	0.37			
	3	11.45	0.17	-0.14			
M9	1	14.87	0.57	0.61	13.63	0.48	0.35
	2	14.43	0.36	0.11			
	3	11.59	0.61	0.15			
M10	1	10.63	0.38	0.54	11.52	0.58	0.59
	2	13.75	0.76	0.81			
	3	10.18	1.04	0.89			
M11	1	8.54	0.13	0.10	7.71	0.15	0.22
	2	5.57	0.06	0.01			
	3	9.02	0.14	0.23			
M12	1	7.72	0.25	0.53	8.64	0.32	0.27
	2	8.64	0.21	0.25			
	3	9.55	0.19	-0.34			
M13	1	10.60	0.61	0.63	10.33	0.56	0.49
	2	10.63	0.69	0.70			
	3	9.77	0.48	0.16			
M14	1	11.98	0.46	0.48	11.95	0.75	0.69
	2	11.94	0.78	0.80			
	3	11.94	0.91	0.64			
M15	1	7.38	0.83	0.85	8.63	0.44	0.36
	2	10.86	0.52	0.66			

	3	7.65	0.17	-0.24			
M16	1	7.59	0.21	0.17	8.55	0.34	0.26
	2	7.47	0.21	0.19			
	3	10.59	0.34	0.17			
M17	1	7.13	0.58	0.49	6.99	0.57	0.44
	2	7.50	0.17	0.12			
	3	6.33	1.23	0.68			
M18	1	5.92	0.30	0.45	7.05	0.18	0.55
	2	7.14	0.42	0.20			
	3	8.08	0.14	0.34			

The bond strength of concrete containing recycled plastic aggregate decreases with increasing quantity of plastic replacement.

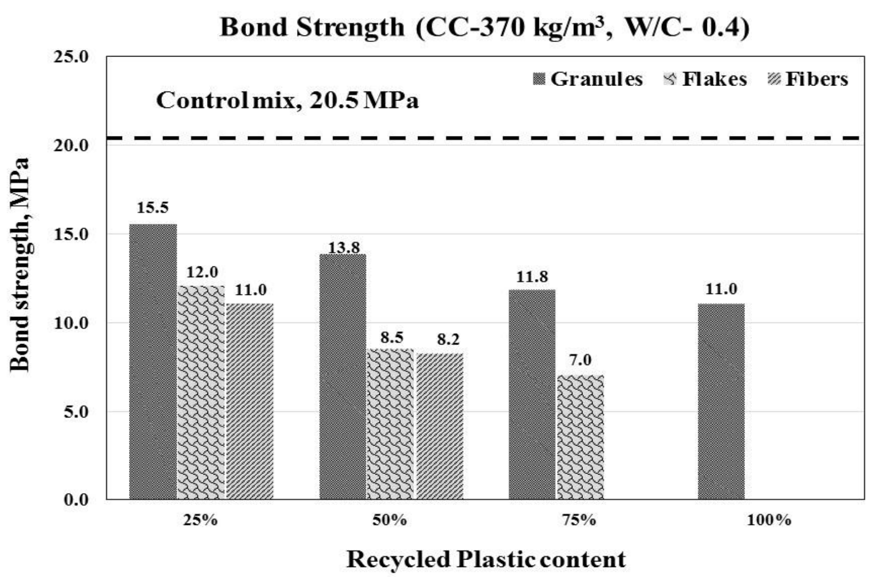


Figure 42: Bond strength at cement content- 370 kg.m^3, w/c- 0.4

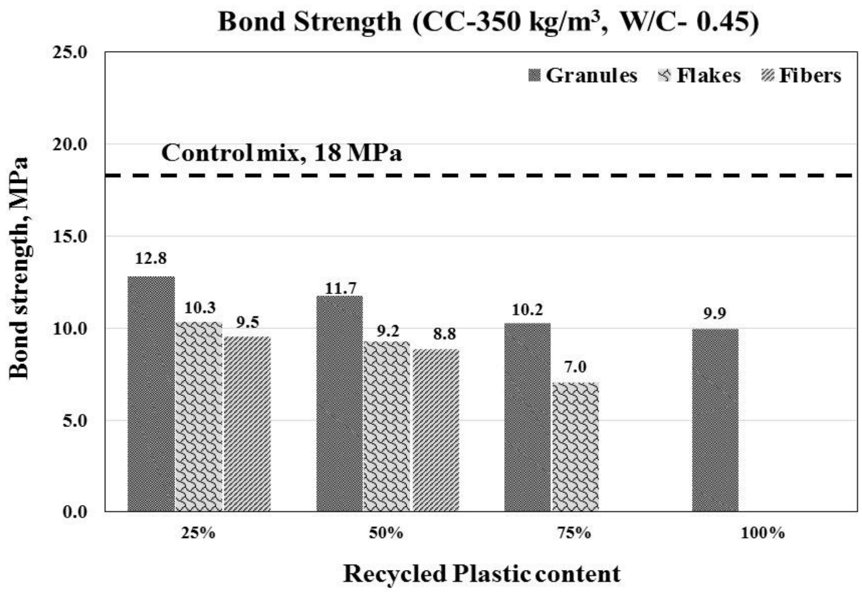


Figure 43: Bond strength at cement content- 350 kg.m^3, w/c- 0.45

4.3.6 THERMAL CONDUCTIVITY

Table 11 shows the thermal conductivity of the concrete specimens containing various percentages of recycled plastic aggregate as a partial/ full substitution of the coarse aggregates with two mix designs. These data are depicted in Figures 44 and 45.

Table 12: Thermal conductivity of the concrete samples

Mix #	Sample #	Reading 1	Reading 2	Average	Average k (W/mK)
M1	1	1.054	1.163	1.109	1.058
	2	1.039	0.978	1.008	
M2	1	1.126	1.200	1.163	1.090
	2	0.728	1.016	1.016	
M3	1	0.968	0.888	0.928	0.851

	2	0.764	0.785	0.775	
M4	1	0.924	0.922	0.923	0.882
	2	0.834	0.847	0.841	
M5	1	0.654	0.669	0.662	0.645
	2	0.613	0.644	0.629	
M6	1	0.706	0.687	0.697	0.669
	2	0.614	0.670	0.642	
M7	1	0.559	0.540	0.550	0.530
	2	0.523	0.497	0.510	
M8	1	0.537	0.530	0.534	0.569
	2	0.616	0.592	0.604	
M9	1	0.977	0.977	0.977	1.058
	2	1.120	1.138	1.138	
M10	1	1.061	1.023	1.042	1.067
	2	1.164	1.021	1.093	
M11	1	0.565	0.582	0.574	0.605
	2	0.638	0.635	0.637	
M12	1	0.628	0.680	0.654	0.613
	2	0.559	0.583	0.571	
M13	1	0.915	0.889	0.902	0.999
	2	1.098	1.094	1.096	
M14	1	1.132	1.048	1.090	0.995
	2	0.875	0.924	0.900	
M15	1	0.853	0.839	0.846	0.850

	2	0.859	0.848	0.854	
M16	1	0.790	0.807	0.799	0.838
	2	0.897	0.859	0.878	
M17	1	0.579	0.574	0.577	0.610
	2	0.628	0.592	0.610	
M18	1	0.489	0.531	0.510	0.591
	2	0.673	0.669	0.671	

The thermal conductivity of concrete containing recycled plastic aggregate decreases with increasing quantity of plastics, thereby indicating that the thermal resistance of plastic concrete is better than that of non-plastic concrete.

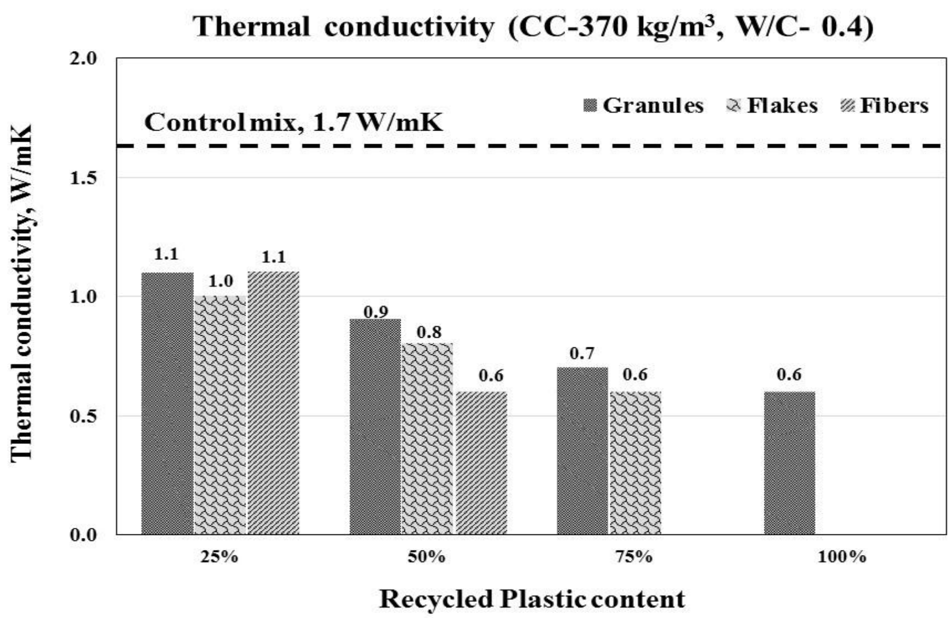


Figure 44: Thermal conductivity at cement content- 370 kg.m^3, w/c- 0.4

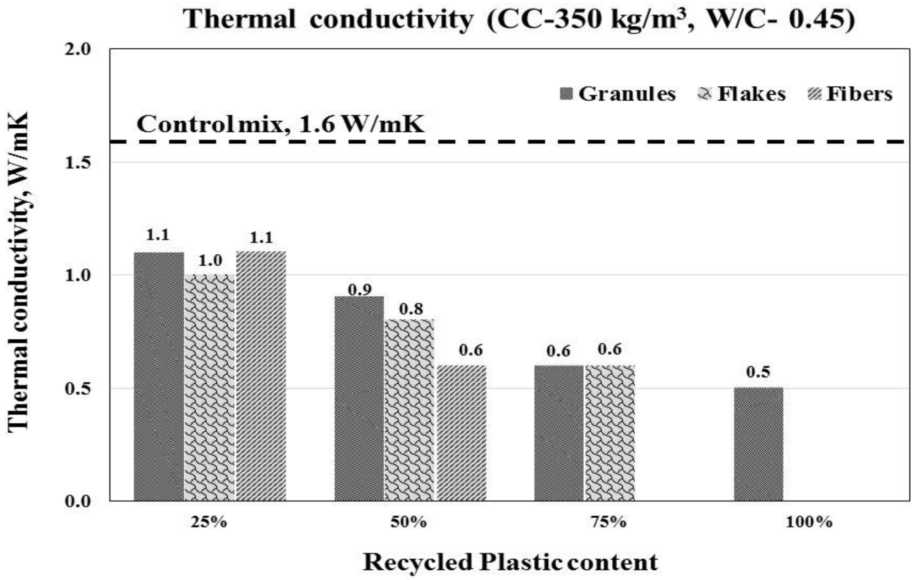


Figure 45: Thermal conductivity at cement content- 350 kg.m^3, w/c- 0.45

4.3.7 SHEAR AND FLEXURAL BEHAVIOR OF RCC BEAMS

Figure 46 through 51 show the failure pattern of beams under pure shear and flexural mode. The shear failure was seen with diagonal cracks at various loads whereas the flexural failure was noted with vertical cracks in the middle of the beam.

Figure 46: Shear failure of RCC beam with 0% plastic content

Figure 47: Shear failure of RCC beam with 25% plastic content

Figure 48: Shear failure of RCC beam with 50% plastic content

Figure 49: Flexure failure of RCC beam with 0% plastic content

Figure 50: Flexure failure of RCC beam with 25% plastic content

Figure 51: Flexure failure of RCC beam with 50% plastic content

Table 12 and 13 show the ultimate failure load in shear and flexure beams and the deflection at the maximum loading. The failure load decreased with increasing quantity of plastic. Whereas the deflection increased.

Table 13: Ultimate load and deflection for beams tested under shear

Recycled plastic content	Ultimate failure load (KN)	Deflection at max. load (mm)
0%	201.3	1.35
25%	175.1	2.012
50%	159.4	2.844

Table 14: Ultimate load and deflection for beams tested under flexure

Recycled plastic content	Ultimate failure load (KN)	Deflection at max. load (mm)

0%	106	5.98
25%	84.25	4.86
50%	79.03	5.11

Figure 52: Load v/s deflection curve of beams under shear failure.

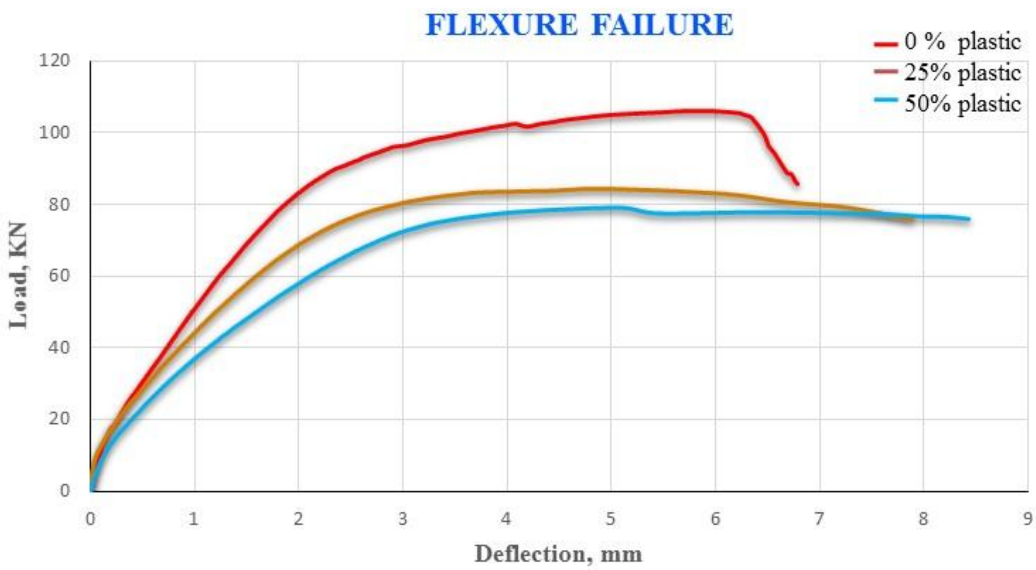


Figure 53: Load v/s deflection curve of beams under flexural failure.

From the data in Figures 52 and 53, it is clear that with the incorporation of recycled plastic aggregates the beams has shown ductile behavior compared to the normal concrete. The ductility increased as the plastic content increased.

4.4 DURABILITY PROPERTIES

4.4.1 WATER ABSORPTION

Table 14 shows the water absorption of the concrete specimens containing various percentages of recycled plastic aggregate as a partial/ full substitution of the coarse aggregates with two mix designs. These data are depicted in Figures 54 and 55.

Table 15: Water absorption in concrete with varying plastic content.

Mix #	Sample #	Dry Weight, gm	SSD Weight, gm	Absorption, %	Average Absorption, %
M1	1	1352.4	1423.5	5.26	5.18
	2	1337.1	1409.8	5.44	

	3	1380.7	1447.7	4.85	
M2	1	1377.5	1442	4.68	4.77
	2	1386.6	1452.4	4.75	
	3	1400.1	1468.3	4.87	
M3	1	1223.0	1289.5	5.44	5.57
	2	1181.3	1250.3	5.84	
	3	1221.9	1288.4	5.44	
M4	1	1212.0	1271.1	4.88	4.83
	2	1233.7	1292.6	4.77	
	3	1209.8	1268.2	4.83	
M5	1	1098.9	1159.6	5.52	5.58
	2	1096.9	1157.1	5.49	
	3	1145.6	1211.3	5.73	
M6	1	1097.9	1155	5.20	5.22
	2	1116.6	1173.4	5.09	
	3	1097.2	1156	5.36	
M7	1	1015.4	1071.8	5.55	5.82
	2	1034.6	1098.4	6.17	
	3	1000.4	1057.7	5.73	
M8	1	1026.5	1081.4	5.35	5.23
	2	1076.4	1129.1	4.90	
	3	1022.1	1074.3	5.11	
M9	1	1353.6	1427.6	5.47	5.40

	2	1409.6	1484.9	5.34	
	3	1383.2	1461.2	5.64	
M10	1	1396.1	1460.8	4.63	4.69
	2	1398.2	1464.1	4.71	
	3	1380.5	1445.9	4.74	
M11	1	1209.8	1274.8	5.37	5.44
	2	1244.4	1305.5	4.91	
	3	1208.7	1275.3	5.51	
M12	1	1223.1	1283.5	4.94	4.82
	2	1229.2	1286.4	4.65	
	3	1190.5	1248.4	4.86	
M13	1	1355.4	1425.2	5.15	5.11
	2	1396.9	1469.7	5.21	
	3	1391.2	1460.2	4.96	
M14	1	1375.4	1438.8	4.61	4.68
	2	1370.0	1434.3	4.69	
	3	1380.7	1445.9	4.72	
M15	1	1228.2	1298.2	5.70	5.38
	2	1207.8	1270.7	5.21	
	3	1236.5	1301.1	5.22	
M16	1	1241.5	1303.5	4.99	5.19
	2	1228.5	1296.6	5.54	
	3	1224.5	1286.1	5.03	

M17	1	1096.6	1172.5	6.92	6.81
	2	1102.2	1179	6.97	
	3	1108.7	1181.3	6.55	
M18	1	1120.3	1184.5	5.73	5.63
	2	1128.7	1188.9	5.33	
	3	1106.4	1170.8	5.82	

The water absorption of the concrete with recycled plastic aggregates did not vary much with the quantity of plastic. Also, the water absorption values were within the acceptable range.

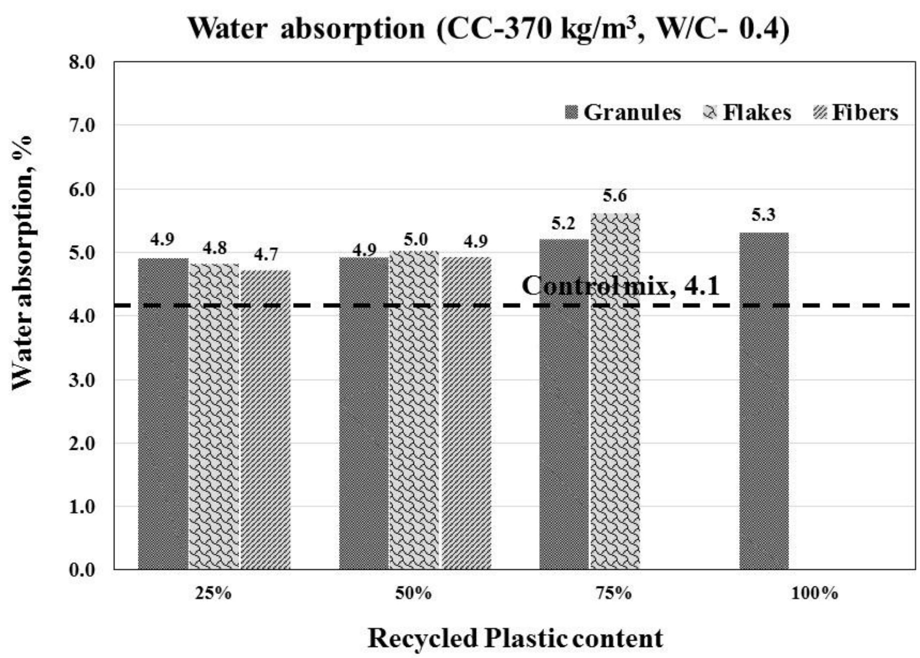


Figure 54: Water absorption at cement content- 370 kg.m^3, w/c- 0.4

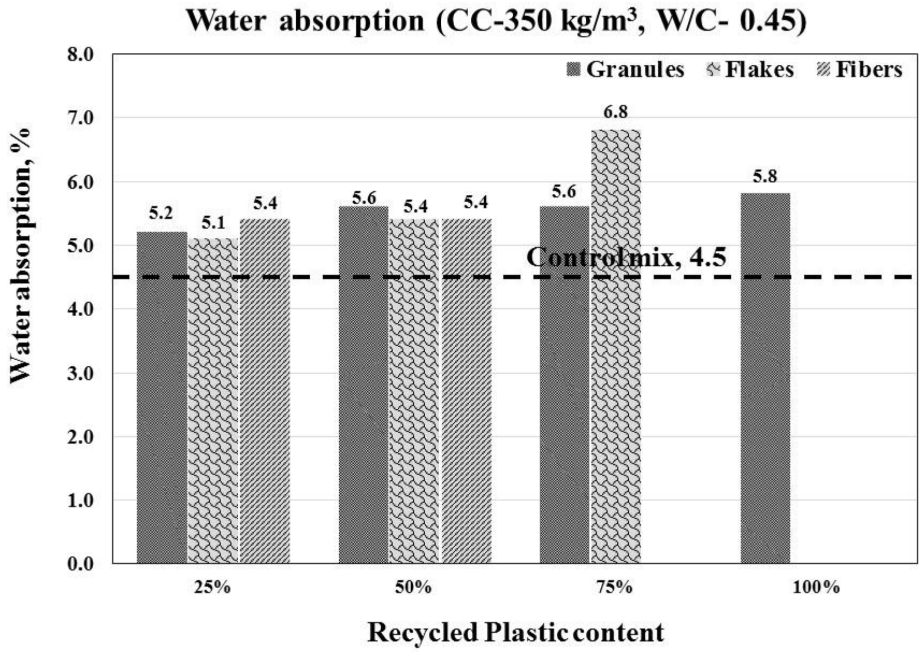


Figure 55: Water absorption at cement content- 350 kg.m^3, w/c- 0.45

4.4.2 RAPID CHLORIDE PERMEABILITY

Table 15 shows the rapid chloride permeability of concrete specimens containing various percentages of recycled plastic waste aggregate as a partial/ full substitution of the coarse aggregates with two mix designs. These data are depicted in Figures 56 and 57.

Table 16: Rapid chloride permeability of the concrete samples.

Mix #	Specimen #	28 Days		
		Charge, Coulombs	Average Charge, Coulombs	Classification
M1	1	1283.00	3211	Moderate
	2	3220.00		
	3	3202.00		
M2	1	2759.00	2568	Moderate
	2	2483.00		
	3	2462.00		

M3	1	2075.00	3194	Low
	2	4158.00		High
	3	3350.00		High
M4	1	3252.00	2946	Moderate
	2	2523.00		
	3	3063.00		
M5	1	3774.00	3332	Moderate
	2	2357.00		
	3	3865.00		
M6	1	2703.00	1809	Low
	2	1219.00		
	3	1505.00		
M7	1	2637.00	2947	Moderate
	2	2104.00		Low
	3	4100.00		High
M8	1	2927.00	2575	Moderate
	2	2222.00		
	3	2883.00		
M9	1	3553.00	3237	High
	2	4011.00		High
	3	2921.00		Low
M10	1	2132.00	2566	Low
	2	2082.00		Low
	3	3485.00		Moderate
M11	1	3121.00	3213	Moderate
	2	3018.00		
	3	3500.00		
M12	1	2389.00		

	2	2941.00	2699	Moderate
	3	2768.00		
M13	1	3370.00	3370	Moderate
	2	3683.00		
	3	4432.00		
M14	1	2541.00	2836	low
	2	2967.00		Moderate
	3	3000.00		Moderate
M15	1	3443.00	3426	Moderate
	2	2180.00		
	3	3409.00		
M16	1	2413.00	2453	Moderate
	2	2489.00		Moderate
	3	2456.00		Moderate
M17	1	4000.00	3561	High
	2	2037.00		Moderate
	3	4645.00		High
M18	1	2815.00	2635	High
	2	2628.00		High
	3	2463.00		Moderate

The chloride permeability was almost in a similar range (moderate) in all the mixtures prepared with a cement content of 370 kg/m^3 and w/c ratio of 0.40. However, it was 'moderate' to 'high' range in the concrete mix prepared with a cement content of 350 kg/m^3 and w/c ratio of 0.45.

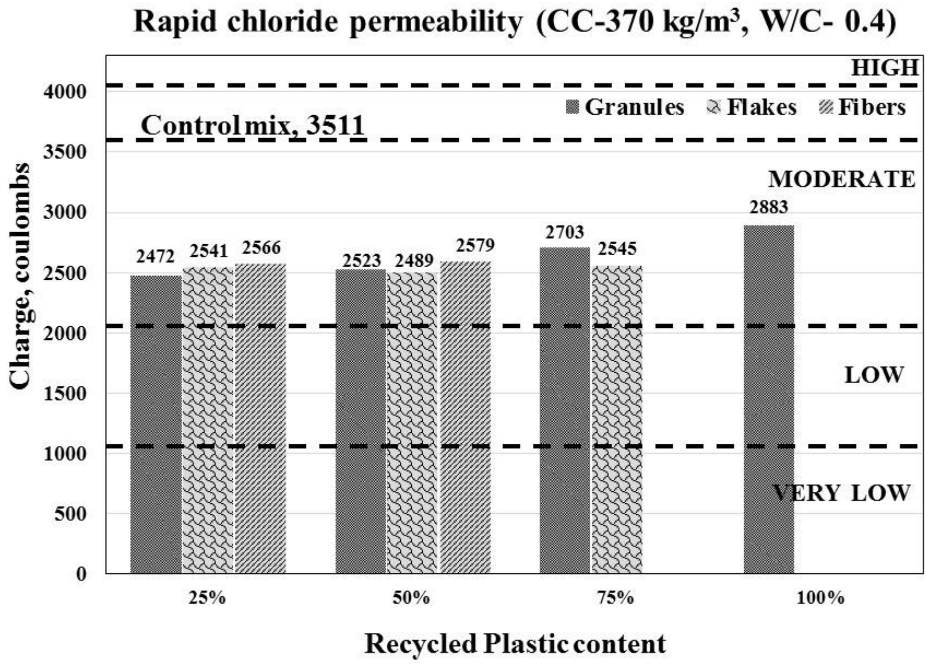


Figure 56: Rapid chloride permeability at cement content- 370 kg.m^3, w/c- 0.4

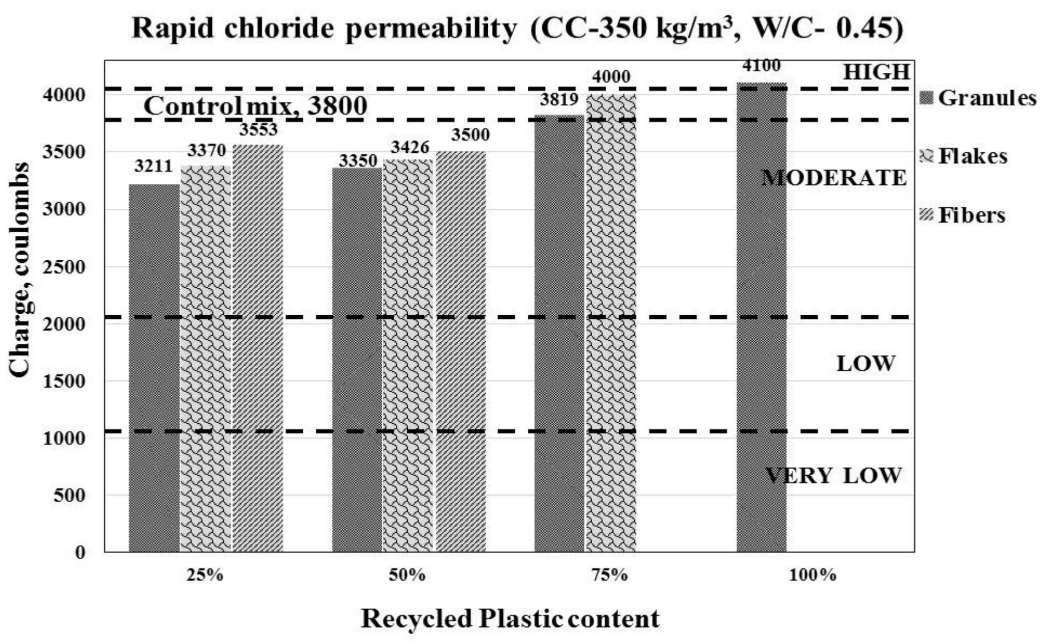


Figure 57: Rapid chloride permeability at cement content- 350 kg.m^3, w/c- 0.45

4.4.3 CORROSION POTENTIALS

Table 16 through 21 shows the corrosion potential of concrete specimens containing various percentages of recycled plastic waste aggregates as a partial/ full substitution of the coarse aggregates with two mix designs. These data are depicted in Figures 58 through 63.

Table 17: Corrosion potentials of concrete with granules (cement content: 350 kg/m^3, w/c: 0.45)

Duration(Days)	Corrosion potentials, mV SCE			
	25%	50%	75%	100%
3	-57	-76	-90	-61
10	-92	-149	-259	-84
17	-105	-168	-174	-165
24	-112	-171	-253	-178
66	-158	-138	-271	-205
73	-120	-155	-233	-173
80	-106	-171	-190	-140
94	-240	-210	-310	-224
101	-112	-221	-197	-113
108	-143	-275	-200	-107
115	-264	-232	-201	-143
130	-247	-245	-135	-90
137	-290	-259	-155	-120
143	-259	-266	-138	-109
160	-275	-305	-174	-126
181	-275	-315	-118	-113
208	-296	-340	-247	-98
228	-415	-349	-280	-110

245	-393	-367	-236	-87

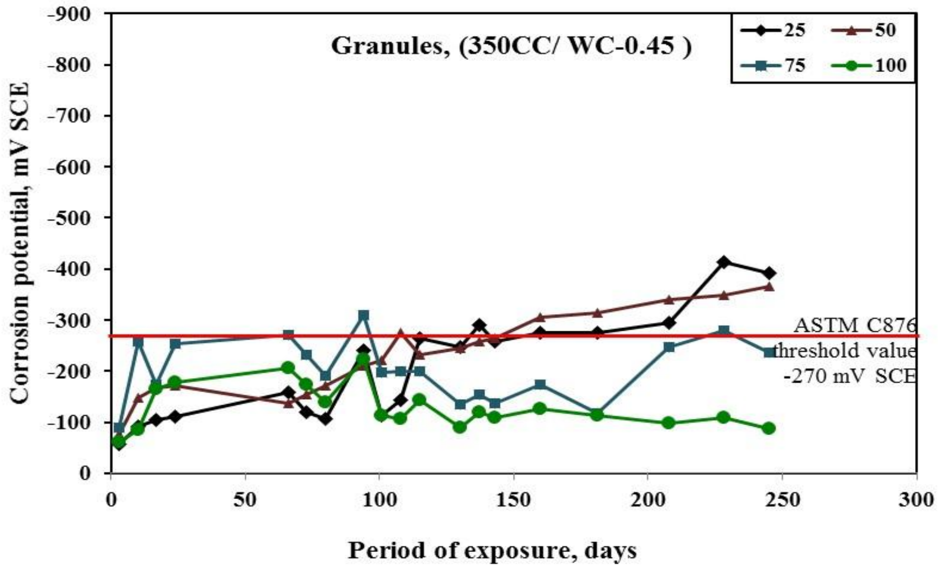


Figure 58: Variation of corrosion potentials with time (Granules: cement content: 350 kg/m^3; w/c: 0.45)

Table 18: Corrosion potentials of concrete with granules (cement content: 370 kg/m^3, w/c: 0.4)

Duration(Days)	Corrosion potentials, mV SCE			
	25%	50%	75%	100%
3	-48	-170	-56	-67
10	-83	-234	-88	-96
17	-92	-150	-96	-100
24	-115	-130	-115	-117
66	-172	-222	-159	-165
73	-203	-180	-118	-125
80	-203	-151	-96	-113
94	-185	-280	-222	-227
101	-202	-173	-93	-112

108	-201	-173	-136	-161
115	-218	-206	-152	-175
130	-190	-131	-87	-108
137	-210	-150	-127	-154
143	-190	-124	-109	-131
160	-206	-131	-121	-181
181	-203	-161	-100	-201
208	-203	-174	-102	-204
228	-213	-184	-94	-197
245	-218	-189	-97	-183

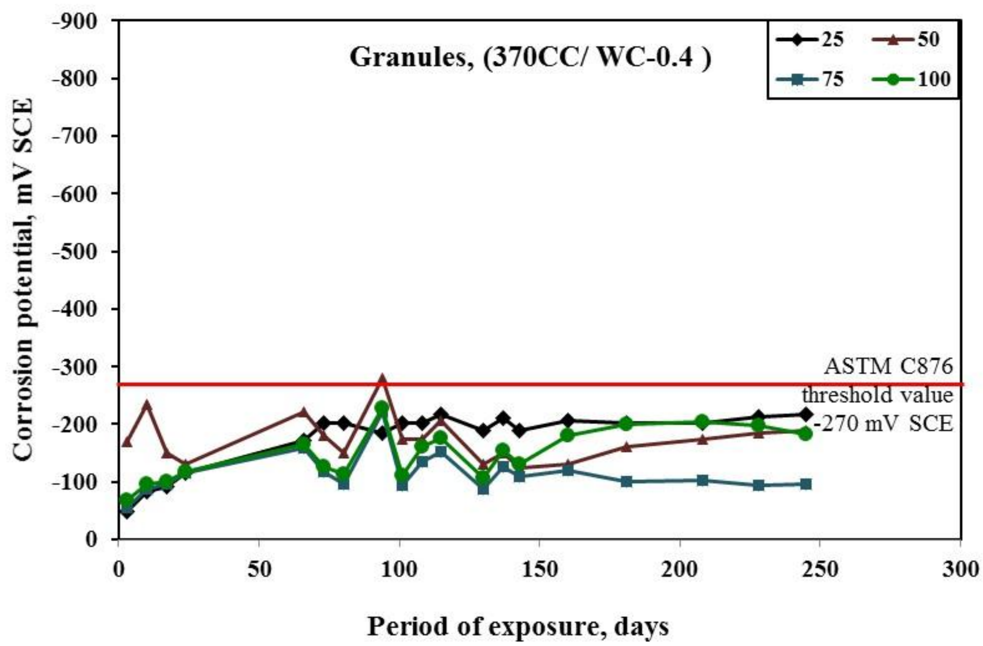


Figure 59: Variation of corrosion potentials with time (Granules: cement content: 370 kg/m^3; w/c: 0.4)

Table 19: Corrosion potentials of concrete with Flakes (cement content: 350 kg/m^3, w/c: 0.45)

Duration(Days)	Corrosion potentials, mV SCE

	25%	50%	75%
3	-183	-241	-71
11	-211	-246	-70
20	-243	-271	-97
27	-295	-285	-154
47	-354	-282	-166
67	-355	-313	-191
84	-346	-289	-201
115	-350	-245	-212

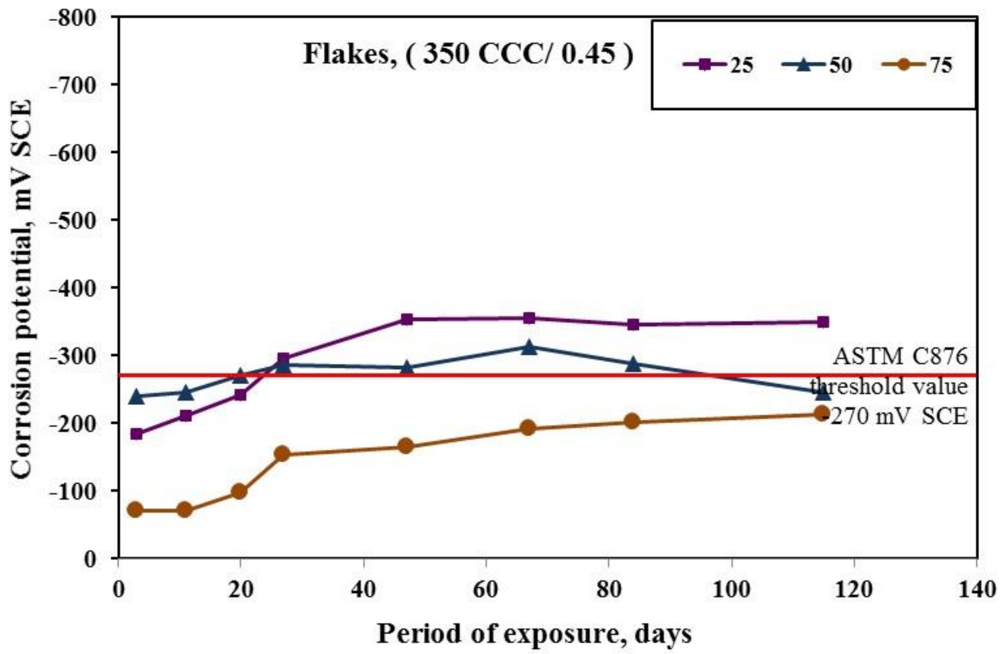


Figure 60: Variation of corrosion potentials with time (Flakes: cement content: 350 kg/m^3; w/c: 0.45)

Table 20: Corrosion potentials of concrete with Flakes (cement content: 370 kg/m^3, w/c: 0.4)

Duration(Days)	Corrosion potentials, mV SCE		
	25%	50%	75%

3	-242	-60	-96
11	-263	-60	-82
20	-223	-73	-161
27	-227	-79	-148
47	-238	-75	-112
67	-343	-64	-121
84	-303	-41	-61
115	-312	-52	-102

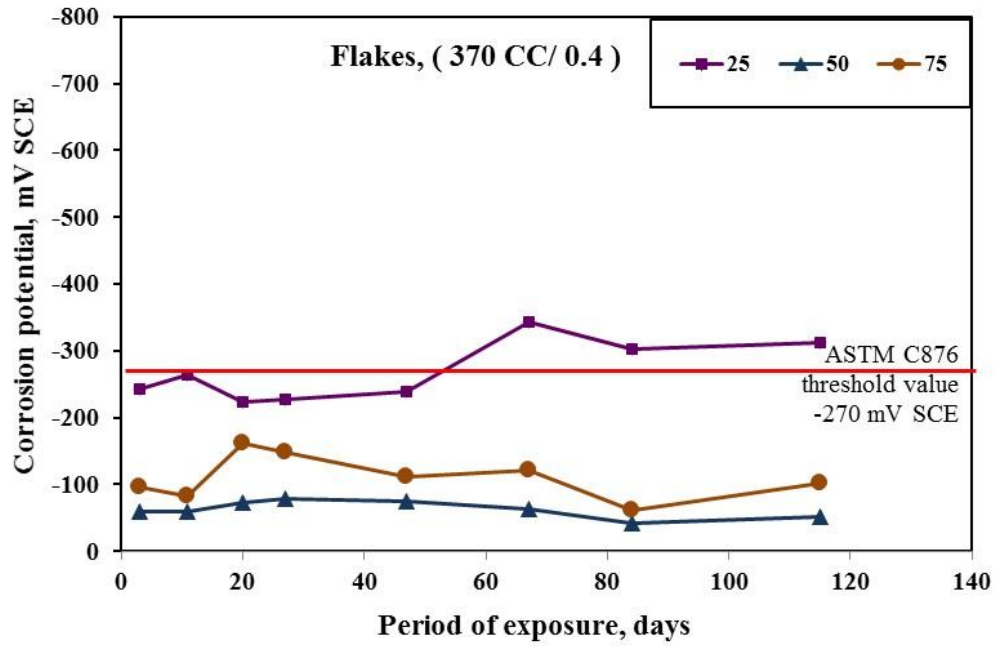


Figure 61: Variation of corrosion potentials with time (Flakes: cement content: 370 kg/m^3; w/c: 0.4)

Table 21: Corrosion potentials of concrete with Fibers (cement content: 350 kg/m^3, w/c: 0.45)

Duration(Days)	Corrosion potentials, mV SCE	
	25%	50%
3	-99	-86

11	-157	-125
20	-143	-234
27	-202	-290
47	-228	-305
67	-196	-316
84	-215	-340
115	-284	-352

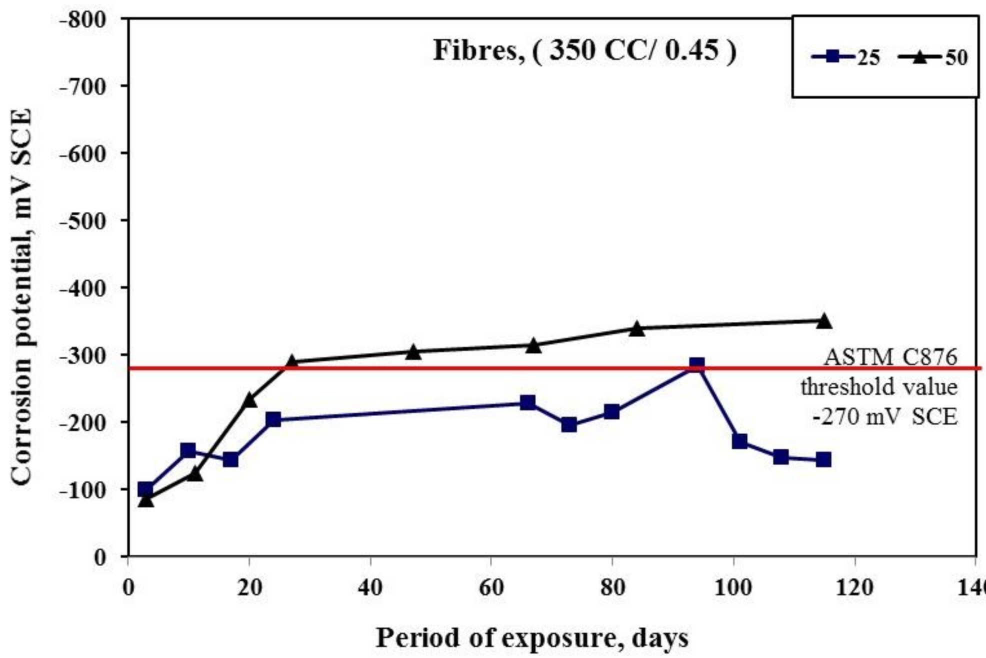


Figure 62: Variation of corrosion potentials with time (Fibers: cement content: 350 kg/m^3; w/c: 0.45)

Table 22: Corrosion potentials of concrete with Fibers (cement content: 370 kg/m^3, w/c: 0.4)

Duration(Days)	Corrosion potentials, mV SCE	
	25%	50%
3	-47	-35
11	-59	-66

20	-99	-104
27	-124	-127
47	-153	-149
67	-167	-245
84	-165	-237
115	-169	-241

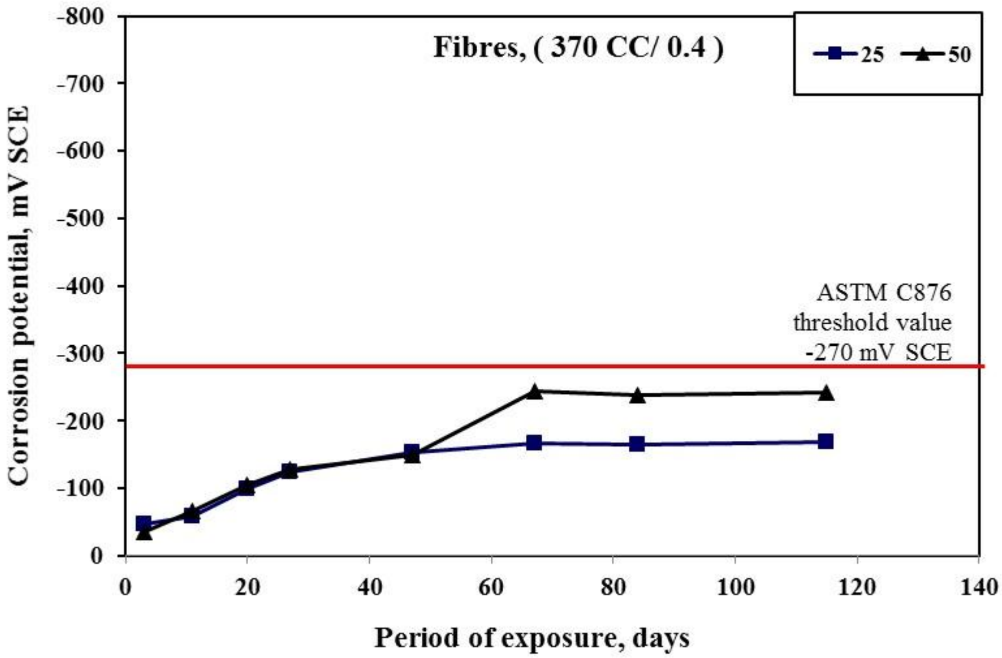


Figure 63: Variation of corrosion potentials with time (Fibers: cement content: 370 kg/m^3; w/c: 0.4)

Table 22 shows the time to initiation of corrosion for the various types of plastics at various percentage replacements.

Table 23: Time to initiation of corrosion

Plastic type	Replacement	TIME TO INITIATION OF CORROSION, DAYS	
		370 / 0.4	350 / 0.45

GRANULES	25%	No	120
	50%	No	145
	75%	No	220
	100%	No	No
FLAKES	25%	80	25
	50%	No	20
	75%	No	No
FIBERS	25%	No	25
	50%	No	No

No corrosion initiation was noted in the concrete specimens prepared with the three types of plastic and cement content of 370 kg/m^3 and w/c ratio of 0.4. In the specimens prepared with a cement content of 350 kg/m^3 and w/c ratio of 0.45, the time to initiation of corrosion increased with the quantity of plastics.

4.4.4 DRYING SHRINKAGE

Table 23 through 28 shows the drying shrinkage of concrete specimens containing various percentages of recycled plastic aggregate as a partial/ full substitution of the coarse aggregates with two mix designs.

Table 24: Drying shrinkage of concrete with granules (cement content: 350 kg/m^3, w/c: 0.45).

Duration(Days)	Drying shrinkage, microns			
	25%	50%	75%	100%
1	35	39	58	41

2	36	177	129	115
3	48	199	158	130
5	55	207	146	138
12	89	231	192	190
19	98	235	205	233
26	98	246	248	233
40	109	270	282	314
54	137	318	352	363
69	172	348	354	424
82	219	411	422	464
110	420	596	602	561
141	420	607	641	611
169	427	610	658	647

Table 25: Drying shrinkage of concrete with granules (cement content: 370 kg/m^3, w/c: 0.4)

Duration(Days)	**Drying shrinkage, microns**			
	25%	50%	75%	100%
1	25	64	49	61
2	49	169	211	151
3	57	178	233	165
5	57	186	243	169
12	72	235	270	259
19	77	248	287	282
26	82	250	320	300
40	96	283	339	326
54	108	346	382	375

69	119	350	381	379
82	139	410	466	435
110	207	509	645	562
141	226	635	665	663
169	260	654	676	703

Table 26: Drying shrinkage of concrete with Flakes (cement content: 350 kg/m^3, w/c: 0.45)

Duration(Days)	**Drying shrinkage, microns**		
	25%	50%	75%
2	28	26	75
5	62	138	85
13	101	215	157
28	152	243	185
41	217	285	244
64	266	325	312
85	314	353	376
110	369	386	452
150	455	423	512

Table 27: Drying shrinkage of concrete with Flakes (cement content: 370 kg/m^3, w/c: 0.4)

Duration(Days)	**Drying shrinkage, microns**		
	25%	50%	75%
2	13	46	15
5	77	69	95

13	131	138	201
28	138	145	219
41	162	219	246
64	171	258	285
85	198	287	360
110	211	312	456
150	256	356	532

Table 28: Drying shrinkage of concrete with Fibers (cement content: 350 kg/m^3, w/c: 0.45)

Duration(Days)	**Drying shrinkage, microns**	
	25%	50%
1	46	65
2	110	143
3	155	227
5	183	169
12	220	219
19	220	228
26	236	239
40	275	305
54	320	377
69	326	376
82	416	393
110	494	523
141	556	596
169	639	635

Table 29: Drying shrinkage of concrete with Fibers (cement content: 370 kg/m^3, w/c: 0.4)

Duration(Days)	**Drying shrinkage, microns**	
	25%	50%
1	47	59
2	138	112
3	243	155
5	161	166
12	204	222
19	240	264
26	219	289
40	279	349
54	315	381
69	315	415
82	365	446
110	506	590
141	565	642
169	611	682

4.4.5 HEAT / COOL EXPOSURE

Table 29 shows the weight loss and compressive strength of concrete specimens exposed to heat/cool cycles for three months. These data are depicted in Figure 64 through 69.

Table 30: Three months heat/ cool exposure of the concrete samples

Mix #	Sample #	Initial Wt at 60^0C (gm)	Final Wt (gm)	Load KN	Loss in Wt (%)	Compressive Strength (MPa)
M1	1	273.30	272.80	89.20	0.18	33.19
	2	276.40	275.80	85.00	0.22	31.71
	3	252.60	252.20	80.00	0.16	30.63
M2	1	269.20	268.40	92.00	0.30	34.13
	2	257.00	256.30	94.00	0.27	35.38
	3	260.40	259.60	97.00	0.31	36.08
M3	1	230.70	230.70	65.40	0.00	24.37
	2	233.30	233.20	57.50	0.04	21.07
	3	243.50	243.50	60.70	0.00	22.14
M4	1	240.30	239.70	75.00	0.25	27.62
	2	243.20	242.90	57.70	0.12	21.85
	3	235.60	235.30	66.80	0.13	25.06
M5	1	222.80	222.50	52.10	0.13	19.31
	2	220.10	219.50	51.00	0.27	18.62
	3	220.70	220.40	52.40	0.14	19.30
M6	1	223.50	221.50	56.40	0.89	20.72
	2	226.80	226.10	51.30	0.31	18.43
	3	221.50	219.60	53.90	0.86	20.00
M7	1	189.10	188.70	44.10	0.21	16.85
	2	189.60	189.00	43.40	0.32	16.24
	3	200.90	200.00	41.20	0.45	15.51
M8	1	200.50	200.00	42.30	0.25	15.61

	2	205.20	204.70	47.90	0.24	17.51
	3	197.20	196.70	44.10	0.25	16.66
M9	1	258.80	258.80	63.10	0.00	23.88
	2	310.30	310.20	56.10	0.03	19.85
	3	288.20	288.10	59.40	0.03	21.32
M10	1	264.70	263.80	67.10	0.34	25.52
	2	287.10	286.30	84.20	0.28	30.95
	3	269.80	269.10	85.10	0.26	32.77
M11	1	242.00	241.30	42.90	0.29	16.30
	2	238.00	237.60	40.50	0.17	15.03
	3	249.10	248.60	37.10	0.20	13.68
M12	1	240.90	240.60	52.20	0.12	18.95
	2	245.20	244.50	42.30	0.29	15.50
	3	237.90	237.30	45.00	0.25	16.47
M13	1	259.40	258.80	80.90	0.23	31.01
	2	284.30	284.00	71.80	0.11	25.85
	3	269.70	269.30	56.30	0.15	20.90
M14	1	272.00	269.10	83.40	1.07	31.47
	2	273.10	270.20	84.40	1.06	31.09
	3	269.50	266.30	96.60	1.19	30.02
M15	1	236.80	235.10	51.60	0.72	19.52
	2	232.50	230.80	53.10	0.73	19.95
	3	248.10	246.20	50.60	0.77	18.50
M16	1	230.80	229.00	56.00	0.78	21.68
	2	236.20	234.40	53.00	0.76	20.38

	3	234.40	232.80	54.00	0.68	21.08
M17	1	209.60	208.80	40.00	0.38	14.99
	2	225.90	224.10	34.90	0.80	12.54
	3	214.40	213.20	38.00	0.56	13.82
M18	1	224.30	222.20	41.00	0.94	14.92
	2	217.40	215.70	40.00	0.78	14.83
	3	226.70	224.90	42.00	0.79	15.22

The compressive strength in the specimens increased with the period of exposure. However, a slight decrease in the compressive strength was noted in the specimens with 100% plastic.

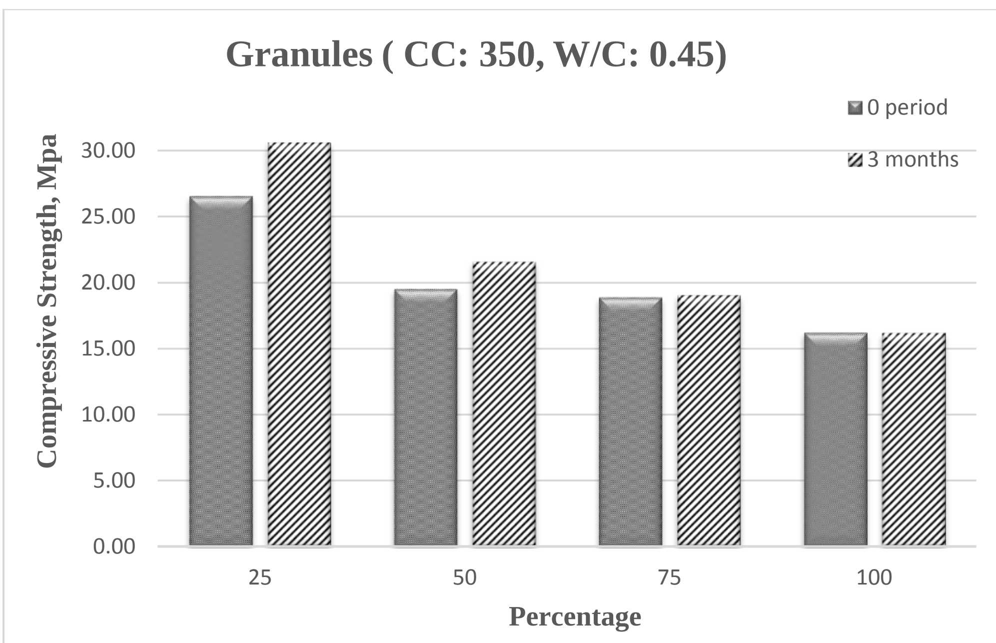


Figure 64: Compressive strength of granules at cement content of 350 kg/m^3 and w/c- 0.45

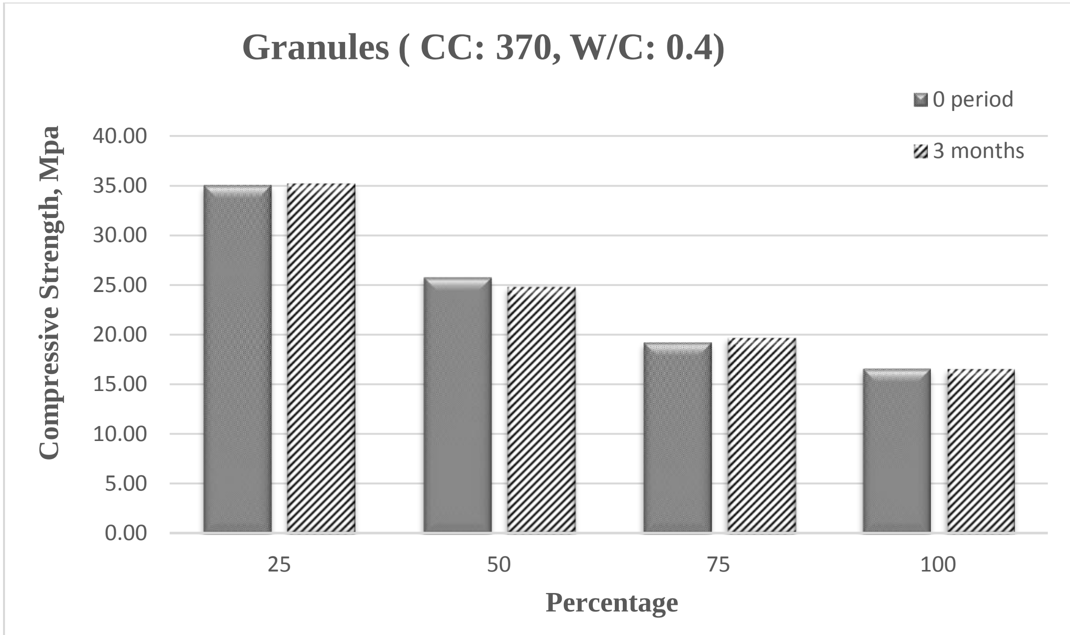


Figure 65: Compressive strength of granules at cement content of 370 kg/m^3 and w/c- 0.4

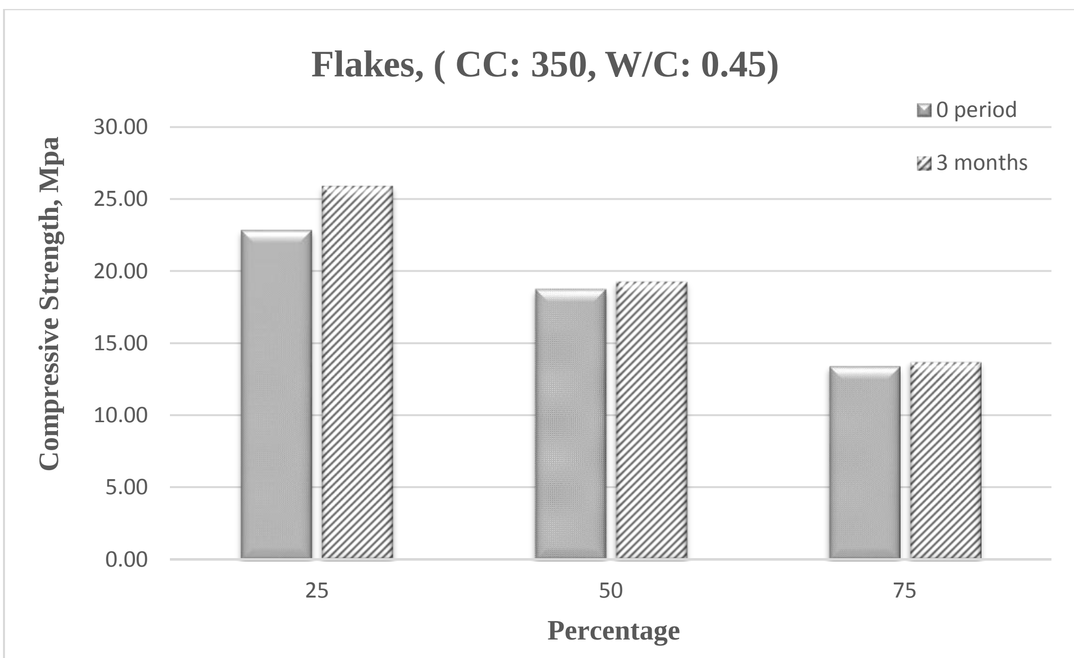


Figure 66: Compressive strength of flakes at cement content of 350 kg/m^3 and w/c- 0.45

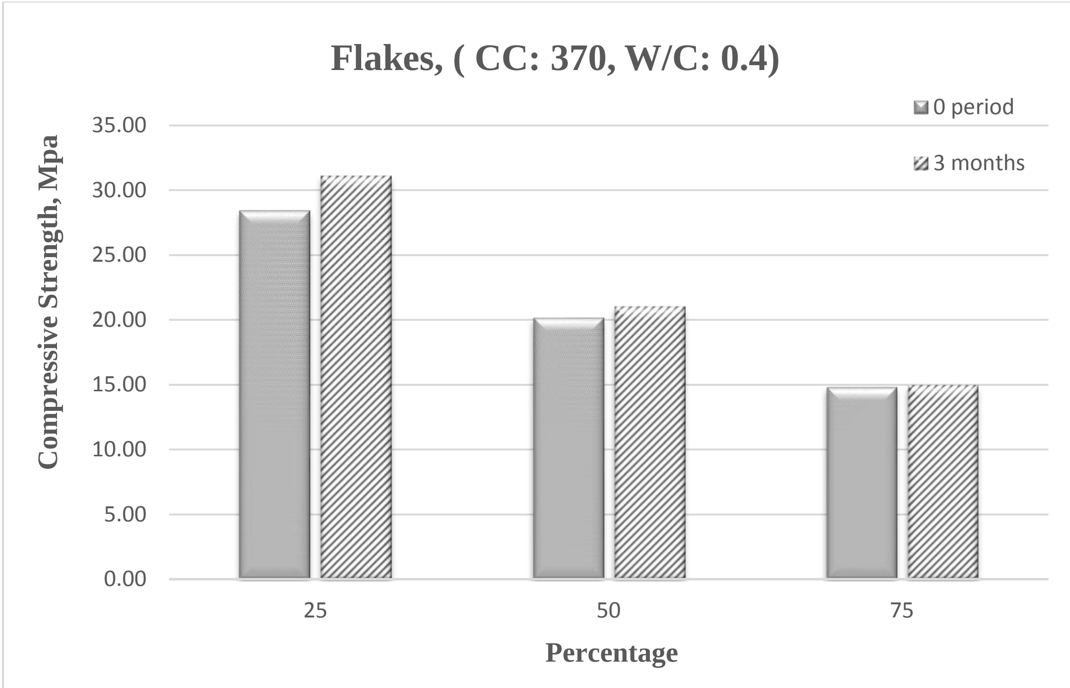


Figure 67: Compressive strength of flakes at cement content of 370 kg/m^3 and w/c- 0.4

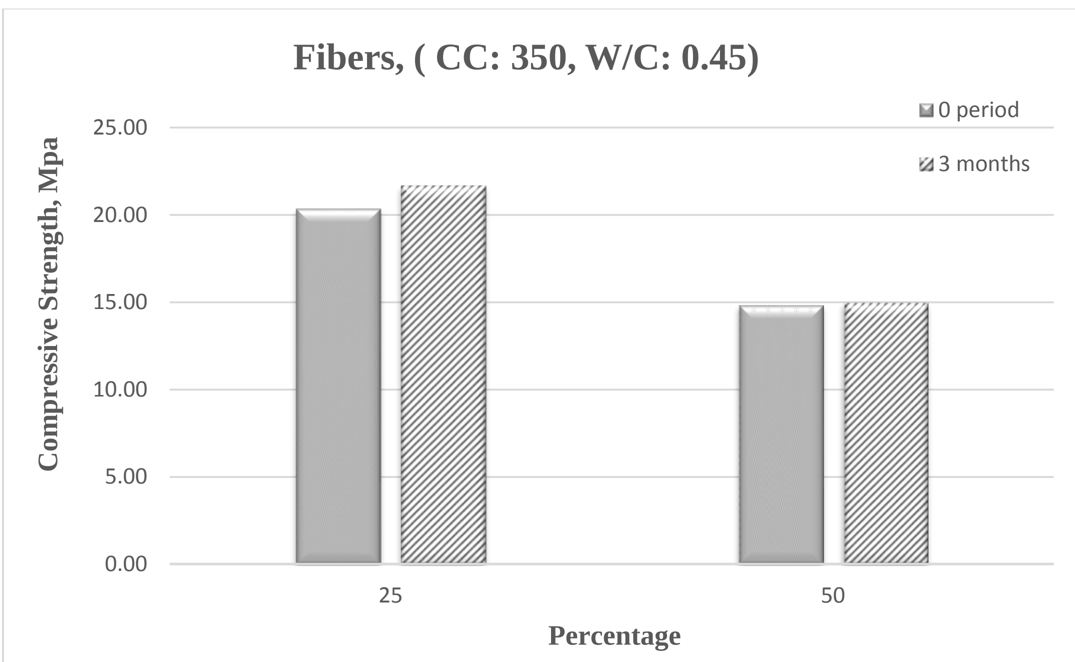


Figure 68: Compressive strength of fibers at cement content of 350 kg/m^3 and w/c- 0.45

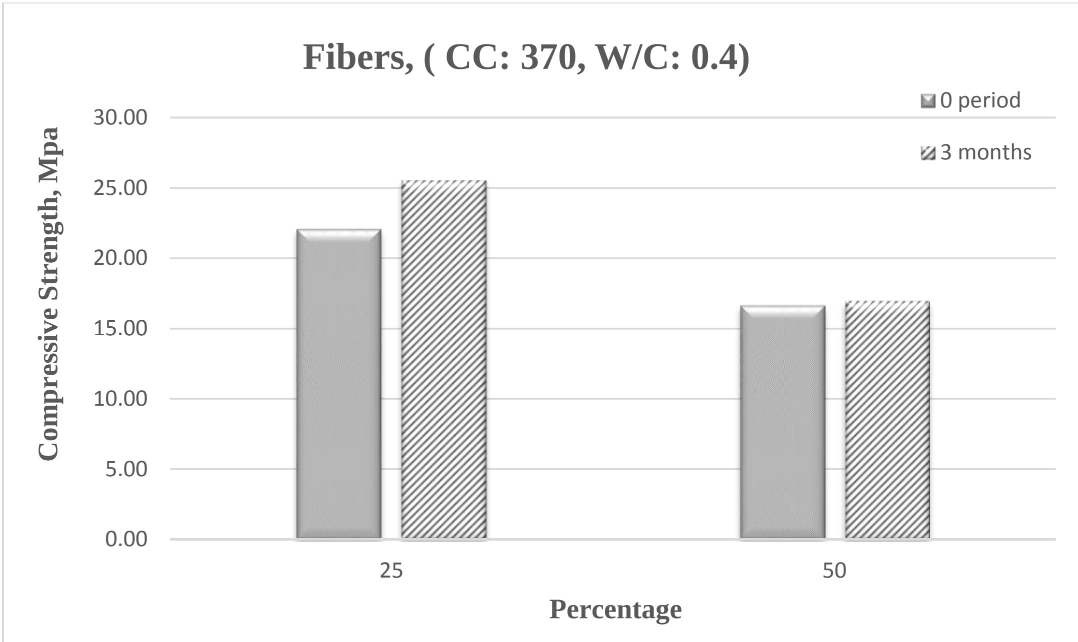


Figure 69: Compressive strength of fibers at cement content of 370 kg/m^3 and w/c- 0.4

4.4.6 WET / DRY EXPOSURE

Table 30 shows the weight loss and compressive strength of concrete specimens exposed to wet/dry cycles for three months. These data are depicted in Figure 70 through 75.

Table 31: Three months wet/ dry exposure of the concrete samples

Mix #	Sample #	Initial Wt at 60^0C (gm)	Final Wt, (gm)	Load, KN	Loss in Wt (%)	Compressive Strength (MPa)
M1	1	286.0	296.70	90.10	-3.74	33.06
	2	258.9	267.10	99.60	-3.17	38.44
	3	253.6	262.00	93.60	-3.31	35.55
M2	1	260.4	269.60	80.90	-3.53	30.57
	2	271.5	280.80	99.50	-3.43	36.69
	3	263.1	272.70	70.10	-3.65	25.42
M3	1	231.5	239.10	58.30	-3.28	21.04

	2	243.9	251.90	67.40	-3.28	24.86
	3	229.4	237.50	58.50	-3.53	21.78
M4	1	234.4	241.90	77.10	-3.20	29.67
	2	242.9	251.20	72.30	-3.42	25.66
	3	244.1	252.70	79.50	-3.52	29.77
M5	1	216.6	224.30	59.70	-3.55	22.28
	2	215.7	223.00	59.30	-3.38	21.56
	3	208.5	215.20	54.50	-3.21	20.55
M6	1	217.2	224.80	60.70	-3.50	22.29
	2	221.0	229.10	59.80	-3.67	22.56
	3	220.9	228.10	56.90	-3.26	20.84
M7	1	192.3	198.50	48.20	-3.22	18.15
	2	191.3	198.40	40.20	-3.71	14.72
	3	188.9	195.20	47.00	-3.34	18.19
M8	1	201.1	207.60	46.50	-3.23	17.29
	2	196.4	202.60	48.10	-3.16	18.32
	3	200.0	206.50	49.10	-3.25	18.55
M9	1	268.3	275.70	69.20	-2.76	25.50
	2	276.9	284.70	75.10	-2.82	27.77
	3	264.2	271.40	72.60	-2.73	27.11
M10	1	278.3	285.20	84.30	-2.48	31.43
	2	273.6	280.00	108.30	-2.34	41.75
	3	287.0	293.50	87.30	-2.26	32.71
M11	1	234.6	241.20	41.80	-2.81	15.16
	2	233.0	239.10	44.10	-2.62	16.75
	3	240.1	246.60	36.90	-2.71	13.61

M12	1	237.9	243.30	40.50	-2.27	14.99
	2	235.2	240.70	44.60	-2.34	16.43
	3	253.1	258.70	39.60	-2.21	14.08
M13	1	282.5	289.40	84.10	-2.44	31.5
	2	268.7	275.20	83.00	-2.42	30.96
	3	275.6	282.50	84.60	-2.50	31.81
M14	1	274.8	279.80	88.40	-1.82	32.7
	2	264.0	269.30	89.50	-2.01	33.76
	3	287.9	293.20	89.20	-1.84	33.49
M15	1	230.7	235.90	52.00	-2.25	19.44
	2	233.8	239.30	51.00	-2.35	19.07
	3	228.9	234.50	52.00	-2.45	19.64
M16	1	246.5	251.40	50.00	-1.99	18.93
	2	235.9	241.20	56.20	-2.25	20.91
	3	253.4	258.70	57.70	-2.09	20.99
M17	1	219.1	224.70	39.70	-2.56	14.47
	2	222.8	228.10	38.70	-2.38	13.97
	3	225.3	230.80	39.00	-2.44	13.99
M18	1	225.2	230.40	43.20	-2.31	15.52
	2	220.5	226.00	33.70	-2.49	11.94
	3	206.5	211.90	37.80	-2.62	14.17

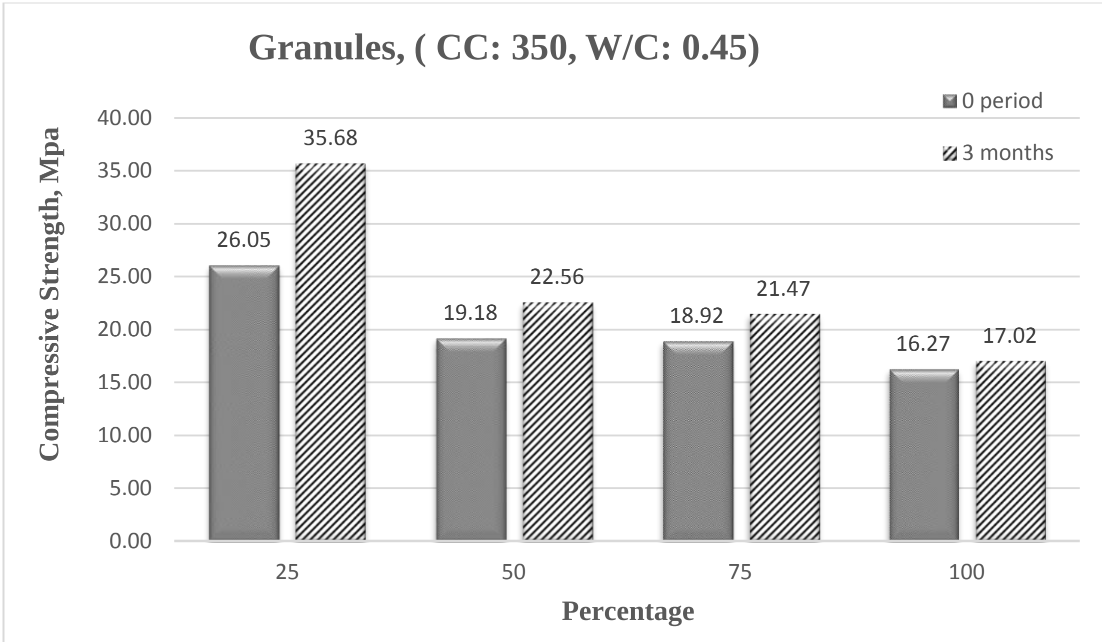


Figure 70: Compressive strength of granules at cement content of 350 kg/m^3 and w/c- 0.45

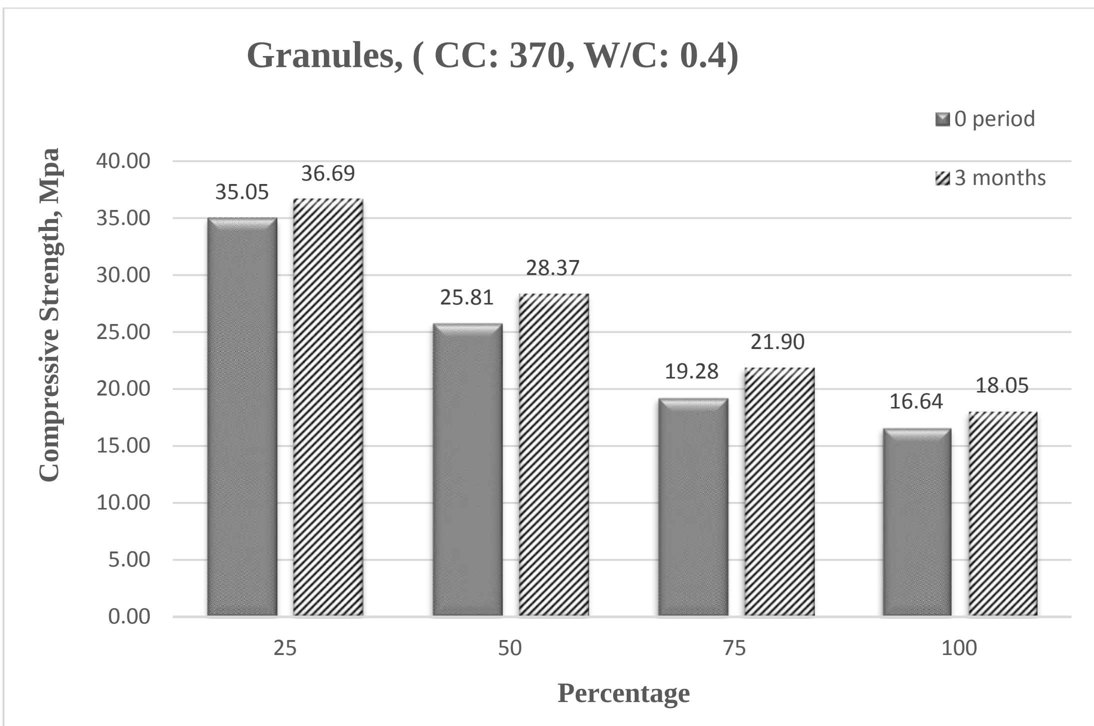


Figure 71: Compressive strength of granules at cement content of 370 kg/m^3 and w/c- 0.4

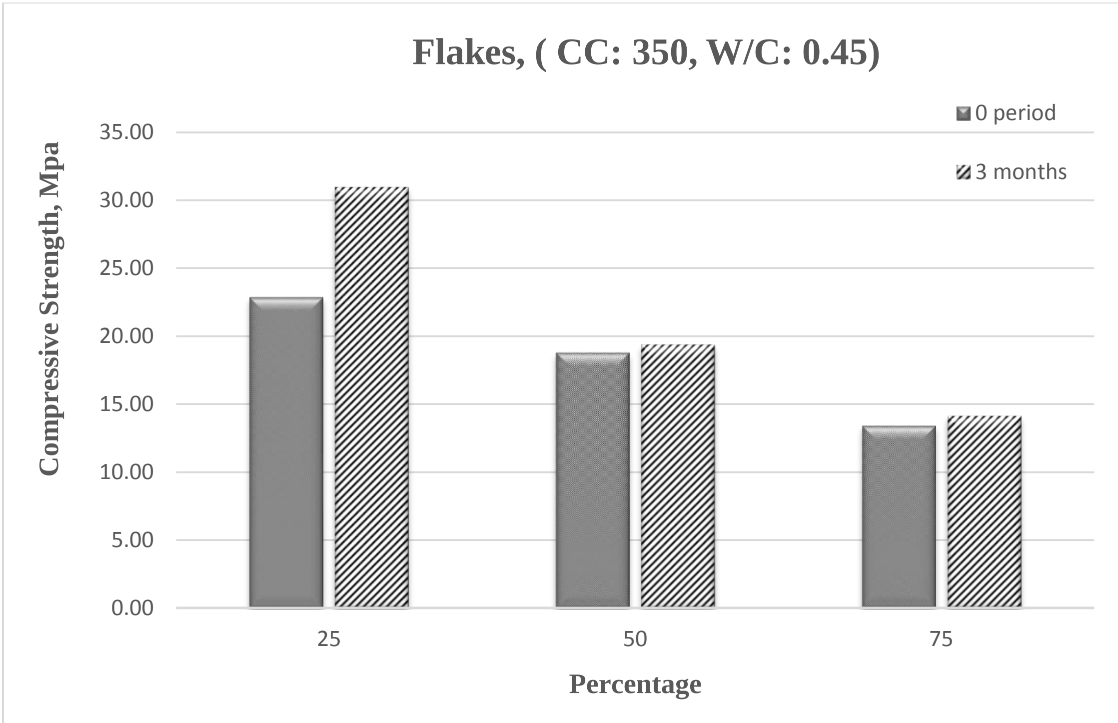


Figure 72: Compressive strength of flakes at cement content of 350 kg/m^3 and w/c- 0.45

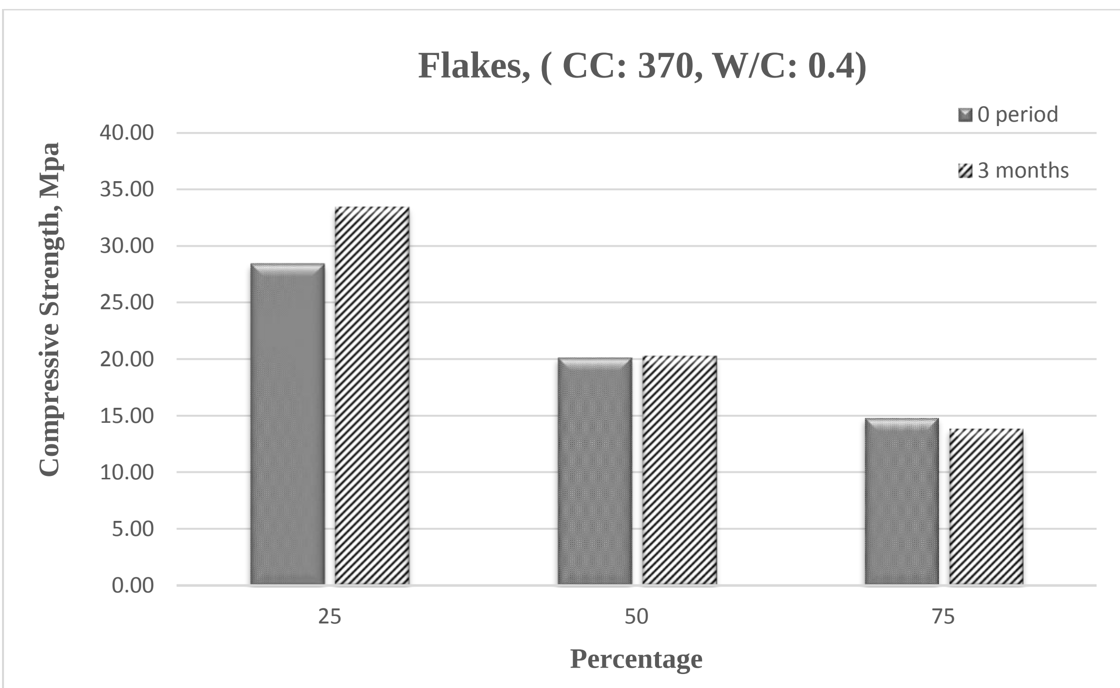


Figure 73: Compressive strength of flakes at cement content of 370 kg/m^3 and w/c- 0.4

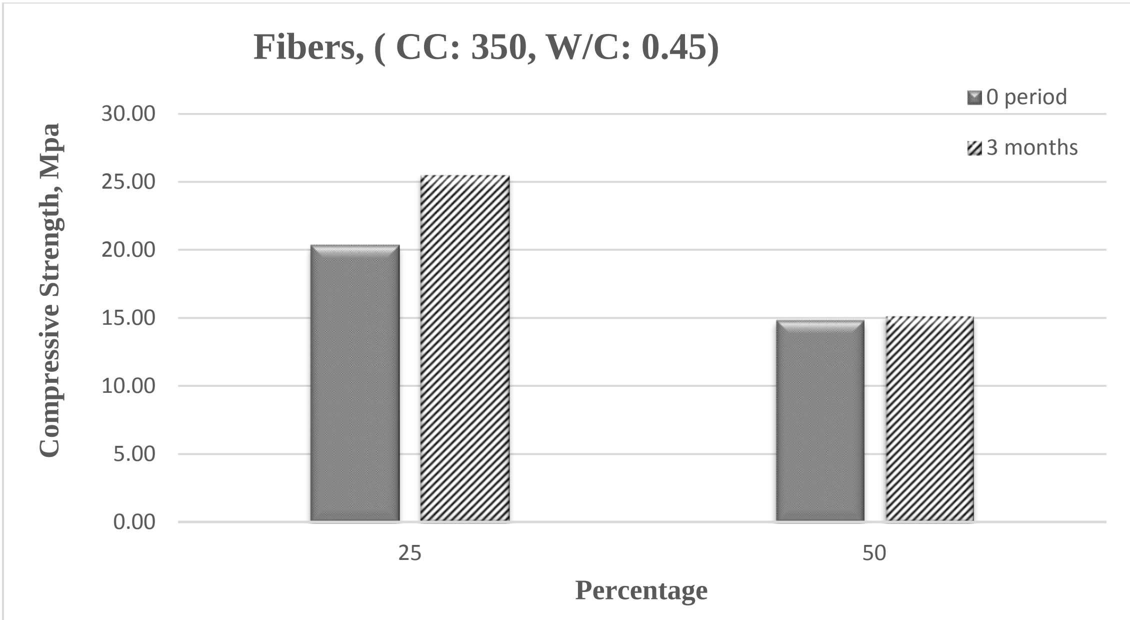


Figure 74: Compressive strength of fibers at cement content of 350 kg/m^3 and w/c- 0.45

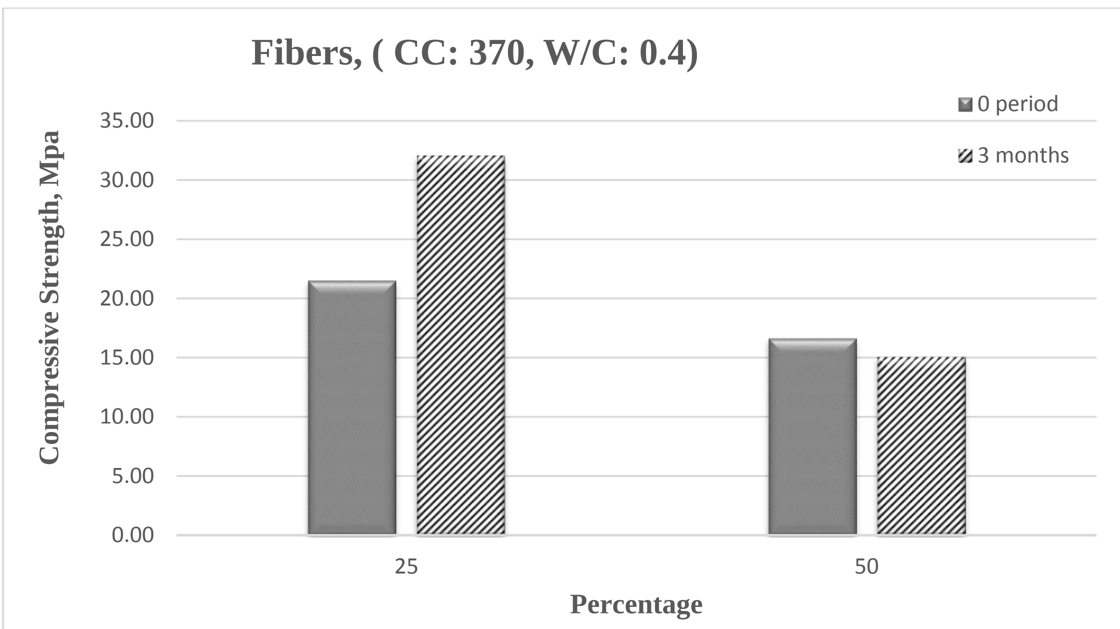


Figure 75: Compressive strength of fibers at cement content of 370 kg/m^3 and w/c- 0.4

The compressive strength in the specimens increased with the period of exposure. However, a slight decrease in the compressive strength was noted in the specimens with 100% plastic.

4.5 MORPHOLOGY

The morphology of concrete specimen prepared with granules, flakes and fibers. Figures 76 through 78 show the SEM of the specimens prepared with the three types of plastics. The main purpose of doing the SEM was to observe the interfacial zone between the plastic and the cement paste. It was noted that the granules and flakes had better bonding with cement mortar compared to fibers. Further granules had a better interfacial bond than the flakes. Hence it could be concluded that the better interfacial zone of granules compared to other plastics showed good performance in most of the mechanical properties.

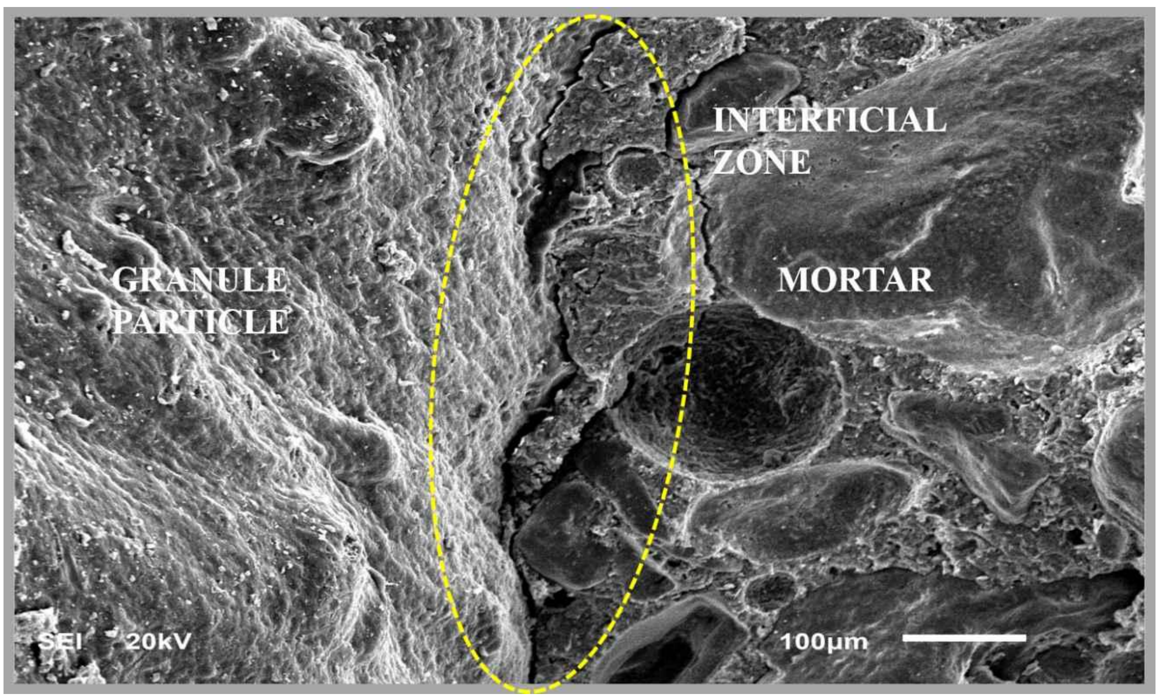


Figure 76: SEM image of concrete with granule type plastic.

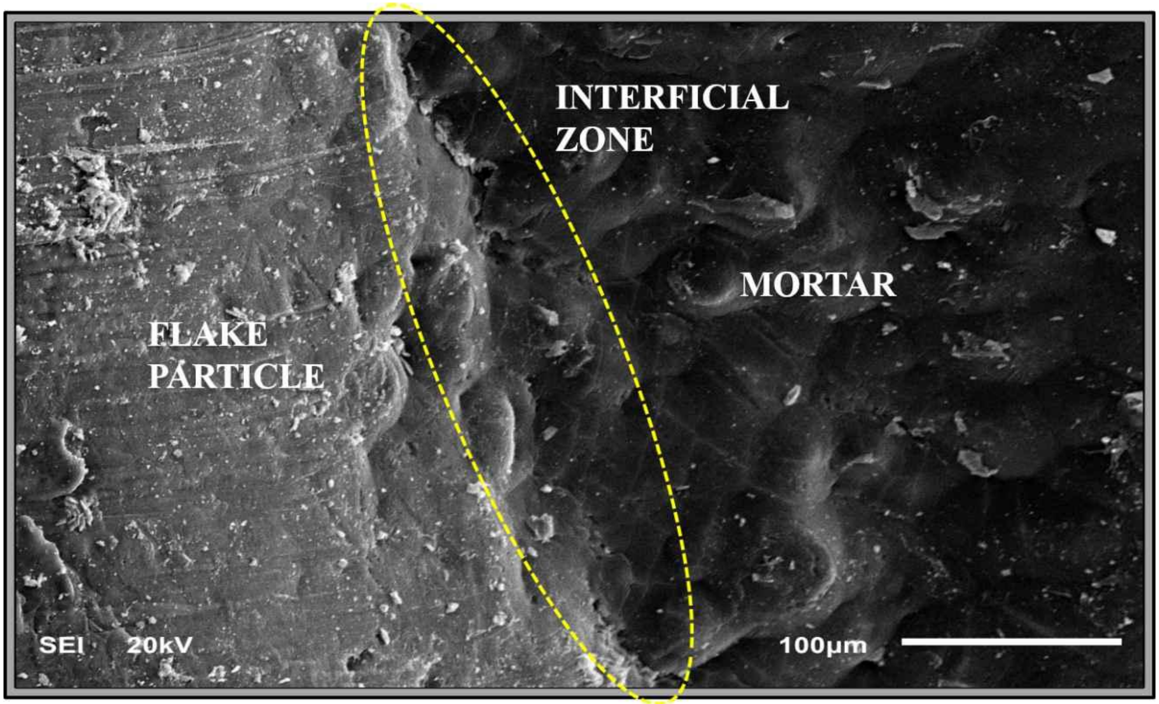


Figure 77: SEM image of concrete with flake type plastic

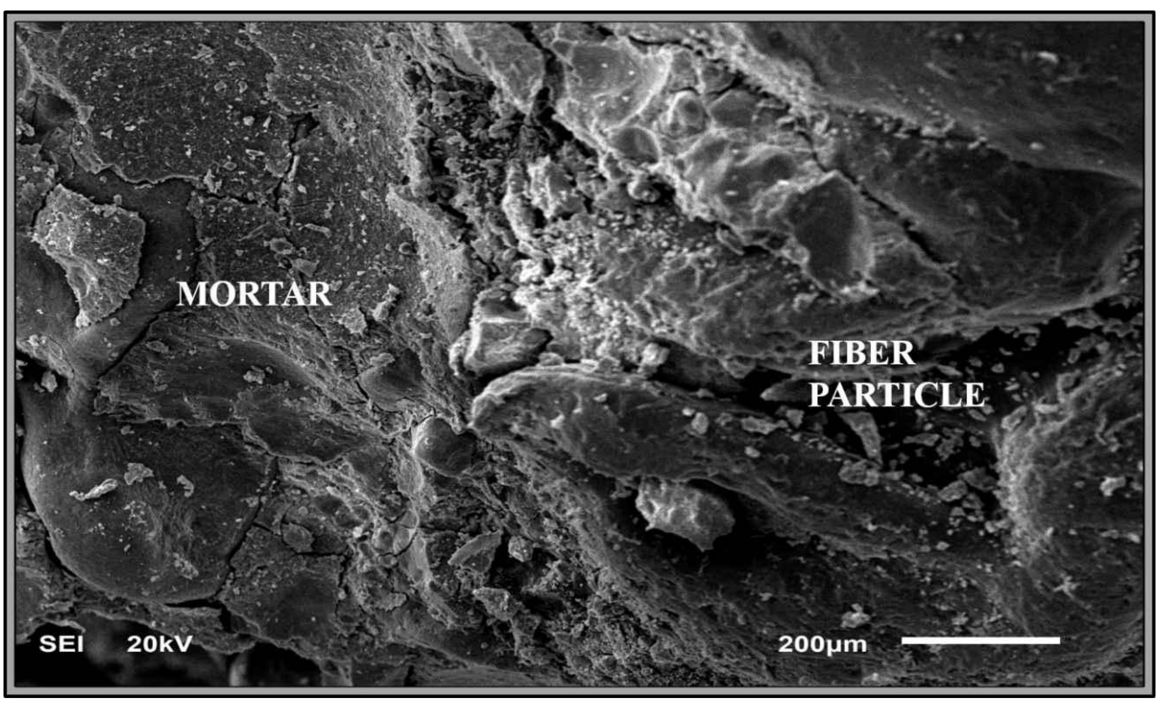


Figure 78: SEM image of concrete with fiber type plastic.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Several trial mixtures were prepared to optimize the various constituents of recycled plastic aggregate. Initially, trials were carried out to determine the optimum fine aggregate to coarse aggregate ratio. It was found that the coarse aggregate to total aggregate ratio of 0.4 was required for a maximum coarse aggregate of 3/8-in. Then the coarse aggregates were replaced with various quantities of different recycled plastic waste aggregates. Four mix compositions differing in cement content and water to cementitious material ratio were prepared for each type and quantity of plastic aggregates. Glenium admixture was used to obtain good workability at low w/c ratio. It was found that an optimum admixture dosage of 1.6% by weight of the cementitious material provided a workable mix. Finally, based on the workability, unit weight and strength criteria certain mixes with different amount of plastic contents were selected for the detail study of the behavior of plastic content in various properties of concrete.

Eighteen mixes with two different mix compositions (cement content:350 kg/m^3- w/c: 0.45, cement content: 370 kg/m^3- w/c: 0.4), four different plastic replacements (25%, 50%, 75% and 100%) with three different types (Granules, Flakes and Fibers) of recycled plastic waste were considered for the detail study. All the concrete properties were studied at 28 days curing period.

Compressive strength, flexural strength, modulus of elasticity, bond strength, unit weight, thermal conductivity, water absorption, rapid chloride permeability, corrosion potentials, drying shrinkage, effect of heat/cool exposure and wet/dry exposures were determined on concrete specimens prepared with the selected recycled plastic aggregate.

As the recycled plastic aggregates are lighter than the conventional aggregates, its incorporation in concrete decreased the unit weight of the concrete with an increase in the plastic content. The cement content and w/c ratio played a minor role in altering the unit weight of the developed concrete. Comparing the three plastic types, almost all had a similar reduction in unit weight at 25%, 50%, 75% and 100% replacement. The type of plastic did not influence the unit weight, it was the percentage replacement which decreased the density of concrete.

The compressive strength varied with the cement content, w/c ratio and even with the type of plastic aggregates used. Concrete with a cement content of 370 kg/m^3 with w/c of 0.4 exhibited better compressive strength than concrete with other composition. Among the plastic types, granules showed a good compressive strength followed by flakes and fibers. The mixture with granules was quite better when compared to other types with respect to workability, filling ability and compaction. The compressive strength decreased with an increase in the plastic content.

The flexural strength of concrete with 25% plastic was better than concrete without plastic. However, as the plastic content was increased the flexural strength decreased. Further, among the different types of plastic aggregates used, flakes exhibited better flexure strength than granules and fibers. Flakes due to their shape, have more load transfer ability at the interfacial zone than the other types, hence the flexural strength of these types of plastic was enhanced to some extent.

The modulus of elasticity decreased as the plastic content increased. The decrease in the compressive strength and low modulus of elasticity of the plastic aggregate itself contributed to the low modulus of elasticity of the concrete prepared with the selected recycled plastic aggregate.

The bond strength decreased as the plastic content was increased. The low bond strength between the plastic aggregate and the concrete matrix decreased the bond strength of concrete with recycled plastic aggregates.

The thermal conductivity of the concrete with plastic aggregates decreased with an increase in the plastic content, thus the developed concrete can be used as a thermal insulation material.

The water absorption of concrete increased with an increase in the quantity of plastic aggregates. However, the water absorption was within the maximum limit of 6%.

The rapid chloride permeability of the concrete with recycled plastic aggregates was less than that of the conventional concrete and it was within the moderate limit. The poor electrical conductivity of the plastic particles incorporated within the concrete decreased the chloride permeability.

The corrosion potentials did not indicate any initiation of corrosion in the specimens with 370 kg/m^3 cement content and 0.4 w/c ratio, while the time to initiation of corrosion increased as the plastic content was increased in the specimens with 350 kg/m^3 cement content and 0.45 w/c ratio.

The drying shrinkage of the recycled plastic concrete was well below the threshold value of 500 microns at 7 days.

There was no loss in strength with heat/cool and wet/dry exposure cycles at a period of three months.

The SEM images clearly showed that the interfacial zone was better in granules compared to other plastic types. This would be the reason for its good strength, whereas the fibers had a poor interfacial bond which lead to a reduction in the mechanical properties.

The workability and filling ability of the concrete with recycled plastic aggregates decreased with an increase in the plastic content. However, the full replacement of about 100% was possible with granules only.

5.2 RECOMMENDATIONS

Based on the data developed in this study, following are the classifications of lightweight concrete

Mixtures			Low strength LW concrete	Normal strength LW concrete	Medium strength LW concrete
Granules	25%	370 / 0.4			✓
		350 / 0.45			✓
	50%	370 / 0.4			✓
		350 / 0.45		✓	
	75%	370 / 0.4		✓	
		350 / 0.45		✓	
	100%	370 / 0.4	✓		
		350 / 0.45	✓		
Flakes	25%	370 / 0.4			✓
		350 / 0.45		✓	
	50%	370 / 0.4		✓	
		350 / 0.45		✓	
	75%	370 / 0.4	✓		
		350 / 0.45	✓		
Fibers	25%	370 / 0.4		✓	
		350 / 0.45		✓	
	50%	370 / 0.4	✓		
		350 / 0.45	✓		

5.3 FUTURE STUDY

- To evaluate the possibility of chemical treatment of the plastic aggregates to improve the mechanical properties of the concrete.

- More research is needed to improve the workability and filling ability of the concrete with recycled plastic aggregates.

- The effect of supplementary cementing materials, such as fly ash, silica fume and natural pozzolan, on mechanical properties of recycled plastic aggregate concrete should be studied.

- The possibility of using powdered recycled plastics as a replacement of fine aggregates should be investigated.

- Various other properties need to be studied, such as the fire resistance of the plastic concrete.

- The behavior of the composite material should be studied with some Finite Element Modelling.

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Vitae

Name	: SHAIK INAYATH BASHA
Nationality	: INDIAN
Date of Birth	: 7/7/1992
Email	: g201407800@kfupm.edu.sa, shaikinayathbasha870@gmail.com
Address	: H.NO: 32 / 476, BADI BEED STREET, I-TOWN POLICE STATION, KURNOOL TOWN, KURNOOL DISTRICT, ANDHRA PRADESH, INDIA
Academic Background	: CIVIL ENGINEERING

Publications	: Effect of recycled plastic aggregates on mechanical properties of concrete (To be submitted).
	Effect of recycled plastic aggregates on durability properties of concrete (To be submitted)