EFFECT OF PARTIAL REPLACEMENT OF CEMENT BY FLY ASH AND SILICA FUME ON STRENGTH CHARACTERISTICS OF RECYCLED COARSE AGGREGATE CONCRETE

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DECLARATION

I hereby declare that the work which is presented in this thesis report entitled **"EFFECT OF PARTIAL REPLACEMENT OF CEMENT BY FLY ASH AND SILICA FUME ON STRENGTH CHARACTERISTICS OF RECYCLED COARSE AGGREGATE CONCRETE"** in partial fulfillment of requirements for the award of the **Masters Degree** in **Structures**, submitted in the **Civil Engineering Department, Thapar University, Patiala,** is an authentic record of the initial work carried out by him under the supervision of **Dr. Shruti Sharma, Associate Prof., Civil Engineering Department, Thapar University, Patiala.**

The matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any degree.

Dated: 15-07-16

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CERTIFICATE

This is to certify that above statement made by the student concerned is correct and true to the best of my knowledge and belief.

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ABSTRACT

Construction activity leads to generation of wastes, which include sand, gravel, concrete, stone, bricks, wood, metal, glass, plastic, paper etc. The management of construction and demolition waste is a major concern due to the increasing quantum of demolition's rubble, continuing shortage of dumping sites, increase in transportation and disposal cost and above all growing concern about pollution and environmental deterioration.

To make the concrete industry more sustainable and environment friendly, researchers are working continuously and they came up with the idea of green concrete (recycled concrete). But in practice, recycled aggregate is not commonly used in the production of cocnrete. one of the reasons is that Portland cement concrete is produced to form structural elements which have to meet strict strength and durability requirements. Extensive research is required to verify the properties of the recycled aggregate concrete before It can be confidently be adopted by the concrete industry.

The aim of the thesis is to provide a base for extensive scientific study for the possible use of recycled aggregates in structural concrete by conducting comprehensive laboratory studies to gain a better understanding of the mechanical, durability and workability properties of cocnrete produced with the recycled aggregates.

The characterstics of the recycled aggregates produced from the laboratory and sourced from a commercially operated pilot C&D material recycling plant was first studied. A mix proportioning was then established to produce a concrete mix of M30 garde with 0.45 water cement ratio. Then a trial study was run by replacing natural coarse aggregate by recycled coarse aggregate at replacement level of 50% and 100%.

The fresh and hardened properties of recycled coarse aggregate were first quantified. The influences of recycled aggregate on the slump and compressive strength were investigated. The results confirmed that the use of recycled coarse aggregates contributed to low slump values and very low degree of compressive strength.

In order to overecome problems during simple replacement of natural coarse aggregate by recycled coarse aggregate, some part of cement was replaced by supplementary materials. Two supplementary materials, i.e. fly ash and silica fume were slelected for the study. The

replacement level of cement by fly ash was selelected at 20%, 35% and 55% while that of silica fume was selected at 5%, 10% and 15% by weight of cement.

The hardened concrete properties were firstly quantified. The influence of recycled aggregate along with the fly ash and silica fume on the compressive strength (3 days, 7 days and 28 days), split tensile strength and flexural strength (both at 28 days) were studied. The test results confirmed that the the use of supplementary materials increased the strength of the concrete. From all the mixes, fly ash and silica fume with replacement level at 35% and 15% respectivelly showed optimum results even with recycle coarse aggaregate upto 50% and 100% replacement level. So these optimum mixes were selected for furthur testing.

The freshconcrete properties were quantified by conducting tests for air content and bleeding test for optimum mix design. The test reults showed that by increasing the content of recycled coarse aggregate resulted in increased air content. When fly ash and silica fume is added the air content decreases. In case of bleeding test same behaviour was experienced. With increase in the content of recycled coarse aggregate, the bleeding rate was increased. But when fly ash and silica fume were added, it resulted in decreased bleeding rate. When bleeding test was started after some time of mixing, it resulted in decreased bleeding rate.

Furthurmore, the testing for durability properies were carried out for optimum level of concrete mix. The tests conducted were rapid chloride permeability, carbonation test and water peneteration test. In all the tests, concrete showed decreased level of resistance with an increase in level of recycled coarse aggregate. When fly ash and silica fume is added, the resistance was increased marginally.

One non destructive test was also performed by using ultrasonic guided waves. It was also clear from the test that with substitution of recyled aggregatre along with silica fume and fly ash resulted in more fast setting time period than that of control sample.

Based upon the test results a number of recommendations were made on how to optimize the use of recycled corase aggregates for structural concrete production.

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CHAPTER 1

INTRODUCTION

1.1 General

With the increase in construction activity, there also immense increase in the amount of waste generation, which includes solid waste like concrete rubble, glass, different stones, bricks, wood, metal, etc. With increase in demolition waste, its proper management becomes a huge concern. The ever going problems like shortage of dumping site for the demolished concrete, environmental deterioration caused by pollution generated from concrete waste, transportation costs poses a challenge for proper management of the concrete waste.

The fast rate of the depletion of natural resources and unsuitable disposal of construction waste adds to the pressure of alternate use of the concrete waste. This all leads to the idea of recycling of the construction waste. Recycling of concrete waste is the optimum management technique

According to a 2010 'Report of the Committee to Evolve Road Map on Management of Wastes in India' by the Ministry of Environment and Forests, it is estimated that the construction industry in India generates 10-12 million tonnes of waste annually. Moreover, about 50 percent of the Construction and Demolition Waste (C&D) is not currently recycled in India.

Concrete ,due to its durable and long lasting properties, is the most favourable material for concrete industry. Due to its popularity in contsruction purpose, its contribution in economic growth and environmental protection is often ingnored. The concrete is mostly economical, durable and felxible in design. Therefore, concrete structures are prefered oner steel structures.

Since concrete is the most popular construction material across the world, there lies a greater potential for its recycling in the construction process. In recycling process, concrete waste can be reprocessed as aggregate either in coarse or finer form. This opens a whole new range of possibilities in the reuse of waste materials in the construction industry. The recycling process of concrete rubble is a good solution to the problem posed by concrete waste unless the final desired concrete fall under the standard parameter. The role of recycled concrete as a structural fill material instead of natural aggregates is becoming more popular day by day.

With every passing year, researchers have focussed their concern on the use of by-products to enhance the properties of concrete. The by- product include materials like fly ash, silica fume, ground granulated blast furnace slag, etc., in concrete manufacturing and civil applications. The potential use of these by-products in concrete may be in the form of partial aggregate replacement or as partial cement replacement, depending on their chemical composition and grain size.

To make the concrete industry more sustainable and environment friendly, researchers are working continuously and they came up with the idea of green concrete (recycled concrete).

Green concrete or recycled concrete is a sustainable type of concrete resulting from aggregate replacements such as RAC, rubber tire, ceramic waste, tile, glass aggregate etc. It could also be a result of portland cement replacements such as fly ash, silica fume and slag or it could result from waste material admixtures such as waste latex paint. As a result, RAC has less environmental impact in terms of energy consumption and emission during its manufacturing process (Hameed, 2009) and can reduce the cost associated with concrete production.

1.2 Natural Aggregate (NA) and Recycled Concrete Aggregate (RCA)

Natural Aggregate (NA): Natural aggregate are derived from rocks and minerals. A mineral is a naturally occurring substance with a solid compact internal structure and composed of chemical composition which varies within narrow limits. Rocks are also solid structure which can be classified into many categories mainly depending upon the origin, i.e. igneous, sedimentary, or metamorphic. Various minerals are mostly present in the rocks.

For example, granite is a rock which is composed of quartz, feldspar, mica. Rocks are subjected to different phenomenon like weathering and erosion of rocks, which results in the disintegration of rocks resulting in smaller particles like stone, gravel, sand, silt, and clay. Many of these particles can be used as aggregates for concrete. NA used for this study is shown in Figure 1.1.

Figure 1.1: Natural Aggregate

(Source: Concrete Lab, Thapar University, Patiala)

Recycled Concrete Aggregate (RCA): Recycled concrete aggregate are the aggregates which are produced from the reprocessing of construction waste rubble. It is a durable and economical source of aggregates which is quite feasible, especially where good aggregates are scarce. For example, recycled coarse aggregate from concrete debris and reprocessed aggregate from asphalt pavement.

Recycled coarse aggregate is produced by squashing clean demolished concrete waste which may be up to a range of at least 95% by weight of concrete. Many other materials may be present in recycled coarse aggregate like gravel, crushed stone and hydraulic-cement concrete. Special types of stone crushing equipment are required which have a lower noise and dust nuisance. RCA used for this study is shown in Figure 1.2.

Figure 1.2: Recycled Concrete Aggregate (RCA)

(Source: Sidhu Crushing Plant, Bhuccho Mandi, Bathinda)

1.3 Advantages and Disadvantages of RCA Concrete

The following are the advantages of recycled coarse aggregate:

- RCA provides feasibility.
- Recycled coarse aggregate reduces the amount of waste material to be used in landfill.
- The transportation cost also reduces as RCA is lighter than natural aggregates.
- RCA reduces the load on consumption of natural aggregates.
- The energy required for the production of RCA is very less as compared to the energy required for the production of Portland cement.
- The production of RCA creates more job opportunities as more skilled persons and drivers are required.
- It trims the amount of CO_2 in the atmosphere as it absorbs large amount of carbon dioxide while being crushed into smaller sizes.
- Recycling requires limited monitoring and reclamation.
- Costs for exploration, mining, or stripping are not incurred as in case of natural aggregates.

The following are disadvantages of RCA

- Recycling plant makes loud noise which can be quite irritating.
- RCA results in water pollution as large amount of water is required for its production.
- The amount of adhered mortar content greatly affects the mix design and the properties of the concrete.
- Lack of Specification and Guidelines.
- Additional huge cost for the land reclamation, site cleanup, and dust and noise reduction may have to be incurred.
- The quality and amount of impurities causes a significant variation in the quality of concrete.
- Unsurity regarding the origin from of recycled aggregate
-

1.4 Types of Recycled Aggregates

The types of recycled aggregates have been broadly classified according to their sources. They are:

a) **Industrial waste aggregates:** These include plastic waste, e-plastic waste, rubber tire waste, mining waste, industrial slag, organic waste, glass, ceramic waste. etc**.**
b) **Construction and demolition waste aggregates:** These include aggregates obtained from existing concrete forms such as building or other structures. These kinds of wastes are obtained from old structures made of reinforced or plain concrete. Concrete used as aggregate from sources such as these have the potential to tremendously reduce the carbon footprint of the construction industry.

1.5 Recycling Business

The recycling process of RCA is somewhat similar to the crushing processes of naturally occurring aggregate. The first basic step involved is breaking of concrete rubble. After this next step involved is removing and crushing of dumped concrete rubble so that it forms into required size and quality such that it meets the requirements for concrete. It is necessary to sort out of different types of waste materials from the crushed concrete to make sure that the good quality materials go to the crusher. The recycled material must be cleaned properly to produce good quality of concrete.

1.6 Sources of Recycled Concrete Aggregate

The basic source for generation of the recycled material to be used for the production of construction aggregates are: (1) road construction and maintenance debris, and (2) structural construction and demolition debris (for example, from demolished buildings, bridges, and airport runways).The amounts of concrete waste generated from these sites are in large amount which apt for recycling batching plant**.**

1.7 Recycling Plant

Recycling plants are favourably situated on the fringe of the hamlet of cities because of noise and air pollution produced during the recycling process. Mostly the machines, which are used in recycling process, are dressed with effective silencers and chimneys to reduce the noise during the recycling activities.

1.8 Transportation

After the completion of demolition process of different concrete forms like buildings and concrete pavements, the demolished waste is sent to the recycling plants for further processing. For the transportation purposes, the most convenient way is transporting it by roll-off containers or large dump truck. Closed box-trailers and covered containers can also be used to transport construction materials.

1.9 Crushing Plant

After transporting the concrete waste, the crushing of the C&D waste for the production of recycled aggregate takes place. The crushing equipment used in this process is jaw crushers or either impacted mill crushers. A special protection for conveyor belts is provided in all the crushers so that any presence of metal impurities especially reinforcement steel may cause damage to the belts.

During the crushing of concrete waste, all the by-product materials like reinforcing steel have to be removed. The sorting and cleaning of the recycled aggregate are done by three main methods, which are, electromagnetic separation, dry separation and wet separation. Electromagnetic separation includes the removal of metal impurities like reinforcing steel, by using a magnet that is fixed across the conveyor belt in the primary and secondary crushers. Dry separation is the process in which air is blowed into heavier material to remove lighter particles. A large amount of dust is generated in this process. Wet separation is method in which low density contaminants are removed by water jets and these results in production of very clean aggregate.

1.10 Locating and Aggregate Recycling Facility

To achieve the economy of the recycled aggregate producing facility, the main factor is the distance between the recycling plant, its supplies and the market should be as minimum as possible. The primary source of recyclable concrete is outmoded structure

1.11 Method of Recycling

After putting the construction and demolition waste through a primary crusher, collected from different sources, the appropriate sizes of the waste is obtained for final crushing. During crushing of demolished waste, the debris should be free from harmful impurities. The tarrying aggregate which are to be recycled are assorted by size.

If large sizes of aggregate still exist, it again undergoes the crushing process all over again till suitable size is not obtained. For reduction of construction cost and the pollution produced while transporting the material from the site, a mobile crusher can be used.

A huge mobile plant can have a crushing capacity up to 600 tons per hour. The main part of the crushing plant consist of an aggregate crusher, a screening plant and a return conveyor belt from the screening plant to the crusher inlet for reprocessing oversize materials to their final size. Another type of crushers, which are available in the market, is called compact, self-contained mini-crushers. These crushers have a production capacity up to 150 tons per hour and they can be used in any given small space.

There are still no particular methods of recycling concrete waste as it may vary from region to region. The individuality of recycled aggregate depends mostly on the way it is reprocessed. Japan has lately developed a technique called ‘heating and rubbing method’ which produces a relatively high quality recycled aggregate. Using this technology, aggregate is reprocessed as a basic material for ready mixed concrete, while fine powder (HRM powder) from cement paste can be recycled as raw material for cement, cement admixture, or soil stabilizer (Hirokazu, et al. 2005) . A detail of this system is shown in Figure 1.3.

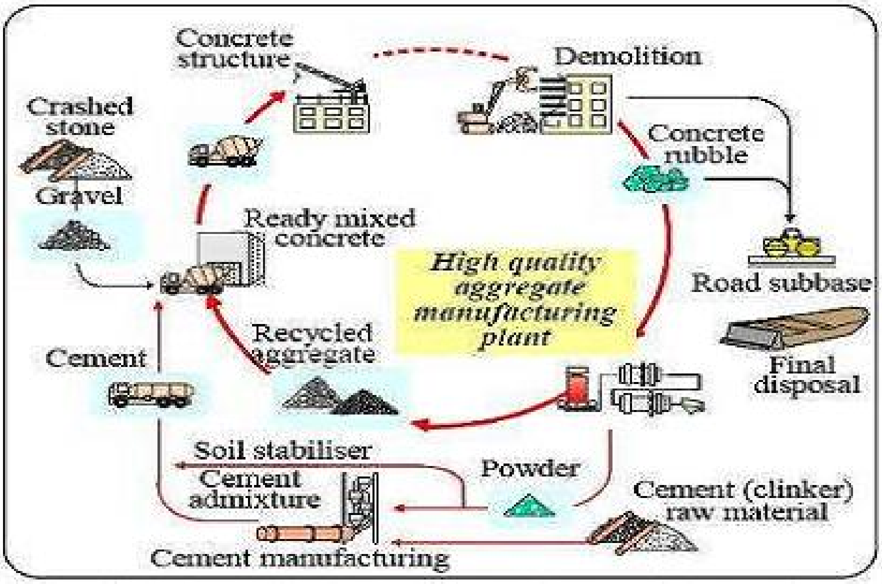

Figure 1.3: Schematic flow of concrete recycling system (Source: Hirokazu et al., 2005)

1.12 Equipment Required For Preparation of RCA

Crushing: The main process is the crushing of the concrete debris into smaller pieces and the equipment involved is either a jaw or an impacted mill crusher. Firstly, the concrete debris is disintegrated to a size about 75 mm by using the primary jaw crusher. During the second stage of crushing, the secondary cone crusher breaks the material between the maximum size which varies between 19mm and 75 mm. Figure 2.4 shows typical mobile crusher for demolition concrete debris

Screening: Screening is the process in which a series of sieves are used that separates the various sizes of RCA. A screening plant involves a series of large sieves to separate the material into the sizes required. The general mesh size of the screen that separates the coarse recycled concrete aggregate and fine recycled aggregate used is normally 4.75 mm. The mesh sizes of the screen are used to separate the coarse recycled aggregate in any required standard size. To separate those particles that are larger than the specified size, one more screen is used.

Figure 1.4: Mobile crusher used for producing RCA

(Source: Sidhu Crushing Plant, Bhuccho Mandi, Bathinda)

1.13 Objectives of the Study

This research is conducted to achieve the following objectives:

- To find out the optimum content of Recycled Coarse Aggregates that can be feasibly used in normal construction practice
- To develop a technique for utilising higher percentage recycled aggregate in concrete by replacing cement by fly ash and silica fume to produce recycled aggregate concete.
- Compare the fresh and hardened properties of modified Recycled Aggregate Concrete (RAC) made with different recycled coarse aggregate (RCA) replacement levels with those of natural aggregate concrete (NAC) using various tests.
- Evaluate the strength and durability performance of modified RAC made with different RCA replacement levels and Fly ash and silica fume as replacement of cement.

1.14 Methodology

- Material testing of cement, fine aggregates, natural coarse aggregates and recycled coarse aggregates
- Mix design prepared as per IS 10262-2009. Different replacement levels of recycled coarse aggregate, fly ash and silica fume.
- Testing of fresh concrete, hardened concrete and durability properties of hardened concrete.

1.15 Thesis Outline

This thesis has been organized into six chapters.

CHAPTER-1 is aimed at providing an overview of recycled concrete. It alsso briefly and generally introduces the reader to the topic of the thesis. This chapter also serves to state the research objectives, the methodology to be followed and sets the stage for overall research presented in the report.

CHAPTER-2 providesa detailed literature review on recycled aggregate concrete.This chapter also covers the properties of recycled aggregate and the fresh, hardened, and durability properties of RAC available in literature.

An effort has been made to briefly describe the maximum possible literature on the use of RCA and mineral admixtures in concrete and their contributions to the composite materials in terms of compressive strength, tensile strength, flexural strength and RCPT (durabilityassessment)

CHAPTER-3 describes the experimental set-up and procedure to test the recycled aggregate concrete at different replacement levels.

It describes thematerial characteristics(physical/chemical),mixture proportions, specimen size, test methods and associated instruments used for experimental investigations.

CHAPTER-4 deals with the presentation,analysis and discussionof different results obtained from the experiments stated in the earlier chapter.

CHAPTER-5 presents the conclusions derived from this study, discusses the limitationsofthis study and provides recommendations for future research directions.

CHAPTER 2

LITERATURE REVIEW

With the increase in world population, there is ever growing need for facilities for various purposes (industry, housing projects, dams, etc.), which in turn puts considerable pressure on the natural resources. For this reason, many industries are looking for alternate ways by re-using materials in manufacture of new products. Construction industry, in this worldwide effort, is no exception. Concrete rubble has the largest proportion in the construction and demolition (C&D) waste. Studies carried out have shown that concrete rubble used in the form of coarse aggregate can be sufficiently used as a partial replacement for natural aggregate (Mehta et al., 1993).

The literature review throws some light on the current scenario of successful uses of recycled aggregate materials in concrete technology and in particular the use of recycled aggregate as a coarse aggregate fraction in non-structural and structural concrete.

2.1 Recycled Aggregates and Properties

Recycled aggregates are the aggregates produced from the reclaiming of waste materials which are generated from major proportion of Construction and Demolition (C&D) waste. Construction and Demolition (C&D) waste mostly comprises of concrete rubble, bricks and tiles, sand and dust, timber, plastics, cardboard and paper, and metals.

It has been demonstrated in chapter 1 that clean crushed concrete rubble is produced after separating it from other C&D waste and by sieving it through proper meshes. This rubble produced can be used as an alternate for natural coarse aggregates in concrete. (Hansen, 1992 and Mehta et al., 1993)

In general, it is seen that the crushed concrete particles are more angular with a rough surface texture as compared with that of natural aggregate. Due to the above factors, the water required is more than the conventional concrete to produce the required workability.

Properties of Recycled Aggregate

Aggregates constitute a major portion of concrete volume which in turn significantly affects the properties of concrete. As the origin of the recycled aggregate is not known, it is often very difficult to get clear and relevant idea about its quality. The idea of application of recycled aggregate to produce new concrete is not only intriguing but also challenging. The major challenge in recycled concrete aggregate is that it may possess many impurities along with the adhered mortar paste owing to the variation in sources from which it is produced. Due to the earlier mentioned reasons, it becomes extremely difficult to predict the properties of new concrete (Smith 2009).

Table 2.1 represents the permissible maximum limit of different harmful ingredients that can present in recycled aggregate.

Table 2.1 Allowable maximum limits of different harmful ingredients (Source: Oikonomou, 2005)

Substance	Arsenic As	Lead Pb	Cadmium Cd	Chromium Cr	Coppor Cu	Nickel Ni	Iodine I	Zinc Zn
Limit (µg/l)	50	100	5	100	200	100	2	400

2.1.1 Gradation, Shape and Texture

The properties of RAC are prominently influenced by the shape, gradation and texture of the recycled aggregate used. Due to the fact that recycled aggregates can be obtained from different sources, their shape and textures are likely to vary over a wide range.

It has been found that recycled aggregate possesses hundred percent crushed faces as aggregates are produced from primary and secondary crushing (Salem et al., 2003). It was also observed that the gradation and attached mortar content of recycled aggregates are not affected by the crushing strength and the age of parent concrete (Katz, 2003). The size of recycled aggregate is dropped down to 50mm by primary crushing process and all types of metal impurities are removed by using electromagnets while transferring from primary to secondary crusher (Corinaldesi et al, 2002) Then particle size is reduced to

14-20 mm during secondary crushing process. The adherent mortar contains of fine and coarse aggregate are 25% and 6.5%, respectively (Katz, 2003).

2.1.2 Density

Since the mortar that is adhered to the original aggregate, the saturated surface density of recycled aggregates is lower than that of natural aggregates because the density of the mortar is low. It also depends on the size of aggregate and the strength of original concrete.

It was seen in study that the density of recycled coarse aggregate was less than natural coarse aggregate due to attached cement mortar mix (Cakır, 2015).

It has been observed that if the quantity of mortar is same, a recycled aggregate will have a higher density value if it has been obtained from a higher strength (Nagataki, 2002).

The aggregates which have a large amount of adhered mortar will have a lower density. If the same amount of grinding energy is used for recycled aggregate with same grinding machine, there will be change in the density with the size of the aggregate (Hansen, 1985).

2.1.3 Water absorption

The main difference between the recycled and natural aggregate is the water absorption capacity of the recycled aggregate in the mixture. It supposedly depends on size of the aggregate, quantity of adhered mortar and density.

The average water absorption of the recycled coarse aggregate in study was 7.4% whereas for same size natural coarse aggregate the water absorption value was 2.2% (Cakır, 2015).

The water absorption capacity is very high if the size of recycled aggregates is small. A high degree of adhered mortar also increases the absorption capacity of recycled aggregate. There is also decrease in the density of the recycled aggregate if the amount of adhered mortar is very high (Poon et al, 2002).

In a study, it was observed that the absorption capacity in case of natural coarse aggregate which is around 0.3%, which is quite low as compared with recycled aggregate which had an absorption capacity of 3.2% to 12% range for fine and coarse recycled aggregates respectively. (Katz 2003).

The absorption capacity of recycled fine aggregate is higher than that of recycled coarse aggregate (Katz 2003, Salem et al. 2003, Gomez-Soberon 2002, Rao 2005).

It is mostly observed that recycled aggregates have an adhered mortar layer which results in low density and high water absorption capacity. Many researchers have tried to find a correlation between density and absorption capacity. In a study involving test of11 samples, it was concluded that the concrete can be produced with the maximum content of 20% recycled aggregates due to the reason that the recycled aggregates have high absorption capacity (Sanchez et al, 2002).

The relationship between absorption and amount of adhered mortar was shown using various samples. It was observed that the average value of water absorption capacity in recycled aggregate was 6.35% whereas in natural aggregate it was 0.90% (Ravindrarajah et al, 2000).

2.1.4 Strength of recycled aggregate

In study involving los angeles abrasion test, the values of natural coarse aggregate for size 4-12 mm and 8- 22 mm was 20 percent for both fractions, whereas for recycled coarse aggregate for fraction size of 4- 12 mm and 8- 22 mm was 30 and 35 percent respectively (Cakır, 2015).

In another study, For a size fraction of 5-13 mm, the corresponding Los Angeles Abrasion Loss Percentage value was 20.1 (Yoshikane, 2000).

As per the Los Angeles Abrasion Test results, the recycled aggregates obtained by grinding a 40 MPa strength concrete have lower abrasion than aggregates obtained by 16 Mpa strength concrete. In a study, the size fraction value of 4-8 mm had Los Angeles Abrasion Loss Percentage as 30.1; the size fraction value of 8-16 mm had Los Angeles Abrasion Loss Percentage as 26.7 and the size fraction value of 16-32 mm had Los Angeles Abrasion Loss Percentage as 22.4 (Hansen and Narud, 1983).

2.1.5 Specific Gravity

It was also observed that the natural aggregate has a specific gravity of around 2.7. On the other hand, the recycled aggregate's specific gravity is less than natural aggregate. The reason for the above observation is attributed to the reason that the presence of attached mortar on the surface of recycled aggregate reduces the specific gravity of recycled aggregate (Salem et al.,2003) and Katz, 2003).

Specific gravity of recycled fine aggregate is from 2 to 2.3 and its value increases with the increased size of RCA and it varies from 2.2 to 2.6 while in saturated surface dry conditions (ACPA 1993, Katz 2003).

Specific gravity of different type of aggregates is shown in Table 2.2.

Table 2.2: Specific gravity of aggregates given by different researchers

	Specific gravity	**Reference**
Natural coarse aggregate	2.11	Alam et al., 2013
Natural coarse aggregate	2.65	Nassar and Soroushian, 2012
Natural coarse aggregate	2.67	Salem et al., 2003
Natural coarse aggregate (lime stone)	2.71	Fathifazl et al., 2009
Natural coarse aggregate (river gravel)	2.74	Fathifazl et al., 2009
Natural coarse aggregate	2.7	Katz 2003
Recycled coarse aggregate	2.59	Katz 2003
Recycled coarse aggregate	2.4	Nassar and Soroushian, 2012
Recycled coarse aggregate	2.4	Salem et al., 2003
Recycled coarse aggregate	2.5	Fathifazl et al., 2009
Recycled coarse aggregate	2.42	Fathifazl et al., 2009
Recycled coarse aggregate	2.03	Alam et al., 2013
Recycled coarse aggregate	2.2	Oikonomou, 2005
Natural fine aggregate	2.65	Nassar and Soroushian, 2012
Natural fine aggregate	2.54	Leite et al., 2013
Natural fine aggregate	2.72	Fathifazl et al., 2009
Recycled fine aggregate	2.45	Leite et al., 2013
Recycled fine aggregate	2.23	Katz 2003

2.2 Recycled Aggregate Concrete (RAC)

Recycled aggregate concrete (RAC) is a construction material which is produced by re-processing of old concrete and used as an aggregate replacement in new concrete. On the other hand, as this concrete gets older and need to be demolished, it will regenerate further concrete waste, which has the potential for similar reuse. Its use in construction industry helps minimize two major environmental problems:

- It reduces environment pollution and
- It helps in preserving limited natural resources.

However, before any large industrial application, the strength and durability properties of RAC must be properly investigated since the prominent characteristics of recycled aggregates differ from the natural aggregates. The differences in mechanical properties of recycled aggregate significantly influence the quality of RAC, and considered as one of the major barriers related to the field application of RAC. The influence of repeated recycled aggregate cannot be fully understood without proper investigation as the aggregate properties might vary significantly with the number of repetitions. In order to provide a sustainable construction material a suitable balance is essential between the quality and cost of RAC.

Recycled concrete aggregate (RCA) generally involves the reproduction of concrete rubble which includes various processes like the crushing of concrete rubble, screening, then removal of contaminants such as reinforcement, paper, wood, plastics and gypsum. Concrete made with such recycled concrete aggregate is called recycled aggregate concrete (RAC) (Wagih et al. 2013).

The source of original concrete, from which the recycled aggregates are derived, is generally not known. Therefore, the variations of the chemical and physical properties are not well defined. Due to this reason the application of the recycled aggregate has been limited. However, it is generally concluded that the properties of recycled aggregate is lower as compared with that of natural aggregate concrete and the decrease in the properties is proportional to the replacement level of natural aggregate by recycled aggregate (Butler et al. 2013).

2.2.1 Fresh Properties of RAC

Workability

It has been proved that the recycled aggregate produced from the commercial processes are smoother and spherical than those produced in the laboratory. Due to the better shape and texture of commercially produced recycled aggregates, they result in better workability as compared to that of commercially produced aggregate (SagoeCrential et al., 2001).

Since the water absorption of the recycled aggregates is quite high due to adhered mortar, the concrete mixes prepared from recycled aggregate is more stiffer and less workable as compared to natural aggregate concrete (Salem et al. 2003).

It was also observed that increasing the amount of the coarse recycled concrete aggregates (RCA) in the Portland Cement (PC) mixes resulted in quite a significant increase of the slump value. This could be explained by the moisture provided by the RCA added to the mix as these aggregates are more porous and have a higher water absorption capacity compared to the natural coarse aggregate (NA). This initial moisture of the coarse RCA has contributed in the improvement of the initial values of the slump for the mixes made with the RCA compared to the mixes made with the NA (Limbachiya et al., 2011).

It was also concluded that due to the rougher surfaces and to the more irregular shapes of the recycled concrete aggregates with respect to the normal ones, the replacement of NAs with RCAs has caused a significant reduction in workability (Lima et al., 2013).

It has also been observed that RAC requires 5-10% extra free water to achieve the same workability than that of NAC though it is significantly influenced by the quality of recycled aggregate (Hasan 1992, Leite et al. 2013).

Slump

Slump value represents the consistency and workability of fresh concrete. At a fixed water cement (w/c) ratio, the workability decreases with the increased amount of recycled aggregate replacement which consequently decreases the slump value of RAC (Topcu and Sengel, 2004). The loss of slump is higher in case of over dry recycled aggregate with similar w/c ratio.

In terms of the fresh concrete properties such as slump, it was found that as the percentage (%) of recycled aggregate increased in the concrete, the concrete slump slightly decreased. However, since the reduction in slump was very small, it can be offset with the use of admixtures (Yang et al., 2008).

After adjusting the required amount of water content of air dry RCA as per its actual moisture state, the slump value was 100 mm for RAC made with 50% RCA where it was 110-100mm for NAC (Poon et al, 2004).

On grading the aggregates from different sources like decommissioned sidewalks, terminal structure and rejected ready mix concrete, negligible difference in slump values between NA and RCA has been observed with all slump values meeting the required specific range (Butler et al., 2013).

The RCA when pre-soaked in acid of different morality and on studying the slump values of both treated and untreated RCA, no significant difference in the slump values was observed. It has been reported that angular and rough surface of RCA decreases the slump values as compared to natural aggregates concrete (Ismail and Ramli, 2013).

The slump values showed decrease in value for pre-soaked recycled aggregate than the natural coarse aggregate (Cakır, 2015).

<u>Air content</u>

Salem et al. (2003) obtained that air content of RAC is higher than NAC. This means that RAC contains high amount of entrapped air compared to NAC. Similar observation was found by Katz (2003).

The air content for 0%, 50% and 100% of recycled coarse aggregates was found to be 2.2%, 2.4% and 2.7% indicating that the value of air content increases with increase in recycled coarse aggregate content (Kou, 2011).

In a study, the value of air content increased with increase in content of recycled coarse aggregate. The value of air content for 0%, 20%, 50% and 100% replacement level of natural coarse aggregate were 1.8%, 2.0%, 2.1% and 2.3% respectively (Cakır, 2015).

2.2.2 Properties of Hardened RAC

The property of the concrete in the hardened phase corresponds to the strength and durability properties of concrete. Many factors affect the strength of RAC (Tavakoli and Soroushian, 1996).

The strength of the recycled aggregate concrete is greatly affected by the original/parent concrete which is recycled. The strength of the recycled aggregate concrete is directly dependent upon the replacement level of coarse aggregate by the recycled aggregate.

2.2.2.1 Physical Properties

Permeability

Concrete made with recycled aggregate has higher permeability by 10-45%than that of NAC almost. Mainly the permeability property of RAC depends on aggregate source (Zaharieva et al. 2003,Abou-Zeid et al. 2005).

The water absorption of recycled concrete aggregate is higher than virgin aggregate. During the harden stage of concrete this water evaporates and causes porosity. Extension of curing period can produce fine pore and thus help reducing the permeability of RAC by 50% (Zaharieva et al. 2003)

It was noticed that the test performed on the specimen made of the 100% recycled coarse aggregate concrete mixture had failed, since the water had passed through the specimen from side to side; this probably happened because of a pre-existing micro-crack which had been further enlarged by the action of the water under pressure (Lima et al., 2013).

Porosity of concrete

In a research, the porosity of concrete made with recycled aggregate and investigation of different properties of RAC such as, the threshold ratio, critical pore ratio, average pore ratio, and theoretical pore radius of concrete were examined mainly at the age of 7, 28, and 90 days. These test results indicated that replacing natural aggregates with recycled coarse aggregates yielded an increase in porosity. The tensile and Compressive strengths of RAC are decreased with increased porosity. It was also found that the modulus of elasticity decreases with the increased porosity (Gomez-Soberon, 2002).

It was observed that by the use of coarse RCA as a partial or full replacement of the NA resulted in significant increase of the Initial surface absorption (ISA). The higher the replacement levels of RCA, the more perceptible the increasing effect on ISA (Limbachiya et al., 2011)

It is difficult to find a proper relation between the total porosity and properties of RAC. It can be improved by distributing the pore radius.

Coefficient of thermal expansion

In an experimental study conducted to find the impact of recycled concrete aggregate on the coefficient of thermal expansion (CTE) of RAC, it was concluded that the concrete performance improved with the increasing percentages of recycled aggregate. It was found that CTE values were 7.28×10-6/°C and 4.10×10-6/°C for virgin concrete and 50% RCA, respectively (Smith and Tighe, 2009).

Whereas in another research, results conflicted with findings of Smith and Tighe (2009), stated above. In this other research, it was stated that the RCA concrete has higher CTE value (Yang et al., 2003). They found 8.9×10-6/°C and 11.6×10-6/°C CTE values for cylinder and prism RCA specimens, respectively.

Ultrasonic pulse velocity

NAC ultra sound pulse velocity is around 69-70 µs and this value increases for RAC which is approximately 92-93 µs (Topcu 1997).

It can be seen that the UPV of the natural aggregate concrete was higher than that of the recycled aggregate concrete. The value of UPV was 4450 m/s for control sample, 4390 m/s for 50% recycled coarse aggregate and 4312 m/s for 100% recycled coarse aggregate (Kou et al., 2011).

2.2.2.2 Mechanical Properties

Researchers have been exploring the possibility of using recycled aggregate especially C&D wastes since 1970 and several researchers found that similar/comparable strength can be achieved by concrete made with RCA instead of natural coarse aggregates(Yang et al. 2008, Poon et al. 2004, Etxeberria et al. 2007).

Compressive strength

The compressive strength of RAC is directly influenced by the amount of recycled aggregate replacement ratio and the effective w/c ratio (Ulloa et al. 2013). Degree of variation in terms of the compressive strength is quite high for 100% replacement where it is comparatively low for lower replacement levels such as 20% to 50%.

It was found that almost 15% reduction in compressive strength as compared to control mix for 25% to 50% RCA concrete (Alam et al., 2013). Test results indicated that if all other factors are kept constant then RAC compressive strength is greatly influenced by the w/c ratio of original/parent concrete (Hansen and Narud, 1983). The strength of RAC will be equivalent or better than NAC if its w/c ratio is lower or at least similar to that of original concrete.

In another study, high strength and high performance RAC mechanical behaviours were investigated. 40-70 MPa concrete were used for producing recycled aggregate. They concluded that for producing RAC with similar workability, a modification in water content is required in the mix design (Ajdukiewicz and Kliszczewicz, 2002).

For producing good quality of structural recycled concrete aggregates the attached mortar content should be below 44%. It was found that the compressive strength of recycled concrete made using this quality recycled concrete aggregates are generally not lower than 25MPa (Juan and Gutierrez, 2006).

When different recycled aggregate replacement levels (30%, 50%, and 100%) were used to produce 40 MPa concrete with recycled aggregate and a water-cement ratio of 50% by weight, it was found that any replacement level of recycled concrete aggregate will produce concrete with the same compressive strength as what is normally found for NAC(Yang et al., 2008).

Research is limited regarding the use of RCA in high strength concrete. High strength concrete was produced using three different replacement percentages of RCA (5%, 10% and 12.5%) (Acker,1996).

With 30% RCA, a compressive strength of 80 MPa at 28th day was achieved. Their aim was to produce high strength concrete (50 MPa or more) using RCA (Limbachiya et al., 2000).

They used rejected precast structural concrete elements as RCA. The study showed that there was no significant effect in concrete strength up to 30% replacement of coarse aggregate by RCA. They suggested that if more than 30% RCA replacement levels are used, it can reduce the strength of RAC. Table 2.3 shows the variations of compressive strength of RAC with different RCA replacement levels compared to NAC as given by different researchers.

Table 2.3 Variation in compressive strength of RAC at different replacement levels

Replacement level	Variation in compressive strength as compared to natural concrete	Reference
25%	9% increase	Etxeberria et al., 2007
25%	15% decrease	Alam st al., 2013
30%	10% decrease	Yang et al., 2008
30%	3% decrease	Cakir, 2015
30%	9.5% decrease	Kwan at al., 2012
30%	Similar	Limbachiya et al., 2007
50%	11% increase	Etxeberria et al., 2007
50%	14.7% decrease	Alam st al., 2013
50%	5%decrease	Yang et al., 2008
50%	5% decrease	Limbachiya et al., 2007
50%	6% decrease	Cakir, 2015
60%	30% decrease	Kwan at al., 2012
100%	7.7% increase	Etxeberria et al., 2007
100%	11% decrease	Yang et al., 2008
100%	2.4% increase	Salem et al., 2003
100%	8.9% decrease	Limbachiya et al., 2007
100%	8% decrease	Ajdukiewicz and Kliszczewicz 2002
100%	13% decrease	Cakir, 2015

Flexural strength

Conflicting results are observed from the literature regarding the impact of recycled aggregate on the flexural strength of concrete. **Table 2.4 provides a summary of the**

variation in flexural strength as a function of RAC replacement level obtained by different researchers.

Table 2.4: Variation in flexural strength of RCA concrete as suggested by different researchers

Replacement level	Variation in flexural strength as compared to natural concrete	Reference
25%	2.2%	Poon 2002
25%	16%	Alam at al., 2013
50%	6.25%	Poon 2002
50%	32%	Alam et al., 2013
75%	10.8%	Poon 2002
100%	13%	Poon 2002
100%	31%	Katz 2003

Tensile strength

Like flexural strength, researchers have come up with contradictory conclusions regarding the tensile strength of RAC. **Table 2.5 shows the variation in tensile strength** results of RAC found in different experimental studies.

Table 2.5: Variation in tensile strength of RCA concrete as given by different researchers

Replacement level	Variation in tensile strength as compared to natural concrete	Reference
15%	Similar	Gomez – Soberon, 2002
25%	6% increase	Etxeberria et al., 2007
25%	34% increase	Alam at al., 2013
30%	2.7% decrease	Gomez – Soberon, 2002
50%	18% increase	Etxeberria et al., 2007
50%	16% increase	Alam at al., 2013

Replacement level	Variation in tensile strength as compared to natural concrete	Reference
60%	8% decrease	Gomez – Soberon, 2002
100%	2% decrease	Etxeberria et al., 2007
100%	10.8% decrease	Gomez – Soberon, 2002

Modulus of Elasticity

In a study at 28 days, the modulus of elasticity values of concrete mixtures R50 and R100 incorporating 50% and 100% recycled aggregate was reduced by 12.6% and 25.2%, respectively, than that of the control mixture (Kou, 2013).

In a study, the dynamic modulus of elasticity was measured after 28 days of curing. Results reported showed that RACs had 20% or 30% lower elastic modulus than the reference concrete, depending on the amount of recycled coarse aggregate, which led to lower or higher paste content, respectively (Corinaldesi & Moriconi, 2009).

Depending on the RCA replacement level and water-cement ratio the modulus of elasticity of RAC is 50-70% of NAC (Rao 2005, Ajdukiewicz and Kliszczewicz 2002, Oliveira et al. 1996).

A technique known as shucking technique, which was established as a secondary process for improving the performance of simply crushed recycled aggregate, to improve the quality of RAC a new technique was proposed. In the investigation, the elastic modulus of shucking RAC made with RCA and reported improved strength and elastic modulus properties of shucking RAC compared to commonly used RAC (Qian et al., 2011).

Drying shrinkage

It was concluded that the drying shrinkage of RAC is higher than NAC (Crentsil and Brown, 2001). Replacement ratio significantly influences the drying shrinkage of RAC.

The value of drying shrinkage increases with the increased recycled aggregate replacement ratio. They reported that the drying shrinkage of RAC increases by 5%, 10%, 15%, and 27.5% for RCA replacement levels of 25%, 50%, 75%, and 100%, respectively (Poon et al. 2002).

It was reported that the greatest strains occurred in the concrete prepared with the recycled aggregate and fly ash, due to the largest volume of micro pores contained in the pore structure of this concrete, which had higher volume fraction of paste. It was quite evident that drying shrinkage may not be a problem for RACs, if the same strength class value as reference concrete was achieved (Corinaldesi & Moriconi, 2009).

In general, the use of RA increased the drying shrinkage of the produced concretes. This might be due to the presence of old cement mortar in and the lower stiffness RA (Kou, 2011).

2.2.2.3 Durability Properties

The ranges of index values for concrete durability are tabulated in Table 2.6 (Alexander et al. 1999).

Table: 2.6: Durability Index (Source: Alexander et al., 1999).

Durability class	**Oxygen Permeability Index (OPI) (log scale)**	**Sorptivity (mm/sqrt (h))**	**Chloride conductivity (mS/cm)**
Excellent	>10.0	<6.0	<0.75
Good	9.5 – 10.0	6.0 – 10.0	0.75 – 1.50
Poor	9.0 – 9.5	10.0 – 15.0	1.50 – 2.50
Very poor	<9.5	>15.0	>2.50

Permeability and water absorption

It was concluded that the initial surface absorption (ISAT-10) measured at 10 minutes had no effect up to 30% coarse RCA and thereafter ISAT-10 is increased with RCA content (Limbachiya et al. 2000). This behaviour is due to the fact that the quantity of attached cement paste in the concrete with 100% coarse RCA increased by three times than that of concrete with 30% coarse RCA.

It was also studied in the same paper that up to 30% coarse RCA had no detrimental effect on air permeability, regardless of concrete strength. However, the amount of the intrinsic air permeability was found to increase with the increase in RCA content beyond this level (Limbachiya et al. 2000).

In a study, it was observed that when both fine and coarse RA are used in the concrete, the permeability increases 6.5 times compared to coarse RA concrete and 13 times compares to that of NAC (Buyle-Bodin et al. 2002).

It has been observed in a study that, at a given percentage of RA content, if the duration of the curing period is increased, Optimum Permeability Index (OPI) of the concrete samples also increases. Between the curing periods of 3 and 56 days and for the concrete mix containing 0% RA, OPI increased by 33.6%. Similar increases of OPI for the concrete mixes incorporating 50% and 100% RA were 37.6% and 38.2% respectively (Olorunsogo et al. 2002).

In a study, it was observed that the permeability, in case of the recycled aggregate (both coarse and fine aggregates) concrete, is significantly more than natural aggregate concrete. If admixtures such as fly ash or silica fume are employed, the porosity and permeability of recycled aggregate (both coarse and fine aggregates) concrete decrease significantly (Zaharieva et al. 2003).

The porous interfacial transition zone microstructure in the normal-strength concrete is observed which can be attributed to the higher porosity and absorption capacity of recycled aggregate. The interfacial transition zone formation was related to moisture movement and chemical reactions in the recycled aggregate concrete (Shui et al. 2004).

In a study, the water penetration test was conducted and it was observed that for 0%, 30% and 60% of recycled coarse aggregate, the height of penetration of water was 36.55 mm, 32.44 mm and 43.11 mm respectively. For 100% of recycled aggregate, sample failed completely (Lima, 2013)

Freezing and thawing resistance

It was observed that the recycled aggregate which originated from concrete made with air entrained admixture produced high quality freeze thaw resistance concrete (Salem and Burdette, 1998 and Zaharieva et al , 2004).

With the high replacement ratio of RAC, the frost resistance of new concrete decreases considerably and it was suggested that it is better not to use recycled concrete aggregate in severe freeze thaw exposure condition (Kasai et al. 1988).

An examination of the durability of RAC under freezing and thawing condition showed that RAC resistance was less than NAC. For freeze thaw, small reduction in resistance was observed up to 30% replacement of recycled aggregate (Yamato et al. 1988).

It was concluded that the concretes with saturated and dry recycled aggregates showed bad resistance to freeze-thaw and the good results of those made with semi-saturated aggregates, when a study of the effects of three different moisture conditions from the recycled aggregate were compared dry, saturated and semi-saturated (Oliveira et al. 1996).

The best method to improve the frost resistance of recycled aggregate concrete is the air entrained method. But this method decreases some of the vital concrete physical properties (Salem et al. 1998).

The concrete produced using up to 100% coarse RCA had durability factor in excess of 95%, showing good freeze/thaw durability potential (Limbachiya et al. 2000).

The frost resistance of saturated recycled aggregate concrete (RAC) is not satisfying, and their use in structures exposed to severe climate is not recommended. The main reason seems to be the high total w/c ratio, including higher porosity and lower mechanical characteristics of RAC, as well as the frost resistance of RA themselves. First, they might contain unsound particles, which would be deteriorated by the repeated action of freezing-thawing cycles, and, second, RA could contribute to the frost damage by expelling water in to the surrounding cement paste during the freezing periods (Zaharieva et al. 2004).

Chloride diffusion/Penetration

Chloride penetration is one of the major causes which generate corrosion in concrete.

In a study, almost 2.2 to 2.3 mm higher penetration depth for RAC than NAC after exposed to chloride solution was obtained (Shayan and Xu 2003).

The use of 100% coarse RCA has no negative influence on the chloride diffusion of resulting concrete (Limbachiya et al. 2000).

It was observed in a paper that at a curing age of 3, 7, 28 and 56 days, the concrete mix that containing 100% RA showed 41.4, 53.6, 73.2 and 86.5% increase in the value of chloride conductivity over the mix that contained 0% RA, respectively. It was concluded that chloride conductivity increases with increase in the replacement levels of RA for a given curing duration of concrete mixes (Olorunsogo et al. 2002).

Considering the effect of curing age on the chloride conductivity of RA concrete, showed that the longer the duration of curing, the lower the conductivity of concrete mix at a particular replacement level of RA. For 0, 50and 100% RA concrete, the mix that was cured for 56 days showed 69.0, 62.7 and 59.2% increase in chloride conductivity over the mix that was cured for 3 days, respectively. Comparing the recommended values of chloride conductivity for concrete durability classified by Alexander et al. (1999), the 100% NA concrete attained the class status of 'good' at the curing age of 56days with a value of 1.48 mS/cm. 50% RA and 100% RA concrete mixes fall under the'poor' (Olorunsogo et al. 2002).

In a paper, the effect of water binder ratio on the chloride resistance was studied. It was observed that the chloride penetration increase with an increase in the water binder ratio. Further it was also observed that for the same water binder ratio, the chloride penetration of recycled aggregate concrete are slightly higher than those of normal aggregate concrete. This may be attributed to the fact that the presence of old ITZ and adhesive mortar in recycled aggregate makes recycled aggregate concrete more permeable than normal aggregate concrete. Decrease in chloride penetration of recycled aggregate concrete can be achieved by using the double mixing method in case of high water binder ratio concrete (Otsuki et al. 2003).

The resistance to chloride ion penetration decreased as the recycled aggregate content increased. However, the resistance was improved by incorporation fly ash in the concrete mixtures. A decrease in the W/B ratio improved the resistance to chloride ion penetration. Further, it was found that the resistance increased as the curing age increased from 28 to 90 days (Shi Congkou et al. 2007).

In another study, the chloride resistance was studied. It was observed that chloride ion penetration could be convincingly reduced by employing a proper a proper mix design. In this experimental study it was deduced that concrete, which had a low w/c ratio and the use of fly ash as an addition of cement, had much better resistance to chloride ion penetration compared to that with high w/c ratio and without fly ash addition (Poon et al. 2007).

In another experimental study, it was deduced that by using the rapid chloride ion test, the concrete containing recycled aggregate showed that it forms a more open pore structure as compared to the control concrete specimens. The use of 30% pulverized fuel ash and 65% ground granulated blast furnace slag in binder resulted in a decrease in the charged passed through concrete specimens, which implies the enhancement resistance to chloride ions permeability in to a concrete body (Ann et al. 2008).

It was observed that the total charge passed increased with the use of RA. The charge passed was 4120 coulombs for control sample, 5000 coulombs for 50% recycled aggregate and 5320 for 100% recycled coarse aggregate after 28 days of curing. It was also observed that the value of charge passing through samples decreased with increase in age of sample. After 90 days, the value of charge passed was 3200 coulombs fro control sample, 3800 coulombs for 50% recycled coarse aggregate and 4100 coulombs for 100% recycled coarse aggregate (Kou et al., 2011)

Carbonation

It was also observed that concrete made with already carbonated recycled aggregate deteriorate by 65% more of carbonation than conventional concrete (Rasheed Uzafar et al. 1984).

In another study, the effect of cement concrete in recycled aggregate concrete, it was observed that the carbonation risk of recycled aggregate concrete using a higher amount of owed significant effect on the carbonation resistance of concrete. It was seen that the carbonation resistance in recycled aggregate concrete with cement content higher than 400 kg/cum of concrete mix was quite low than in conventional concretes. It was also reported that if the cement content is between kg/cum and 400 kg/cum, the carbonation depth in recycled aggregate concrete and conventional concrete is similar in both cases. This occurs when the cement is added; the aggregates are saturated or very humid. In poor concrete, using less than 300 kg/cum of cement, the carbonation depth is similar in both concretes (Barra et al. 1998).

The variation of depth of carbonation with time under accelerated exposure conditions is a parabolic rate law for coarse RCA concrete with OPC cement as with the reference mix. The coarse RCA concrete with slag cement shows a slight deviation from this trend, suggesting the possibility of a different mechanism of carbonation (Sagoe-Crentsil et al.2001).

It was deduced from another study that the process of CO_2 diffusion in concrete with fine and coarse recycled aggregate follows parabolic rate law established with classic concrete. The only difference is that the rate of carbonation in case of concrete with fine and coarse recycled aggregate was faster than natural aggregate concrete. However, it was also observed that by extending curing age of concrete made with fine and coarse recycled aggregate, decreases the carbonation rate (Buyle-Bodin et al. 2002).

The quality of the concrete cover is affected by the amount of replacement level of natural aggregates by recycled aggregates. Due to the carbonation rate in case of recycled aggregate (both coarse and fine aggregates) concrete (RAC), this limits the use of recycled aggregate in the production of reinforced concrete elements (Zaharieva et al.2003). Nevertheless, based on the criteria proposed in other studies, RAC can be characterized as being of moderate quality rather than poor quality. Mixed aggregate concrete is intermediate between RAC and NAC. It can be concluded that the main problems of durability are caused by the use of recycled sand. Therefore, the use of the fine recycled aggregate needs to be restricted. Another way of increasing the durability of RAC is to use extended curing using a moist environment.

In another study, the effect of water binder ratio upon the recycled aggregate is studied. It was observed that the carbonation depth increases with an increase in the water binder ratio. Further it was also studied that for the same amount of water binder ratio, the carbonation depth of recycled aggregate concrete was slightly higher than those of normal aggregate concrete. This was attributed to the fact that due to the presence of old ITZ and adhesive mortar in recycled aggregate, it becomes more permeable than normal aggregate concrete. Decrease in carbonation depth of recycled aggregate concrete can be achieved by using the double mixing method in case of high water binder ratio concrete (Otsuki et al. 2003).

Many researchers reported that the carbonation depth of RAC is 1.3 to 2.5 times higher than virgin concrete (Levy-Salomon and Paulo 2004, Katz 2003, Crentsil et al. 2001, Shayan and Xu 2003).

The carbonation depth decreased when the replacement was 20 or 50% of coarse recycled masonry aggregate (CRMA) and coarse recycled concrete aggregates (CRCA). For CRMA concrete family, this better behaviour also occurred when the replacement ratio was 100%. This behaviour shows that carbonation depth depends strongly on the chemical composition of the concrete and not only on the physical aspects (Levy et al. 2004).

It was concluded that, for concretes prepared with lower water/cement due to the refinement of the pore system, carbonation did not present evidence of risks for reinforcement corrosion. This is due to the very low permeability of the concretes, even if a porous aggregate, such as recycled aggregate, was used (Corinaldesi & Moriconi, 2009).

It can be observed that the use of recycled aggregate in concrete decreased the resistance of concrete to carbonation at all test ages. This may be attributed to the recycled aggregate being more porous (Kou, 2013)

Water Sorptivity or water absorption

The rate of movement of a wetting front through a porous material under the action of capillary force is defined as Sorptivity.

In a case study, it was reported that water sorptivity increased with an increased replacement levels of RA for a constant age of curing. At a curing age of 3, 7, 28 and 56 days, the concrete mix that containing 100% RA concrete showed 47.3, 43.6, 38.5 and 28.8% increases in the value of water sorptivity over the mix that contained 0% RA, respectively. It was shown that these percentage increments decreased with duration of curing, for a considerable curing length of time there was no difference in water sorptivity values (Olorunsogo et al. 2002).

It was determined that the water absorption by immersion of concrete with coarse RA from CDW made mostly of concrete. All the mixes were produced in order to have a compressive strength of 27 MPa. For full replacement, the authors found that the water absorption by immersion increased between 5.5% and 14.2% (Oliveira et al, 2004)

The results in a study which were represented graphically lead to the conclusion that the replacement of NA with RA caused an increase of the water absorption by immersion. This can be partly justified by the effective w/c ratio of the mixes with RA, needed to keep the slump constant in all mixes. On the other hand, the greater water absorption of the RA relative to the NA may have contributed to increase the water absorption of concrete. Most of RA analysed here contain materials with high water absorption capacity (Bravo et al, 2015)

Reinforcement corrosion

It was observed in a paper that the rate of corrosion decreased considerably, if the water cement ratio used in the recycled aggregate was lower than that used in conventional concrete (Rasheed Uzafar et al. 1984).

Little difference in the performance of the RCA and NA concrete mixes suggested that there is equal corrosion activity. However, the corrosion currents of the steel in 100% coarse RCA concrete were slightly higher and the corrosion initiation time was shorter than concrete containing NA and up to 50% coarse RCA (Limbachiya et al. 2000).

Chloride, sulphate and carbonate exposure conditions are mainly responsible for the corrosion of concrete. Less corrosion risk for RAC using half-cell potential test was observed (Shayan and Xu, 2003).

The chloride threshold level for steel corrosion was not affected by pulverized fuel ash (PFA) or ground granulated blast furnace slag (GGBS) as partial replacement for cement in binder, but the OPC concrete with only recycled aggregate indicated the lowest level of chloride threshold level. After the onset of corrosion, the corrosion rate was significantly reduced by PFA and GGBS, due to the restriction of cathodic reaction, which need a sufficient supply of oxygen and water (Ann et al. 2008).

It was observed in a study that in the six months of exposure the corrosion potentials, of all the reinforced concrete systems, show fluctuation ranging from -550 to -400 mV / Cu-CuSO4 with a slight decrease during the months, towards more noble values; according ASTM C 876 these E_{corr} values indicate that exists a 90% probability of active corrosion during all the exposure period (Higuera et al.,2011)

Creep, elastic shrinkage and drying shrinkage

For the recycled aggregate mortars the drying shrinkage reduces 15% when the metallic fibres are added and tiny changes when the polypropylene fibres are added (Mesbah et al. 1999).

It was reported that both natural and recycled aggregate concretes display similar trends with regard to the rate of shrinkage. The shrinkage strains associated with recycled concrete made with slag cement are over 35% higher and with Portland cement are over 15% higher than the reference mixture (Sagoe-Crentsil et al. 2001).

The use of low w/c ratio or fly ash as a addition of cement is a good way to reduce the potential high drying shrinkage of concrete prepared with recycled aggregate. Drying shrinkage of recycled aggregate concrete tended to decrease with an increase in compressive strength. Reducing w/c ratio from 0.55 to 0.40 was a more effective way to mitigate the drying shrinkage of concrete compared to adding 25% fly ash in the concrete mix (Poon et al. 2007).

As the replacement ratio of recycled coarse aggregate increases the drying shrinkage strain increases. However by estimating the decrease in quality by relative quality values and adjusting the replacement ratio, the quality required for the concrete can be ensured (Eguchi et al. 2007).

2.3 Studies on Application of Fly Ash to Concrete

Fly ash is one of the principal by-products of the coal-fired power plants. It is well accepted fact that it can be used as a pozzolanic material that may be used in either form as a component of blended Portland cements or as a mineral admixture in concrete. Generally, fly ash has been used as a limited level in the total cementitious material. The dosage of fly ash is mostly limited to 15%-20% by mass of the total cementitious material. The use of fly ash improves the physical properties like workability and cost economy of concrete. The main limitation of fly ash that limits its use as a whole binder material is that it may not be enough to sufficiently improve the durability to sulphate attack, alkali-silica expansion, and thermal cracking. For this purpose, larger amounts of fly ash, on the order of 25%-35% are being used.

Since fly ash is a by- product of the coal power generation, it consists of SiO_2, Al_2O_3, Fe_2O_3 and CaO and some impurities. According to ATSM C618, fly ash can be classified into two main categories. Fly ash belongs to Class F if (SiO_2+Al_2O_3+Fe_2O_3)> 70%, and belongs to Class C if 70% > (SiO_2+Al_2O_3+Fe_2O_3) > 50%. Usually, Class F fly ashes have a low content of CaO and exhibit pozzolanic properties, but Class C fly ashes contain up to 20% CaO and exhibit cementitious properties.

Low Calcium fly-ash is produced by burning anthracite or bituminous coal, and high-calcium ly ash is produced by burning lignite or sub-bitumious coal. Low calcium fly ash is categorised as a normal pozzolan, a material consisting of silicate glass, modified with aluminium and iron (Papadakis et al, 1999).

The fly ash can be incorporated into the concrete mix by three different techniques.

- Simple replacement method involves direct replacement of a part of Portland cement with fly ash, with a subsequent adjustment of concrete for yield.
- Addition method involves direct weight addition of fly ash to cement, replacing part of the aggregate in concrete, in order to achieve the correct yield.
- Partial replacement method involves replacement of a part of Portland cement with excess weight of fly ash, replacing also part of the aggregate in order to achieve the correct yield.

It was observed that mineral admixtures such as silica fume and fly ash improve engineering properties and performance of concrete when they are used as mineral additives or as partial cement replacements (Malhotra et al, 1994)

Compared to fly ash, the availability of materials such as ground granulated blast furnance slag, silica fume, metakaolin and rice-husk ash is limited.

Utilization of fly ash as a supplementary cementitious material adds sustainability to concrete by reducing the CO2 emission of cement production. The positive effects of fly ash as a partial replacement of cement on the durability of concrete are recognized through numerous researches; however, the extent of improvement depends on the properties of fly ash

When fly ash was incorporated in the recycled aggregate, the problem of high drying shrinkage value of recycled concrete was reduced considerably as compared to that of conventional concrete. The different applications of fly ash produce concrete with very different properties (Costabile, 2001)

If fly ash is used as a partial replacement of cement, it was observed that it lead to decreased value of the compressive strength, tensile splitting strength and static modulus of elasticity. But if fly ash is used as an additional admixture along with the cement in RAC, it increased the value of the compressive strength, tensile splitting strength and static modulus of elasticity (Shicong, 2006).

The use of fly ash both as a partial replacement of cement and as an additional admixture in RAC was able to reduce the drying shrinkage and creep and increased the resistance to chloride-ion penetration of the RAC. Fly ash replacement at a level of 25% also increased the bond strength and fracture energy of RAC and a great improvement in the post-peak ductility for the RAC (Shicong, 2006)

.In another study, durability properties of high strength concrete utilizing high volume Class F fly ash sourced from Western Australia have been investigated. The fly ash concrete samples showed less drying shrinkage than the control concrete samples when designed for the same 28-day compressive strength of the control concrete. Inclusion of fly ash reduced sorptivity and chloride ion permeation significantly at 28 days and reduced further at 6 months. (Nath et al, 2011). In general, incorporation of fly ash as partial replacement of cement improved the durability properties of concrete.

2.4 Studies on Application of Silica Fume to Concrete

Silica fume (SF) is a by-product of the silicon and ferrosilicon industry. The reduction of high-purity quartz to silicon at temperatures up to 2000˚C produces SiO_2vapours, which oxidizes and condense in the low-temperature zone to tiny particles consisting of non-crystalline silica. SiO_2content of the silica fume is related to the type of alloy being produced (Siddique, 2011).

Fig. 2.1 show the schematic diagram of silica fume production. Silica fume is also known as micro silica, condensed silica fume, volatilized silica or silica dust. Silica fume colour is either premium white or grey. (Siddique, 2011)

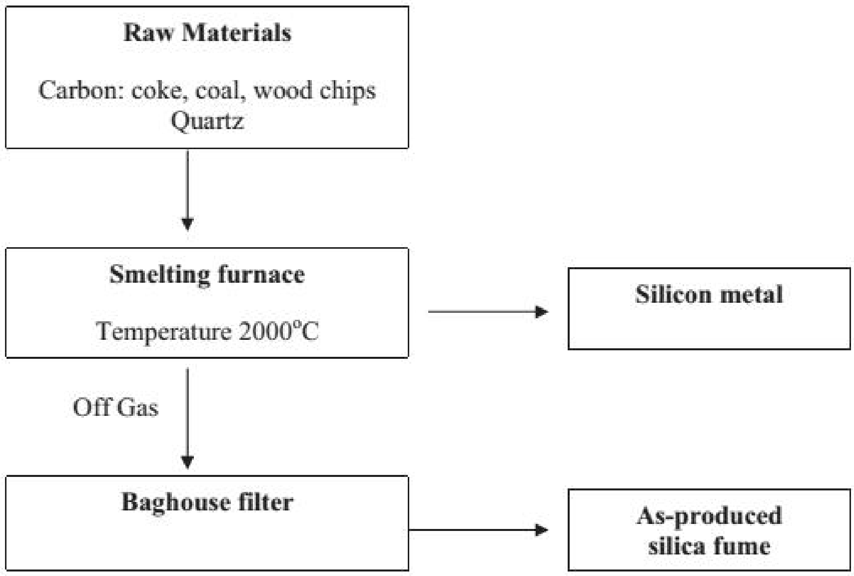

Fig. 2.1. Schematic diagram of silica fume production(Source: Siddique, 2011)

Silica fume has a very high content of amorphous silicon dioxide and consists of very fine spherical particles. Small amounts of iron, magnesium, and alkali oxides are also found (Titherington and Hooton, 2004).

Advantages of using silica fume:

- High early compressive strength
- High tensile, flexural strength, and modulus of elasticity
- Increased toughness
- High bond strength
- Enhanced durability
- Very low permeability to chloride and water intrusion
- Increased abrasion resistance
- Superior resistance to chemical attack from chlorides, acids, nitrates and sulphates, etc.
- High electrical resistivity and low permeability

In study involving of recycled aggregates along with silica fume, it was observed that the compressive strength of the RAC decreases with the replacement of the NA with RA.

However, SF addition gave an alternative way to increase the compressive strength of RAC to use concrete in structural industry (Dilbas, 2014).

The effects of incorporating silica fume (SF) in the concrete mix design to improve the quality of recycled aggregates in concrete were studied by replacing Portland cement with SF at 0%, 5% and 10%. Concrete properties were evaluated by means of compressive strength, tensile splitting strength, water absorption and ultrasonic pulse velocity and it was found that, using 10% SF as a cement replacement for recycled aggregate concretes enhanced the mechanical and physical properties of concrete (Cakır and Sofyanlı, 2014).

At all the test ages the tensile splitting strength gain of the natural aggregate concrete mixture (NA) with and without SF was higher than that of the recycled concrete mixtures. Continuous and significant improvement in the tensile splitting strength of recycled aggregate concretes incorporating SF was observed (Cakır and Sofyanlı, 2014).

It was observed in a study that the compressive strength of concrete containing recycled aggregate at 1, 4, 7, 28 and 90 days was lower than that of the control specimen, but could be compensated by the use of 10% SF or 15% MK. 10% SF (silica fume) showed better results than 15% MK (Metakaolin), 30% FA (fly ash) or 55% GGBS (Ground granulated blast slag) (Kou et al., 2011).

In the same study, it was observed that SF and MK increased UPV of both the natural and recycled aggregate concrete. The drying shrinkage values of the natural and recycled aggregate concrete made with SF and MK were higher than that of the control. The test results show that SF and MK can improve both mechanical and durability properties of recycled aggregate concrete. But the use of FA and GGBS significantly improved the durability performance of the recycled aggregate concrete (Kou et al., 2011)..

In a study sample, by adding 10% silica fume increased the compressive and tensile strengths of recycled aggregates concrete as compared with comparable concrete without silica fume. The 28-day bond strength of recycled aggregate concrete was improved up to 10% due to the presence of silica fume. Adding silica fume decreases the porosity of recycled aggregates concrete. The volume of micro pores was reduced causing benefits in terms of mechanical performances (Elhakam et al, 2012).

Results obtained in the series of experimental part showed that if fly ash is added to RAC, the pore structure is improved, and particularly the volume of macro pores is reduced, causing benefits in terms of mechanical performances such as compressive, tensile and bond strengths (Corinaldesi et al., 2009).

It was observed that by the addition of fly ash proved to be very effective in reducing carbonation and chloride ion penetration depths in concrete, even in RAC. Its use can be beneficial in increasing the service life of RAC structures because it increases the initiation period for reinforcement corrosion (Corinaldesi et al., 2009).

Adding ultra fine SF particles decreases the porosity and enhances the matrix and transition zone between aggregates and cement mortar. Addition of silica fume to the recycled aggregate concrete and conventional concrete reduces the density (Gonzalez et al., 2008).

SF's effects (the pozzolanic effect and filler effect) improve all the mechanical properties of the concrete but, particularly, its compressive strength (Fonteboa, 2008).

Adding SF as a supplementary binder material can also improve the mechanical and physical properties of concrete prepared with recycled concrete aggregate (Rao et al, 2007).

In an experimental study on the early-age tensile creep behaviour of high-strength concrete(HSC) comprising of silica fume concrete under uniaxial restraining stresses, it was found that about 70% of free expansion deformation was compensated by compressive creep within the first day. After this period, the compressive creep was replaced by tensile creep due to high tensile stress development in specimens(Tao and Weizu, 2006).

In another research, the creep of high performance concrete having silica fume (0, 6, 10 and 15%) was studied. The w/c ratio was 0.35. It was found that silica fume had a significant influence on the long-term creep. As the proportion of silica fume increased to 15%,the creep of concrete decreased by 20–30% (Mazloom et al, 2004).

In an experimental study on the autogenous shrinkage of Portland cement concrete (OPC) and concrete incorporating silica fume up to the age of 98 days, the autogenously shrinkage increased with decreasing w/c ratio and with increasing silica fume content (Zhang et al. , 2003).

The inclusion of silica fume (0–15% as partial replacement of cement) resulted in more significant reductions in porosity in mixtures. However, the reduction in the porosity was greater when silica fume was incorporated at up to 10% replacement level, beyond which the reduction was marginal or reversed (Khan, 2003).

The elastic modulus of the Portland cement concrete was approximately equal to silica fume concretes at 28 days but continued to increase at later ages in a research on the modulus of elasticity of silica fume concretes up to the age of 365 days (Hooton, 1993).

CHAPTER 3

EXPERIMENTAL PROGRAM AND DETAILS

3.1. Methdology and Test Matrix

In this chapter, the material properties, mix proportions and test methods used in this study are presented.

- Ordinary Portland Cement 53 Grade under Brand JK, Class F fly ash and micro silica (sillca fume) was used.
- The recycled aggregates employed in the study were taken from recycling plant at Bhuccho Mandi in Bathinda district (Punjab).
- Crushed angular coarse aggregates and crushed Ghaghar fine sand was used as natural aggregates.

In total, three Series of specimens were prepared with different replacement levels of coarse aggregate with RCA. The target strength fixed for the control sample was M30.

- In Series I, the main purpose was to study the influence of using of recycle coarse aggregates as partial and full replacement on the properties of normal strength (30 MPa) concrete. The concrete mixtures in Series I were prepared with cement content of 438 kg/m^3 and water cement ratio of 0.45.
- Series II and III aimed to study the influence of fly ash and silica fume respectvely, as a cement replacement level on the properties of RCA with target strength of 30 MPa.
- In series II, fly ash was used as 25%, 35% and 55% by weight replacement of cement.
- In series III, micro silica was used as 5%, 10% and 15% by weight replacement of cement.
- In all the three concrete mix series, recycledcoarse aggregates were used as 0, 50 and 100% by weight replacement of the natural coarse aggregate.

The flow chart for the test matrix followed is shown as under:

FLOW CHART FOR TEST MATRIX

Three series of specimens

(The target strength fixed for the control sample was M30.)

Series I

Recycled coarse aggregate (50% and 100% by weight of natural coarse aggregate)

Series II

Recycled coarse aggregate (50% and 100% by weight of natural coarse aggregate) + fly ash (25%, 35% and 55% by weight of cement)

Series III

Recycled coarse aggregate (50% and 100% by weight of natural coarse aggregate) + silica fume (5%, 10% and 15% by weight of cement)

Test conducted for selection of optimum specimens for durability testing from each series

- **Slump test for workability**
- **Compressive strength test for 3 day, 7 day and 28 day***
- **Split tensile strength test for 28 day***
- **Flexural strength test for 28 day***

Optimum Specimens Selected for further testing

Fresh Stage Properties

- **Air content test**
- **Bleeding test**

Durability Properties

- **Water Penetration Test**
- **Rapid Chloride Permeability Test (RCPT)**
- **Carbonation depth test**

Non Destructive Testing

- **Ultrasonic guided waves test (UGV test)**

** Average of three samples were taken for testing of each specimen*

3.2 PROPERTIES OF MATERIALS USED

3.2.1 CEMENT

The ordinary portland cement with trade name JK equivalent to garde 53 was used in the project. The cement was tested as per IS:4031- 1968 and satisfied the requirements of IS: 12269-1987.

The chemical composition of the cement is shown below in Table 3.1. The physical properties of the cement are shown in Table 3.2. Same type of cement was used throughout the work.

Table 3.1: Chemical properties of cement
(Source: http://www.jklakshmi.com/opc-53-grade-cement/)

Contents	Cement
SiO_2	21.0
Al_2O_3	5.9
Fe_2O_3	3.4
CaO	64.7
MgO	0.9
Na_2O	-
K_2O	-
TiO_2	-
SO_3	2.6
Loss of ignition (%)	1.2
Specific gravity (g/cm^3)	3.15
Fineness (>45 μm)	-
Specific gravity (cm^2/g)	3520

Table3.2: Physical properties of cement			
S.No.	**Characteristics**	**Experimental Results**	**IS:4031-1988 Requirements**
1.	Colour of cement	Deep Grey	-
2.	Standard consistency	27.0 %	-
3.	Specific gravity	3.15	3.14- 3.15
4.	Setting time (minutes) (a) Initial setting time (b) Final setting time	 112 min. 218 min.	 Less than 30 min. Not more than 600 min.
5.	Compressive strength (MPa) (a) 3 day (b) 7 day	 31 MPa 42.1 MPa	 Less than 27 MPa Less than 37 MPa
6.	Soundness –by Lechatliers Method	2.0 mm	Not more than 10 mm
7.	Fineness (by sieve analysis) residue on IS sieve No.9	6.5 percent	Mot more than 10 percent

3.2.2. Fly Ash

Fly ash is used as partial replacement of cement in all the cases of the experiments. Class F fly ash is procured from Guru Nanak Dev Thermal Plant (GNDTP), Bathinda, Punjab having specific gravity as 2.31 and satisfying IS 3812-1999. Chemical composition of fly ash is given in table 3.3.

Table3.3: Chemical and physical properties of Fly ash Used (Source: QC&M Branch,GNTP,Bathinda)	
Contents	**Fly ash**
SiO_2	56.79
Al_2O_3	28.21
Fe_2O_3	5.31
CaO	<3
MgO	5.21
Na_2O	-
K_2O	-
SO_3	0.68
Loss of ignition (%)	3.90
Specific gravity (g/cm^3)	2.31
Fineness (>45 µm)	-
Specific gravity (cm^2/g)	3950

3.2.3. Silica Fume

Silica Fume according to IS 15388-2003 with a specific surface area of about 15,000 m^2/kg and relative density of 2.3 was used. The chemical composition, physical and mechanical properties of silica fume are listed in Tables 3.4 .

Table3.4: Chemical and physical properties of silica fume (Source: Guru Coporation, Ahmedabad)	
CONTENTS	**SILICA FUME**
SiO_2	85-96
CaO	<1
SO_3	<2
Structure of material Condensed	Condensed microsilica
Colour	Amber
Density (kg/litre)	0.55-0.70
Chlorine ratio	<1
Activity index (%)	>95
Loss of ignition (%)	3.50
Specific gravity	2.22
Fineness (>45 µm)	3-5
Specific gravity (cm^2/g)	18650

3.2.4 Aggregates

3.2.4.1. Natural Aggregate (NA)

The natural aggregate used was greywacke with nominal sizes of 20 – 10 mm which has been used in all the steps in this thesis. Greywacke refers to the stone which is a popular aggregate resource and it found in majority around Panchkula.

Greywacke is stone is formed by thermal metamorphism of argillaceous rocks. It consists of quartz, feldspar, mica and iron oxides. It also has a fine grained micro structure which is responsible for its good performance.

The greywacke stone is crushed to form an elongated and flaky aggregates rather than good cubical shape. It is used widely in structural and non-structural concrete construction. The main reason behind its wide application is mainly due to the reason that the inherent characteristics of this natural stone can be varied moderately such that the greywacke rock may produce a variety of hardened concrete properties.

3.2.4.2 Recycled Coarse Aggregate (RCA)

The recycled coarse aggregate selected should be such that there physical properties are not very different from the natural coarse aggregate so the variation in the concrete properties is not very large. The main reason is that the total volume of aggregates ranges from 60 to 75 percent of the total volume of concrete. So the performance of the concrete changes drastically if recycled aggregate is employed. The RCA was collected from Sidhu Crushing Plant, Bhuccho Mandi, and Bathinda. The concrete rubble at the crushing plant site was mostly from a multi-storeyed building demolished whose grade was M-20.The size of all three aggregates ranged from 9.5 – 19 mm and their physical characteristics have been discussed later.

3.2.4.3 Fine Aggregate (FA)

Fine aggregate elected was local Ghaggar sand available in the market. Fine aggregates should be selected carefully as they contribute up to 30% of the total volume of conventional concrete. The grading of the aggregate, the cement content, particle shape and the grading of the coarse aggregate as well as the intended use of the concrete are the main desired properties of the workable concrete. Ghaggar sand was used as fine aggregate with a fineness modulus (FM) of 2.19.

3.2.5 Water

In this experimental work, water that was used in the concrete mixing and the curing of the specimens was normal tap water (potable water) with an approximate unit weight 1000 kg/m^3.

The impurities present in the water (groundwater in most cases) plays a great role in the concrete properties as the setting time and the strength of concrete might vary with excessive impurities in mixing water which also may cause the corrosion of steel, a volume change of concrete, efflorescence, staining and a reduced durability of the concrete structure

3.3 Aggregate Grading

The natural and recycle coarse aggregate had similar size in the range from 20mm – 4.75mm. All the particle size distributions were in accordance with IS 2386-5 (1963).

While making recycled coarse aggregate concrete, the size fractions of recycled coarse aggregate 20 - 10 and RCA 10 - 4.75 were mixed by the method of equivalent mix proportion so that the gradation curve of the combined recycled coarse aggregate was similar to that of the natural coarse aggregate. The final mix ratio for recycled coarse aggregate was achieved as 65% of RCA 20-10 mm and 35% of RCA 10-4.75 mm. The mix proportion of different size fraction of RCA was decided by hit and trial method. Table 3.4 and 3.5 shows the sieve analysis results of the natural coarse aggregates and recycled coarse aggregate respectively. It may be seen that the recycled coarse aggregate satisfies the IS 383:2007 specified gradation criteria.

TABLE 3.5: Gradation of NCA Used				
Sieve size (mm)	**Weight retained (g)**	**Cumulative % weight retained**	**% passing**	**% passing required (IS:383-1970)**
20	0	0	100	95-100
12.5	1040	12.4	87.6	-
10	3700	50.4	49.6	30-50
4.75	4570	99.48	0.52	-

TABLE 3.6: Gradation of RCA Used				
Sieve size (mm)	**Weight retained (g)**	**Cumulative % weight retained**	**% passing**	**% passing required (IS:383-1970)**
20	0	0	100	95-100
12.5	1530	16.40	87.6	-
10	3565	54.7	45.3	30-50
4.75	4215	99.97	0.03	-

The recycled coarse aggregate gradation in table 3.6 is seen to have a close resemblance to the NA gradation tables and hence the size distribution of the recycled coarse aggregate particles is acceptable.

The sieve analysis of fine aggregate is shown in table 3.7:

TABLE 3.7.: Gradation of fine aggregate			
Sieve size (mm)	**Weight retained (g)**	**Cumulative % weight retained**	**% passing**
4.75	0	0	100
2.36	49	4.9	95.1
1.18	115	16.4	83.6
600µ	215	37.9	62.1
300µ	308	68.7	31.3
150µ	221	90.8	9.2
PAN	92	100	0
TOTAL		218.70	

FINENESS MODULUS = 2.19

3.4 Mechanical Properties of Natural and Recycled Coarse Aggregates

A concrete matrix is largely composed of aggregates mainly coarse aggregates. The basic properties as well as the durability and structural properties of concrete are dependent upon the quality of the aggregates. The micro-structural, physical and mechanical properties of the aggregates significantly affect the plastic and hardened characteristics of the concrete.

The most important properties of aggregate for ordinary concrete are the particle size distribution, aggregate shape, porosity and possible reactivity with cement.

Aggregates which are cubical shaped stones with a rough surface, produces high strength concrete than that produced with smooth faced uncrushed gravel. The reason may be attributed to the fact that the bonding between aggregate and cement paste is greatly increased in case of cubical shaped stones with a rough surface.

Many other properties that characterize concrete aggregate include strength and rigidity expressed as a crushing value, soundness which defines aggregate resistance to normal weathering conditions, abrasion resistance, dimensional stability, alkali reactivity, density and water absorption. The strength of concrete not only depends upon the mechanical strength of aggregates but also to a greater extent on its absorption, modulus of elasticity, shape and size, bulk density, porosity, moisture-content, fineness modulus, grading of aggregates etc.

In this section all the mechanical properties of the natural and recycle coarse aggregates are determined by required tests. These aggregates should be used in concrete production, and their values of their mechanical properties must be in accordance with IS: 2386.

3.4.1 Flakiness Index

Flaky refers to the thin and flat particles. The presence of flaky material is considered undesirable as they may cause inherent weakness with the possibility of breaking down under the heavy load. Another problem with flaky aggregates that if they are present in the concrete mix, there are increased chances of segregation as they tend to break down during compaction, creating additional fines.

Flakiness Index is defined as the mass of flaky particles expressed as a percentage of the mass of the sample.

The flakiness index test according to IS 2386-1 (1983) was conducted on NA and RCAs. The apparatus used in flakiness index test is shown in Figure 3.1.

The results are as shown in Table 3.8.

Figure 3.1: Apparatus used in flakiness index

3.4.2 Specific Gravity and Water Absorption

The specific gravity (relative density) and absorption capacity of natural and recycled coarse aggregates were determined according to IS 2386-3 (1963). The results of different types of aggregate properties tests are shown in Table 3.8.

The specific gravity of RCA was 2.25 which were lower by 15% than that of natural coarse aggregate. It is due to the adhered mortar of RCA. The adhered mortar also increased the absorption capacity of RCA which was 4.75 times higher than that of natural coarse aggregate. The bulk densities of natural and recycled coarse aggregates were 1576.8kg/m^3 and 1374.8 kg/m^3, respectively.

The absorption rate of the aggregates is important as it influences the concrete mix design by reducing the effective water-cement ratio Also; the absorption rate affects the bond between the aggregate and cement paste as well as the specific gravity of the aggregate.

Figure 3.2: bucket method used for measuring specific gravity of aggregate

3.4.3 Aggregate Impact Value

The aggregate impact value test is done on both normal and recycled aggregate as per IS: 2386-IV (1963). The 'aggregate impact value' gives a relative measure of the resistance of an aggregate to sudden shock or impact, which in some aggregates differs from its resistance to a slow compressive load. The impact value of recycled aggregate is 2.90 times more than that of normal coarse aggregate indicating the poor resistance of recycled aggregates to sudden impact load. The value of recycled aggregate is well within limit of 45 percent as prescribed by BIS.

Figure 3.3: Aggregate Impact Value Test Apparatus

3.4.4 Aggregate Crushing Value

The aggregate impact value test is done on both normal and recycled aggregate as per IS: 2386-IV (1963).The 'aggregate crushing value' gives a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load. The impact value of recycled aggregate is 1.57 times more than that of normal coarse aggregate indicating the poor resistance of recycled aggregates to sudden impact load. The value is given the table below.

Figure 3.4: Aggregate Crushing Test

TABLE 3.8: PROPERTIES OF NATURAL AND RECYCLED COARSE AGGREGATE					
Content	**Flakiness index (%)**	**Aggregate impact value (%)**	**Aggregate crushing value (%)**	**Specific gravity**	**Water absorption (%)**
Normal Coarse aggregate	25	13.04	16.71	2.65	0.81
Recycled Coarse Aggregate	19	37.93	26.23	2.25	4.023

3.4.5 Water: Cement Ratio

The water: cement ratio is the ratio of the weight of water to the weight of cement used in a concrete mix and influences the quality of the concrete. To achieve high strength, it is necessary that the water cement ratio should be lower. But the problem that lies with lower water cement ratio is that mixing, handling and placing this concrete become more difficult. To solve this problem, special plasticizers can be employed in the concrete mix. If water level is in excess, setting time of fresh concrete is delayed and the segregation of coarse and fine aggregates takes place. In this dissertation, the water: cement ratio was 0.45.

3.5 Preparation of Specimens

3.5.1 Mix Design

In mix design of the concrete, the coarse and fine aggregates, Portland cement and water, are used in the production of the concrete. It may also contain some other cementitious materials (slag, fly ash, silica fume) and chemical admixtures. IS 10262-2009, states that as far as possible, the selection of concrete proportions should be based on experience or on test data of the materials actually to be used. The following information of available materials will be useful:

• Grading analysis of coarse and fine aggregate particles.
• Relative density of coarse and fine aggregate.

• Required amount of mixing water of concrete for available aggregates.

• Relationship between water: cement ratio and other cementitious materials and strength of concrete.

• Specific gravity of cement and other cementitious materials, if used.

In this thesis it was the aim to make concrete with target strength 30 MPa. IS 10262-2009 concrete mix design was followed and details of the mix design of NA and RCA concrete is already shown in Table 3.10.

A total of three series were prepared in the laboratory which is discussed as under:

- The concrete mixtures in series I, II and III were prepared with OPC content of 438 kg/m^3 and water to cement ratio of 0.45.. In concrete mixtures, the 10 mm and 20 mm aggregates were used in relative percentage of 35% and 65% respectively.
- In this study, the recycle aggregate was used as 0, 50 and 100 percent by weight replacements of the natural coarse aggregates.
- In series II, fly ash was used as 25, 35 and 55% by weight replacement of the cement.
- In series III, silica fume was used as 5, 10 and 15% by weight replacement of the cement.

The mix notations of concrete mixture in three series are shown in table 4.9 below

TABLE 3.9: MIX NOTATION OF CONCRETE MIXTURE				
SERIES	**FLY ASH (%)**	**SILICA FUME (%)**	**RECYCLED AGGREGATE (%)**	**NOTATION**
I	0	0	0	**R0**
	0	0	50	**R50**
	0	0	100	**R100**
II	25	0	0	**R0 F25**
	25	0	50	**R50 F25**
	25	0	100	**R100 F25**
	35	0	0	**R0 F35**
	35	0	50	**R50 F35**
	35	0	100	**R100 F35**
	55	0	0	**R0 F55**
	55	0	50	**R50 F55**
	55	0	100	**R100 F55**
III	0	5	0	**R0 SF5**
	0	5	50	**R50 SF5**
	0	5	100	**R100 SF5**
	0	10	0	**R0 SF10**
	0	10	50	**R50 SF10**
	0	10	100	**R100 SF10**
	0	15	0	**R0 SF15**
	0	15	50	**R50 SF15**
	0	15	100	**R100 SF15**

*** R= recycled aggregate concrete added by % weight of natural coarse aggregate**
F= fly ash added by % weight of cement
SF = silica fume added by % weight of cement

TABLE 3.10: MIX DESIGN PROPORTIONS OF CONCRETE										
SERIES	**FA %**	**SF %**	**RA %**	**Notation**	**water (Kg/m^3)**	**cement (Kg/m^3)**	**S.F. (Kg/m^3)**	**sand (Kg/m^3)**	**C.A. (Kg/m^3)**	**R.A. (Kg/m^3)**
I	0	0	0	R0	193.00	438.00	0.00	628	1153	0
	0	0	50	R50	193.00	438.00	0.00	628	576	559
	0	0	100	R100	193.00	438.00	0.00	628	0	1124
II	25	0	0	R0 F25	193	328.5	109.5	613	1153	0
	25	0	50	R50 F25	193	328.5	109.5	613	576	559
	25	0	100	R100 F25	193	328.5	109.5	613	0	1124
	35	0	0	R0 F35	193	284.7	153.3	593	1153	0
	35	0	50	R50 F35	193	284.7	153.3	593	576	559
	35	0	100	R100 F35	193	284.7	153.3	593	0	1124
	55	0	0	R0 F55	193	197.1	240.9	564	1153	0
	55	0	50	R50 F55	193	197.1	240.9	564	576	559
	55	0	100	R100 F55	193	197.1	240.9	564	0	1124
III	0	5	0	R0 SF5	193.00	187.25	250.76	613	1153	0
	0	5	50	R50 SF5	193.00	187.25	250.76	613	576	559
	0	5	100	R100 SF5	193.00	187.25	250.76	613	0	1124
	0	10	0	R0 SF10	193.00	177.39	260.61	593	1153	0
	0	10	50	R50 SF10	193.00	177.39	260.61	593	576	559
	0	10	100	R100 SF10	193.00	177.39	260.61	593	0	1124
	0	15	0	R0 SF15	193.00	167.54	270.47	564	1153	0
	0	15	50	R50 SF15	193.00	167.54	270.47	564	576	559
	0	15	100	R100 SF15	193.00	167.54	270.47	564	0	1124

3.6 Specimen Casting and Curing

In this section detailed procedure for different tests are discussed.

3.6.1 Workability

Workability of the concrete refers to easiness with which the concrete can be placed and casted into any desired shape and size at any given position after mixing of all the ingredients of the concrete. Workability of concrete is similar to the “consistency” as both refer to the ability of fresh concrete to flow.

Normally a slump test is carried out to measure the workability of concrete. An “Abrams cone” is used to measure the slump of a fresh batch of concrete. The cone is placed on a levelled non absorbing surface. The cone is filled in three layers with each layer being tampered 25 times with steel rod. Then the cone is lifted and the concrete is allowed to flow. The fall in the level of the concrete is called as slump value.. A relatively dry concrete sample will slump very little and will have a slump value of 25 or 50 mm whereas a relatively wet concrete sample may slump almost 200mm.

The slump of concrete can have various shapes called true slump, shear slump and collapse slump as shown in Figure 4.5. If the slump falls under shear or collapse slump, the slump test must repeated again as a collapsed slump indicates that the mix is too wet which may lead to the segregation of the aggregates.

Typical slump range of concrete in different application has shown in Table 3.11

TABLE 3.11: SLUMP RANGE OF CONCRETE IN DIFFERENT APPLICATIONS

Concrete Mix type	Slump range (mm)	Application
Very dry	0-25	Road construction
Low workability	10-40	Foundation with light reinforcement
Medium workability	50-90	Normal reinforcement concrete with little vibration
High workability	>100	Normal reinforcement concrete

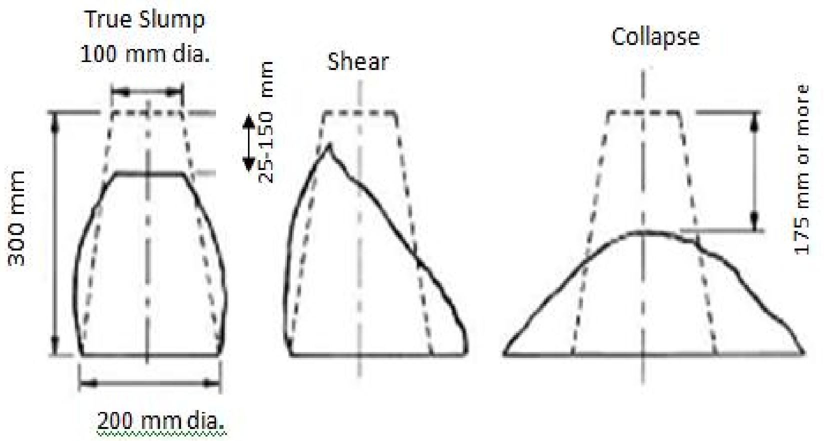

Figure3.5 Typical slump shades of concrete

3.6.2 Air Content of Concrete

The air content in the concrete is necessary as it is necessary for proper compactness of the concrete. Sometimes air is added to the concrete by adding certain admixtures which entraps the air between their particles. If air is present in the concrete, the resistance to freeze thaw cycle increases. Another advantage of having air entrapped is that it can lead to low water demand which reduces the risk of bleeding and segregation. High level of air content is also harmful as it causes difficulty in finishing.

In this research work, pressure method is used to calculate the air in the concrete.

The general recommendations on this regard are shown in Table 3.12.

Table 3.12 Recommended total target air content for concrete (Source: BS EN 12350-7:2000)

Nominal Maximum size of aggregate (mm.)	% air content		
	Severe exposure	Moderate exposure	Mild exposure
9.5	7.5	6	4.5
12.5	7	5.5	4
19.0	6	5	3.5
25.0	5.5	4.5	3

Pressure Method

The basic principle followed is Boyle's law which states that the applied pressure is proportional to the volume occupied by air. There are two types of meters designated by A and B. The type B meter is used which is shown in Figure 3.9 and consists of a separate air chamber connected through a valve to the test bowl that is filled with concrete.

The basic operation of this apparatus is that there are two valves. When the valve is closed, the air chamber can be set at a predetermined pressure. When the valve is opened, the air present in the concrete expands in the test chamber. Due to this, there is pressure drop which is in proportion to the air contained within the concrete sample. The pressure gauge is read in units of air content.

Figure 3.6: Air content apparatus

(Source: QC & D Lab, HPPWD, Shimla)

3.6.3 Bleeding Test

There is standard method to measure the bleeding of the concrete mixture. There is a cylindrical container with diameters of 290 mm and 285 mm at the top and bottom respectively, and a height of 285mm. The fresh concrete is poured into the container in two layers and vibrated for 10 seconds for each layer on vibrating table. During this entire process, the container was covered with a lid to prevent evaporation of the water. The container after vibration is kept on a levelled surface. A pipette was used to draw off the bleed water for at 10 minutes interval during the first 70 minutes and at 30 minutes interval thereafter until cessation of bleeding.

In this study, the test was started at 30, 60, 120 minutes after mixing. For these additional tests, the concrete used earlier was remixed and reused. Again, the same procedure was followed.

The weight of the test samples with fresh concrete weighed 20 kg.

Bleeding water per unit area of surface was calculated as follows:

$V=V_1/A$ ....equation 3.1

Where,

V_1= volume of bleeding water measured during the selected time interval, mL, and

A= area of exposed concrete, cm^2

The accumulated bleeding water, expressed as a percentage of the net mixing water contained with the test specimen was calculated as follows:

$C= (w/W) \times S$ ....equation 3.2

Bleeding, % = (D/C) x 100

Where,

C = mass of water in the test specimen, g,

W = total mass of the batch, kg,

w= net mixing water (the total amount of water minus the water absorbed by the aggregates), kg ,

S = mass of the sample, g, and

D = mass of the bleeding water, g, or total volume withdrawn from the test specimen in cubic centimetres multiplied by $1 g/cm^3$

3.6.4 Static Compressive Strength Test

Three cube specimens for each mix of size 150×150×150mm were casted for static compressive strength for 3 day, 7 day and 28 day. For each batch of concrete, the quantities of cement, coarse aggregate, fine aggregate, silica fume, fly ash and water were weighed separately. The cement, silica fume and fly ash were mixed dry to a uniform colour separately. Then water was added to the mix. Firstly, 50 to 70% of water was added to the mix and then mixed thoroughly for 3 to 4 minutes. The cubes are filled with fresh concrete using vibrating table. Immediately after casting cubes, the specimens are covered with gunny bags to prevent water evaporation. The compressive strength is calculated by dividing the failure load by average cross sectional area. The compressive strength testing machine of capacity 5000 kN is used for determining the maximum compressive loads carried by concrete cubes. At the test age, the specimens are taken out of the curing tank and kept outside for 10 minutes. Then one specimen is placed on the steel plate of the machine such that the specimen is tested perpendicular to the casting position. Then the test is carried out at the loading rate of 5 kN/s specified IS: 516 - 1959. Maximum load on the specimen was recorded as load at which specimen failed to take any further increase in load

3.6.5 Splitting Tensile Strength Test

Three cylindrical specimens of 150Ømm diameter and 300mm height were casted for splitting tensile strength. The quantities of cement, coarse aggregate, fine aggregate, silica fume, fly ash and water for each batch replacement was weighed separately. The cement, silica fume and fly ash were mixed dry to a uniform colour separately depending upon the mix batch. Fine aggregate was mixed to this mixture in dry form. The coarse aggregates were mixed to get uniform distribution throughout the batch. Water added to the mix. Firstly, 50 to 70% of water was added to the mix and then mixed thoroughly for 3 to 4 minutes. The moulds were filled with fresh concrete and were vibrated properly. After casting the cylinders were covered to prevent evaporation of water. Three cylinders were casted for each mix. The tests were carried out on 7 day and 28 day.

The cylinders were tested by placing them uniformly in the compression testing machine of capacity 5000 kN. This test was performed on Compression Testing Machine (CTM) as shown in figure 4.8. The test is carried out at the loading rate of 1 kN/s specified IS: 5816 -1999.

The magnitude of tensile stress acting uniformly to the line of action of applied loading is given by formula

f_{ct}= 2P/ πlD ....equation 3.3

where

f_{ct} = split tensile strength , (N/mm^2)

P = maximum applied load to the specimen, (N)

l = length of the specimen (mm)

D = cross sectional dimension of the specimen, (mm)

Figure 3.7: Testing of splitting tensile strength

(Source: Concrete Lab, Thapar University, Patiala)

3.6.6 Flexural Strength Test

Three beams of size 700×150×150mm were casted for flexural strength. The quantities of cement, coarse aggregate, fine aggregate, silica fume, fly ash and water for each batch replacement was weighed separately. The cement, silica fume and fly ash were mixed dry to a uniform colour separately. Fine aggregate was mixed to this mixture in dry form. The coarse aggregates were mixed to get uniform distribution throughout the batch. Water added to the mix. Firstly, 50 to 70% of water was added to the mix and then mixed thoroughly for 3 to 4 minutes. The moulds were filled with fresh concrete and were vibrated properly. After casting the cylinders were covered to prevent evaporation of water. Three beams were casted for each mix. The test was carried out on 28 day.

The beams were tested by placing them uniformly in the universal testing machine of capacity 1000 kN. Specimen were taken out from curing tank at the age of 28 days of standard curing and tested after surface water dipped down from specimens. This test was performed on universal testing machine (UTM) as shown in figure 4.9. The test is carried out at the loading rate of 70 kN/min.

The magnitude of flexural stress acting uniformly to the line of action of applied loading is given by formula

$f_b = p \times l / b \times d^2$ ....equation 3.4

where

f_b = flexural strength in N/mm^2

p = maximum applied load to specimen in Newton

l = length of the span on which the specimen was supported

b = measured width of the specimen

d = measured depth of the specimen at point failure

Figure 3.8: testing for flexural strength

(Source: Concrete Lab, Thapar University, Patiala)

3.6.7 Rapid Chloride Permeability Test

Two cylindrical specimens of 100Ømm diameter and 200mm height were casted for rapid chloride permeability test. The quantities of cement, coarse aggregate, fine aggregate, silica fume, fly ash and water for each batch replacement was weighed separately. The cement, silica fume and fly ash were mixed dry to a uniform colour separately depending upon the mix batch required. Fine aggregate was mixed to this mixture in dry form. The coarse aggregates were mixed to get uniform distribution throughout the batch.

Water was added to the mix. Firstly, 50 to 70% of water was added to the mix and then mixed thoroughly for 3 to 4 minutes in mixer. The moulds were filled with fresh concrete and were vibrated properly. After casting the cylinders were covered to prevent evaporation of water. Two cylinders were casted for each mix. The test was carried out on 28 day

The test method (according to ASTM C 1202-97) covered the determination of the electrical conductance of concrete to provide a rapid indication of its resistance to the penetration of chloride ions. According to Table 3.13, the chloride ion penetrability was decided on the basis of charge passed. Specimens were placed in the vacuum desiccator's bowl as shown in Fig 4.10 which illustrates the setup of the vacuum pump, desiccator with stopcock, vacuum gauge and valve and the de-aerated water container after the water has filled the desiccators. The vacuum was maintained in the desiccators bowl for 3 hours. The de-aerated water was allowed to flow into the desiccator, so that it completely covers the specimens and no air was allowed to enter. The test method consisted of monitoring the amount of electrical current passed through 50 mm thick slices of 100 mm nominal diameter cylinders for a 6-h period.

A potential difference of 60 V dc was maintained across the ends of the specimen, one of which was immersed in a sodium chloride solution, the other in a sodium hydroxide solution (3.0% NaCl and 0.3 N NaOH solutions) were filled in the two cells. The total charge passed, in coulombs, was related to the resistance of the specimen to chloride ion penetration.

Charge passed (coulombs)	Chloride ion permeability

>4000	High
2000 – 4000	Moderate
1000 – 2000	Low
100 – 1000	Very low
<100	Negligible

Figure 3.9 Chloride ion penetrability based on charge passed (ASTM 1202-97)

Figure 3.10: Vacuum desiccators bowl

(Source: Concrete Lab, Thapar University, Patiala)

Figure 3.11: Rapid chloride permeability test

(Source: Concrete Lab, Thapar University, Patiala)

3.6.8 Carbonation Test.

Carbonation of concrete refers to the process by which carbon dioxide present in the air penetrates into the concrete through pores and reacts with calcium hydroxide to form calcium carbonates responsible for lower pH. An accelerated carbonation test was carried out using carbonation air dried specimens of cubes were sealed with an epoxy resin coating on all four sides and kept in chamber for 28 days. A temperature of 20°C, relative humidity 65% and CO_2 concentration 20% were maintained in the carbonation chamber during the test. After 28 days, all the cubes were fractured in two halves and observed for carbonation by phenolphthalein test. Phenolphthalein solution consisted of 1% solution in 70% ethyl alcohol and the solution was sprayed onto the concrete surface. Before spraying of solution, concrete surface was cleaned of dust and loose particles. Alkaline nature of the concrete was observed due to the change in colour of phenolphthalein. If there is no coloration, it means that the carbonation has taken place and the depth of the carbonated surface layer can be measured.

3.6.9 Water Penetration Test

The very basic procedure in this test is that water is applied to the specimen at certain pressure for a specified duration of time. After completion of specific period, the specimen is bifurcated perpendicularly to the face along which the water is injected. After, splitting, the depth of penetration is determined. The test is carried out according to German Standard DIN 1048 on concrete specimens of size 150x150x150 mm, at an age of 28 days.

In the test cell assembly, three cubes could be tested at same time. Once the cube specimens were placed in the test cells, a water pressure at steady rate of 300 KPa (3 bar) was applied for 72 hours. The steady water pressure was applied by using an arrangement which consisted of a water tank connected to an air compressor through a valve, to adjust the pressure according to required rate.

FIGURE 3.12: Water penetration test

(Source: Concrete Lab, Thapar University, Patiala)

Figure 3.13: Sample ready for splitting test **Figure 3.14 Water penetrated Sample**

Figure 3.15 Sample after splitting **Figure 3.16 Water penetrated Sample**

3.6.10 Ultrasonic Guided Waves

In all cubes of size 150 cm x 150 cm x 150cm were cast. A mild steel bar of diameter 25mm was embedded in each slab at the centre position(7.5cm,7.5cm,7.5cm in global coordinates).The testing apparatus consisted of a DPR 300 pulser/receiver which generates pulses for a specified time interval. This pulse after generation is sent to a transducer which converts the signal to an ultrasonic wave. Figure 3.16 shows the experimental setup.

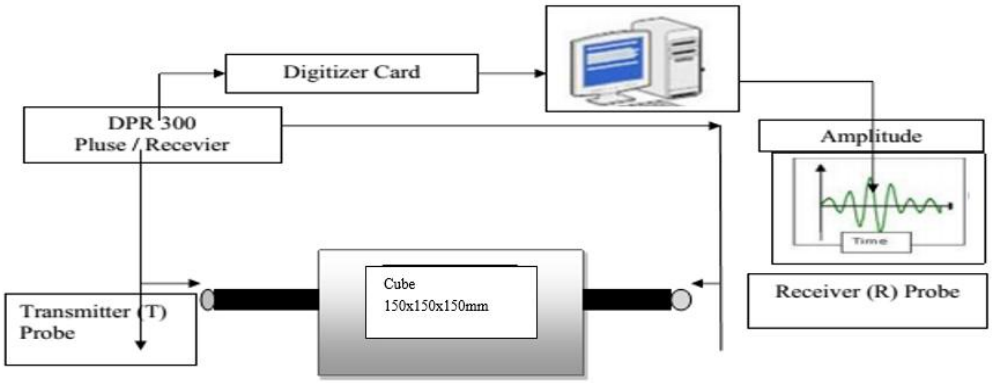

Figure 3.17 Experimental setup of UGW for cube Specimen 150x150x150mm

The ultrasonic pulse propagates through the mild steel bar in form of guided waves. After the concrete setting process starts, the concrete surrounding the mild steel bar begins to bond with the bar thus resulting in attenuation, that is, loss of wave energy. This wave energy loss is due to the absorption of the wave energy by the material and energy leakage into surrounding concrete. Finally, the receiver transducer picks up the wave signal after attenuation and converts it to an electrical signal to be processed by software. Figure 4.17 gives the work flow diagram of the UGW test method.

The key elements of the apparatus were:

a) Transducers: S24 HB 0.1 S and S 24 HB 0.1E (KARL DEUTSCH) were the standard transducers of 0.1 MHz frequency and 24 mm diameter used in this experiment. The transducers are given in Fig 4.18

Figure 3.18 Transducers -S24 HB 0.1 S and S 24 HB 0.1E (KARL DEUTSCH)

b) JSR Ultrasonics DPR 300 Pulser/receiver system:

This device can produce a high voltage electrical excitation pulse upto 475V and transfers this pulse to the instrument's T/R connector. Figure 4.17 shows a sample of the cube while testing.

Figure 3.19JSR Ultrasonics DPR 300 Pulser/receiver system

This device can be configured for both pulse echo and through operations using the computer software. During the echo mode, signals reflected from interfaces or defects within the specimen are converted into electrical signals. The DPR 300 amplifies the signals before these are passed through adjustable high pass and low pass filters.   Figure 4.19 shows the pulser- receiver system and table 3.13 shows the specifications for the same.

Table 3.13 Specifications of JSR pulse-receiver

Pulser	
Pulse Type	Negative Spike Pulse
High Voltage Supply	100Vto475V
Initial Transition (Fall Time)	<5ns(10-90%)typicalfor475Vpulsars
Pulse Amplitude	-475Vpeak. Amplitude depends on Energy, Impedance, Damping control settings, and pulser type
Pulse Energy	1.55µJoulesminimum, 304µJoulesmaximumfor475Vpulsers. Dependent upon energy and voltage setting
Pulse Duration	Typically10-70nsFWHMfor50 Ω load. Function of the Energy, Impedance, and Damping controls
Damping	16Dampingvalues:331,198,142,110,92,77,67,59,52,47, 43, 39,37,34,32, and30Ω
Mode	Pulse-echo or through transmission
Through Mode Isolation	Typically80dBat10MHz
Pulser Repetition rate	Internal: 100 Hz -5 kHz for 475V pulsers. External: 0-5 kHz for 475 V pulsers.
Sync Output	Maximum +5V, tr<30ns, tw=50ns.min. TTL and CMOS compatible. Minimum value of load impedances 50Ω
Pulser Trigger Source	Selectable by computer between internal oscillator and external source
External Trigger Input	2-5Vpositive going pulse. Triggering will occur synchronously with leading edge of trigger signal. TTL and CMOS compatible
Receiver	
Gain	-13to66dBin1dBstepscontrolledbythe host computer
Phase	0°(non-inverting)
Input Impedance	500Ω (through transmission)

Bandwidth	.001-35MHz(-3dB)or.001-50MHZ
High Pass Filter	DC,1,2.5,5,7.5and12.5MHz
Low Pass Filter	3,7.5,10,15,22.5(35MHzBW)or5,10,15,22.5,35(50MHzBW)
Pulse Energy	1.55 µ Joules minimum, 304 µ Joules maximum for 475V pulsers. Dependent upon energy and voltage setting
Pulse Duration	Typically10-70nsFWHMfor50 Ω load. Function of the Energy, Impedance, and Damping controls
Damping	16Dampingvalues:331,198,142,110,92,77,67,59,52,47, 43, 39,37,34,32, and30Ω
Mode	Pulse-echo or through transmission
Through Mode Isolation	Typically80dBat10MHz
Pulser Repetition rate	Internal: 100 Hz -5 kHz for 475V pulsers. External: 0-5kHz for 475 Vpulsers.
Sync Output	Maximum+5V, tr<30ns, tw=50ns.min. TTL and CMOS compatible. Minimum value of load impedanceis 50Ω
Receiver Noise	Typically49µVpk-pkinputreferred(measuredat60dB,35MHz bandwidth)
Output Impedance	50Ω
Output Voltage	±0.5Vinto50Ω
Receiver Noise	Typically49µVpk-pkinputreferred(measuredat60dB,35MHz bandwidth)
Output Impedance	50Ω
Output Voltage	±0.5Vinto50Ω

Excitation mode and frequency:

The selection of a suitable test mode and frequency is done after analyzing the dispersion curves using the software Disperse. According to Sharma and Mukherjee (2010), modes that have lowest signal attenuation and at the same time are easily distinguishable are selected. Generally, modes at low attenuation are used to maximize the inspection range and at the same time to minimize the effects of dispersion and also minimize the interference of other modes in the received signal. Curves for a mild steel bar of 25mm diameter are shown in figure 3.21.

Testing procedure:

KARL DEUTSCH contact transducers with a central frequency of 0.1 MHz was chosen and its surface was applied with an ultrasonic gel. This gel helps to make the surface smooth and remove the air gap. The transducers are then connected to the ends of the mild steel bar embedded in the concrete slab. One transducer acts as a transmitter and the other as a receiver. The transducers used had longer wave form duration and a relatively narrow frequency bandwidth with central frequency of 0.1 megahertz as the objective was to monitor bonding between the mild steel bar and the surrounding concrete in the slab.

Figure 3.21 shows the specimen details for UGW tests.

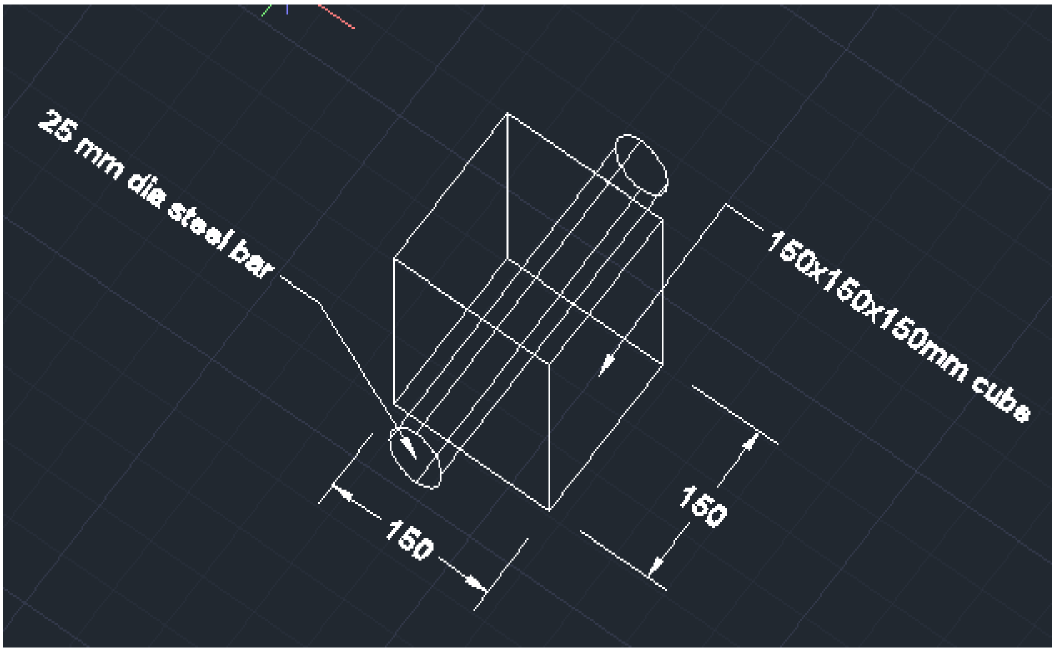

Figure 3.21 Cube specimen for UGW testing

CHAPTER - 4
RESULTS AND DISCUSSIONS

4.1 Introduction

The properties measured are the only way to compare the conventional concrete and recycled aggregate concrete. The concrete produced from recycled coarse aggregate must have properties similar to that of conventional concrete. The resultant properties of the recycled aggregate concrete must prevail between the standard guidelines and the specifications as laid for the conventional concrete. In this chapter, the results obtained from different tests conducted on recycled aggregate concrete (RAC) are presented and then these properties are analysed whether the values of these properties meet the standard criteria laid down for standard structural concrete.

The tests conducted on RAC and NAC were conducted on fresh stages to compare these two concretes. Fresh stage tests conducted were slump, air content and bleeding test. After hardening of concrete, tests performed were compressive strength test, split tensile strength and flexural test. To compare the durability parameters of the different type of concretes, tests performed were rapid chloride permeability test, carbonation depth and ultrasonic guided waves.

The results of the performed tests are discussed in the later part given below:

4.2 Slump of Concrete

The slump values obtained fir different series of mixes with NCA and RCA are presented in Table 4.1 and figure 4,1 respectively. The water cement ratio for control sample was 0.45.

Table 4.1: Slump values for different concrete mixes prepared

Mix	Slump (mm)
R0	118
R0 F25	105
R0 F35	125
R0 F55	92
R0 SF5	109
R0 SF10	114
R0 SF15	132
R50	87
R50 F25	75
R50 F35	68
R50 F55	58
R50 SF5	60
R50 SF10	69
R50 SF15	74
R100	28
R100 F25	35
R100 F35	46
R100 F55	52
R100 SF5	38
R100 SF10	51
R100 SF15	60

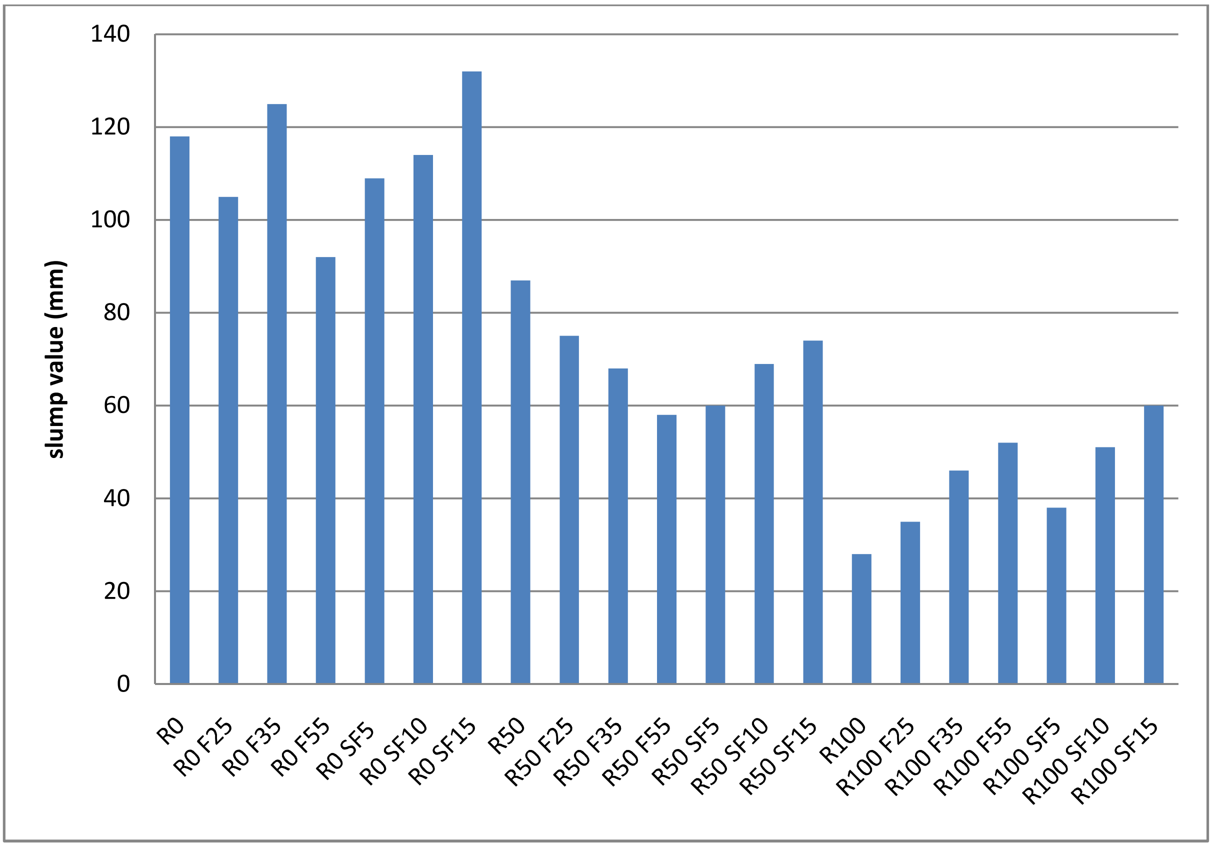

FIG.4.1: Slump values

- The initial slump value measured for R0 (NCA=100%) was 118 mm and 28 mm for R100 (RAC=100%), respectively (Figure 4.1). The main reason for the above values is mainly due to the fact that absorption capacity of RCA is quite high due to adhered mortar paste in comparison to NAC.
- The value of slump at the respective replacement levels by recycled coarse aggregates increased, when fly ash and silica fume was added to the concrete mix. The reason behind such behaviour is that the particle size of fly ash and silica fume are finer than the cement particles. Moreover, the particles of fly ash and silica fume are spherical also. So the added fly ash and silica fume particles act as 'ball bearing effect'. The lighter particles (fly ash and silica fume) act as a ball bearing between heavier particles that exists in the concrete matrix.
- Furthermore, in case of silica fume, the slump value for higher even at less percentage of silica fume than the batch with same replacement level containing more percentage of fly ash. For example, at 50% replacement level, the slump value of silica at 15% was 74 mm whereas for fly ash with 55%, the value was 55 mm. This

may be due the reason that silica fume particles are finer as compared to that of fly ash.

- At 50% replacement level, the slump value was high which means that the recycled aggregate concrete is easily workable and there was no difficulty in compacting and placing of the concrete.

Figure 4.2 Slump for RAC50 %

Figure 4.2 Slump for RAC 100 %

4.3 Compressive Strength

Three cubes (150mm) from each batch of concrete mix are casted and cured for 7 and 28 days in order to determine compressive strength of RCA concrete. Table 4.2 shows the average compressive strength of different mix combinations tested at 3, 7 and 28 days

Table 4.2: Compressive strength at 3days, 7 days and 28 days for different mixes

Designation	3 Day (N/mm^2)	7 Day (N/mm^2)	28 Day (N/mm^2)
R0	17.12	28.02	38.86
R0 F25	16.82	28.93	40.25
R0 F35	15.28	30.18	42.54
R0 F55	13.56	26.13	37.45
R0 SF5	16.94	28.15	41.52

Designation	3 Day (N/mm^2)	7 Day (N/mm^2)	28 Day (N/mm^2)
R0 SF10	16.24	29.83	42.77
R0 SF15	18.88	32.07	46.26
R50	14.94	24.12	34.56
R50 F25	17.02	27.84	39.75
R50 F35	18.13	31.05	42.21
R50 F55	14.07	25.14	35.64
R50 SF5	15.1	27.56	38.64
R50 SF10	17.97	31.54	41.13
R50 SF15	18.76	30.42	42.25
R100	11.8	19.67	26.12
R100 F25	11.4	19.73	29.54
R100 F35	12.14	20.12	39.63
R100 F55	10.1	16.08	32.54
R100 SF5	11.62	17.34	31.34
R100 SF10	10.82	18.25	34.65
R100 SF15	12.25	19.51	39.83

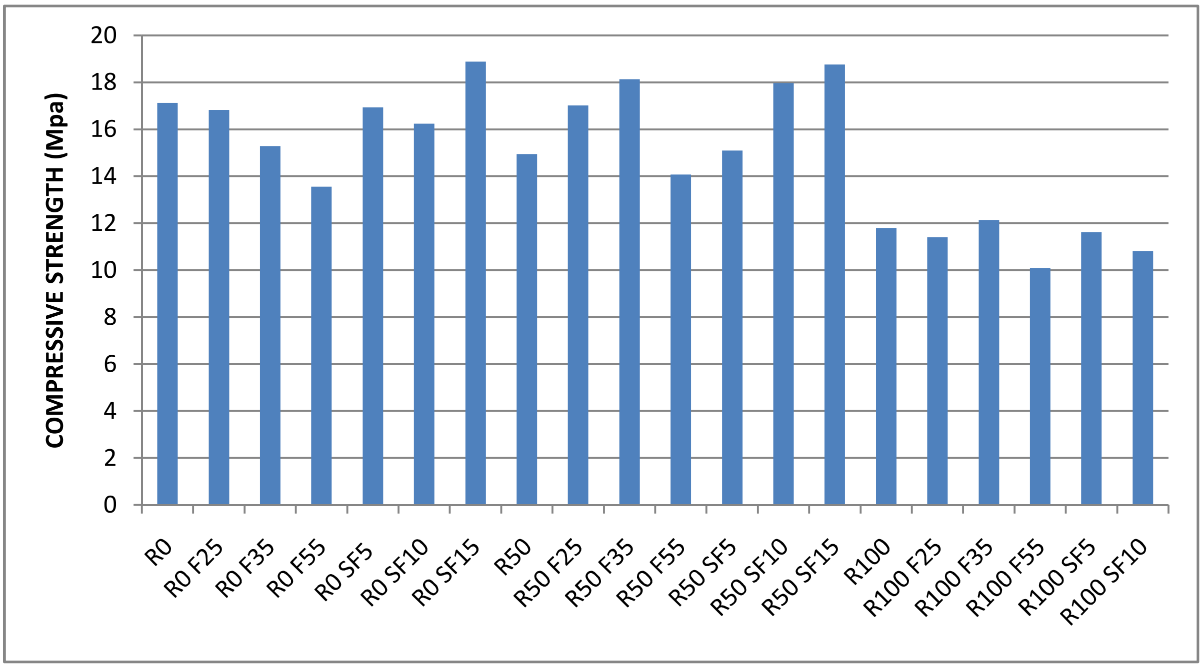

Fig.4.2: Compressive strength at 3 days

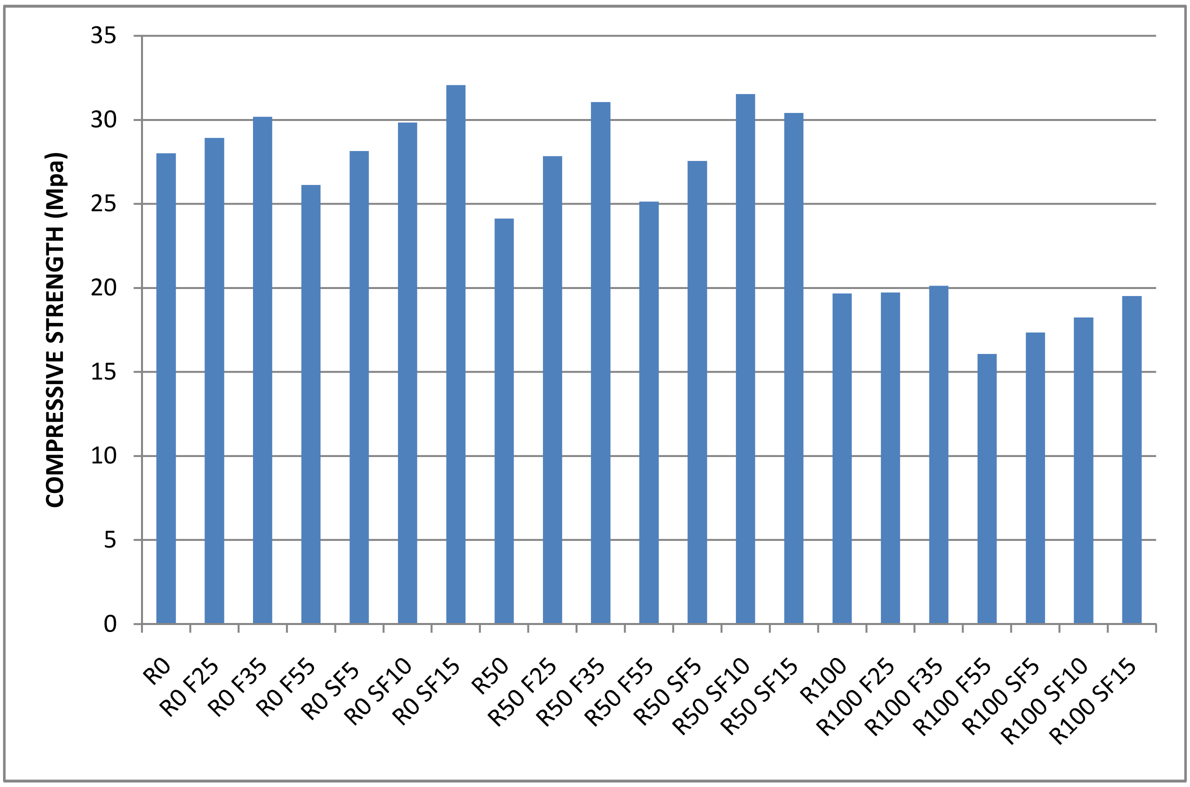

Fig 4.3: Compressive strength at 7 day

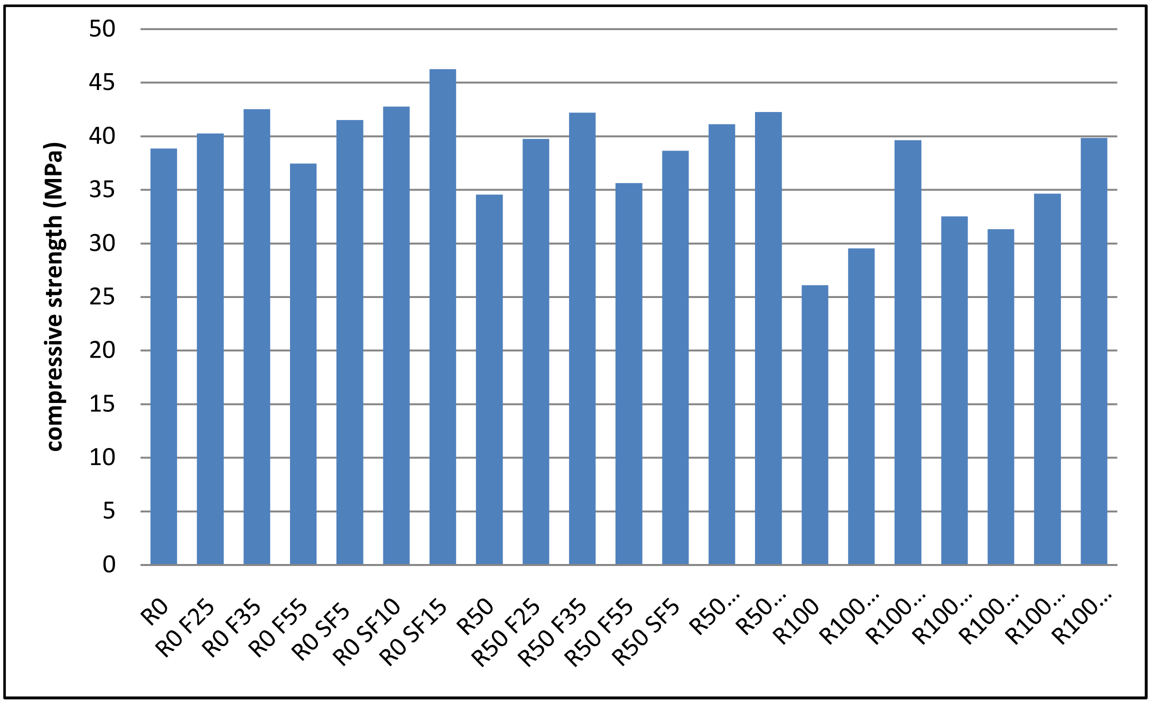

Fig 4.4: Compressive strength at 28 day

From the result in table 4.2 and figures 4.2, 4.3, 4.4, it is observed that

- The compressive strength decreases when recycled aggregate are used without any mineral admixture or other supplementary materials.
- Use of fly ash and silica fume contributed to recover some strength losses of recycled aggregate concrete.

To make a comparative study for the percentage variation of compressive strength of different mixes, a detailed study is carried out as under:

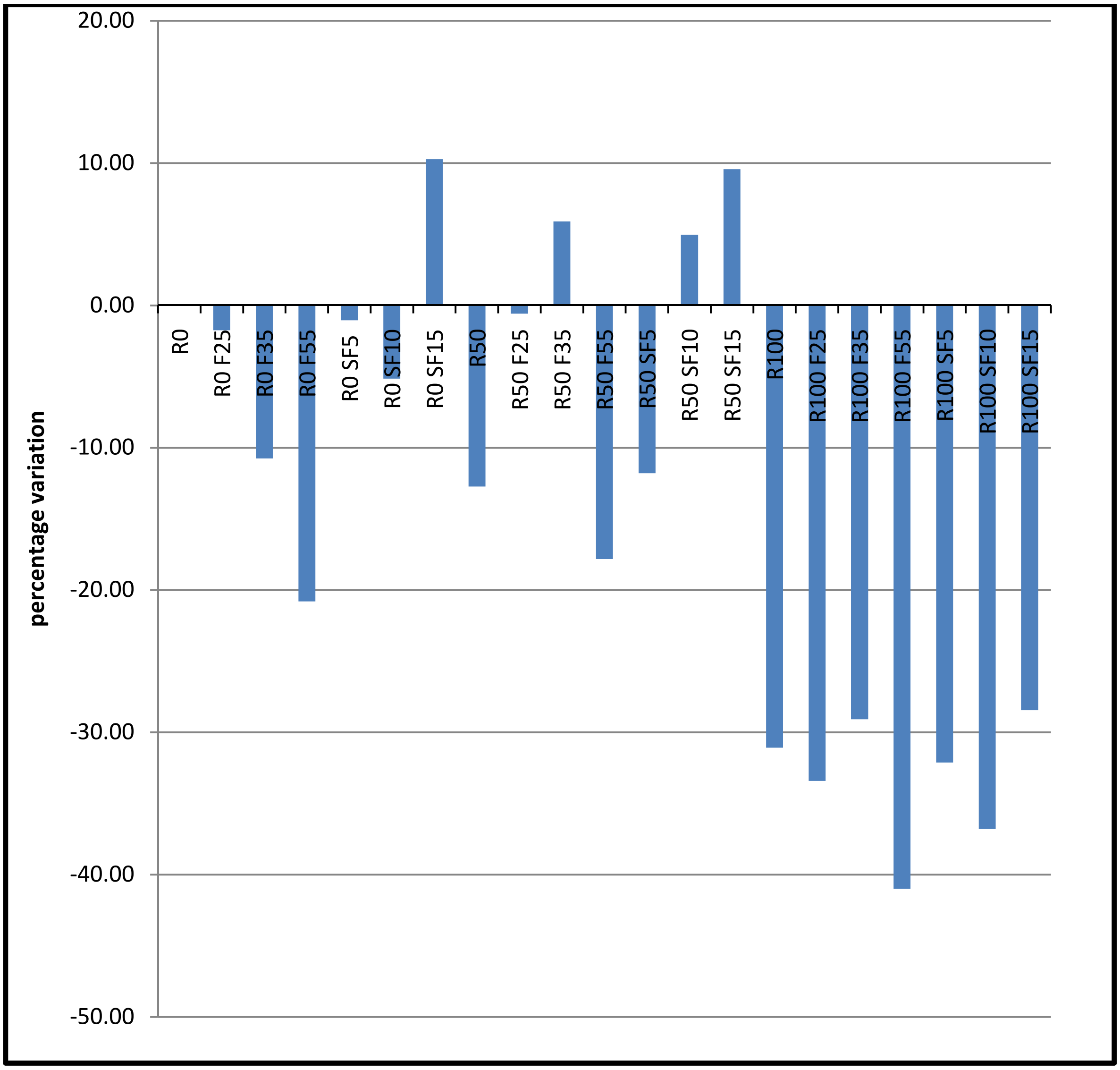

Fig. 4.5: Percentage variation of 3 day compressive strength

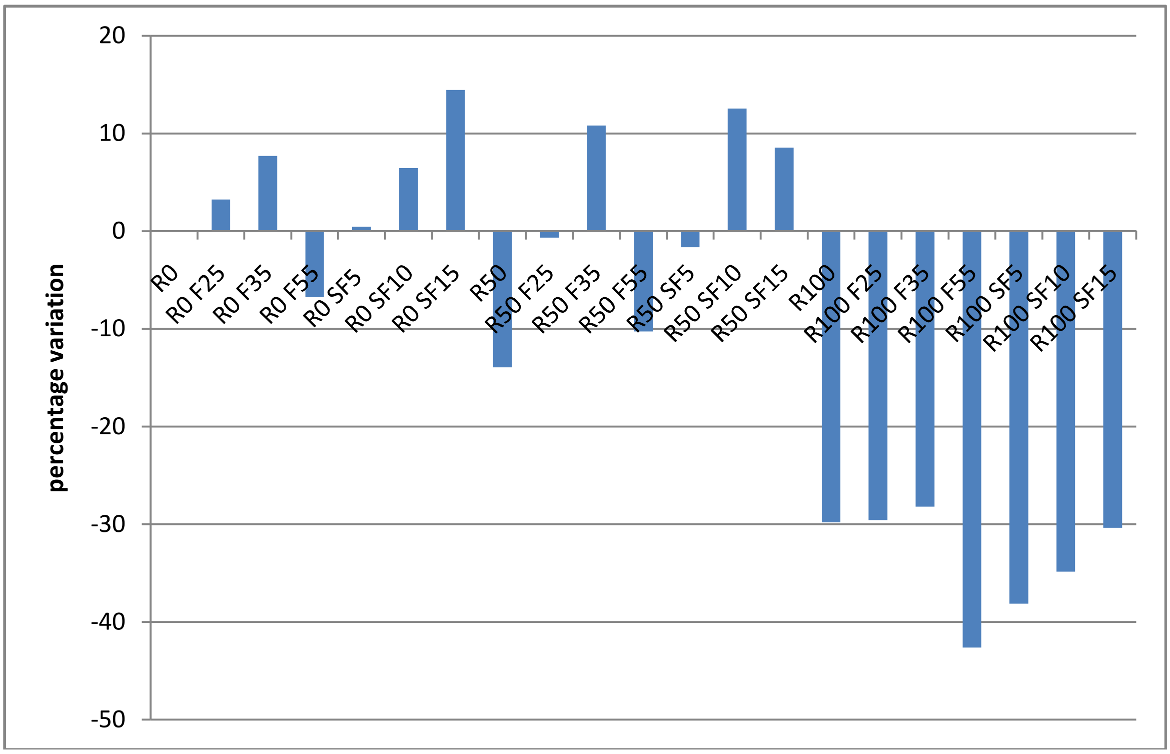

Fig 4.6: Percentage variation of 7 day compressive strength

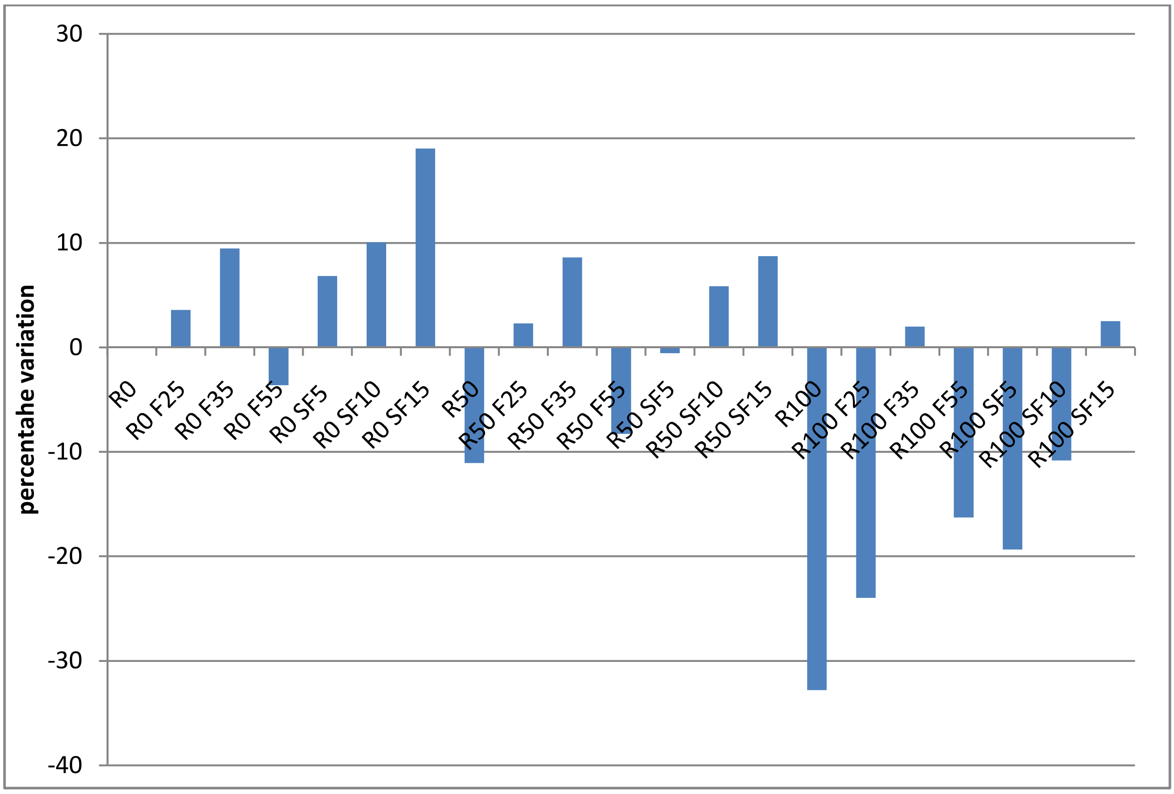

Fig 4.7: Percentage variation of 28 day compressive strength

From figure 4.5, 4.6 and 4.7, it is clear there is considerable variation in the strength at all the stage for all the different mixes. A detailed discussion at each replacement level has been carried out as under:

First we simply replaced natural coarse aggregate with recycled coarse aggregate and studied its effect on the compressive strength of concrete in table 4.2 (a):

Table 4.3 (a) Compressive strength variation at different replacement level of natural coarse aggregate

Replacement level of natural coarse aggregate (% weight of coarse aggregate)	3 days compressive strength variation (%)	7 days compressive strength variation (%)	28 day compressive strength variation (%)
0	-	-	-
50	-12.73	-13.92	-11.07
100	-31.07	-29.80	-32.78

- From table 4.2 (a), it was observed that the compressive strength decreased considerably as the replacement level of natural coarse aggregate is increased.
- As compressive strength decreases, it means that additional supplementary materials are needed to be added.

Table 4.3 (b) Compressive strength variations for different level of fly ash (0% replacement by recycled aggregate)

Replacement level of fly ash (% weight of cement)	3 days compressive strength variation (%)	7 days compressive strength variation (%)	28 day compressive strength variation (%)
25	-1.75	+3.25	+3.58
35	-10.75	+7.7	+9.47
55	-20.79	-6.75	-3.63

- Table 4.2 (b) shows that if we add fly ash in normal concrete as a partial replacement of cement, there is increase in strength.
- If we add fly ash content up to 55%, there is decrease in strength. It may be due to the high content of alumina which slows the pozzolanic action of the fly ash.
- The increase in strength of concrete may be due to the fact that fly ash has a high silica content and finer size of particles.
- From the above table, it is clear that fly ash can be used in recycled aggregate concrete.

At 0% replacement by recycled aggregate the amount of increase, in case of silica fume, compressive strength is shown below:

Table 4.3 (c)Compressive strength variations for different level of silica fume (0% replacement by recycled aggregate)

Replacement level of silica fume (% weight of cement)	3 day compressive strength(% variation)	7 day compressive strength(% variation)	28 day compressive strength(% variation)
5	1.05(decrease)	0.46(increase)	6.85(increase)
10	5.14(decrease)	6.46(increase)	10.06(increase)
15	10.28(increase)	14.45(increase)	19.04(increase)

- Table 4.2(c) clearly shows that if we add silica fume as a partial replacement of cement, there is significant increase in strength. It may attributed to the fact that silica fume has a high silica content which leads to the strong pozzolanic action. This leads to the increase in strength.
- It clearly shows that silica fume can be incorporated in case of recycled coarse aggregate.

At 50% replacement of recycled aggregate the amount of increase, in case of fly ash, the compressive strength is shown in tabular form.

Table 4.3 (d)Compressive strength variations for different level of fly ash (50% replacement by recycled aggregate)

Replacement level of fly ash (% weight of cement)	3 day compressive strength(% variation)	7 day compressive strength(% variation)	28 day compressive strength(% variation)
25	0.58 (decrease)	0.64 (decrease)	2.29(increase)
35	5.90(increase)	10.81(increase)	8.62(increase)
55	17.82(decrease)	10.28(decrease)	8.29(decrease)

- From table 4.2 (d), it is clear that at 25% replacement level of fly ash, there is decrease in strength at initial stages (3 days and 7 days). But at 28 days, there is increase in compressive strength. At initial stages, the strong pozzolanic action takes place due to high amount of alumina. But at later stages, the strong pozzolanic action is complete leading to a strong matrix.
- At 35% replacement level of fly ash, there is increase in strength at all the stages (3 days, 7 days and 28 days) of the recycled aggregate concrete. This is the optimum amount of fly ash which leads to a strong matrix of concrete.
- But at 55% replacement level of fly ash, there is decrease in compressive strength at all stages. It is clear that if we use excess amount of fly ash (55%), there is decrease in strength. It may be attributed to the high amount of alumina.
- We got the best results at 35% of replacement level of fly ash.

At 50% replacement of recycled aggregate the amount of increase, in case of silica fume, the compressive strength is shown in table 4.2 (e)

Table 4.3 (e) Compressive strength variations for different level of silica fume (50% replacement by recycled aggregate)

Replacement level of silica fume (% weight of cement)	3 day compressive strength(% variation)	7 day compressive strength(% variation)	28 day compressive strength(% variation)
5	11.80(decrease)	1.64(decrease)	0.57(decrease)
10	4.96(increase)	12.56(increase)	5.84(increase)
15	9.58(increase)	8.57(increase)	8.72(increase)

- At 5% replacement level of silica fume, there was decrease in strength at all the stages. This means that the amount of silica fume used is deficient.

- At 10% and 15% replacement level of silica fume, there is increase in strength at all the stages. It may due the fact that the silica content is quite high in silica fume and particle sizes are very fine. It means that silica fume has high specific area for strong pozzolanic action leading to s strong matrix of concrete.

At 100% replacement of recycled aggregate the amount of increase or decrease, in case of fly ash, the compressive strength is shown in table 4.2 (f).

Table 4.3 (f)Compressive strength variations for different level of fly ash (100% replacement by recycled aggregate)

Replacement level of fly ash (% weight of cement)	3 day compressive strength(% variation)	7 day compressive strength(% variation)	28 day compressive strength(% variation)
25	33.41(decrease)	29.59(decrease)	23.98(decrease)
35	29.09(decrease)	28.19(decrease)	1.98(increase)
55	41.00(decrease)	42.61(decrease)	16.26(decrease)

- At all stages for all the replacements levels of cement, there is decrease in strength except at 28 days for 35% replacement level
- From above discussion it is clear that optimum level is 35% of fly ash.

At 100% replacement of recycled aggregate the amount of increase or decrease, in case of silica fume, the compressive strength is shown in table 4.2 (g).

Table 4.3 (g)Compressive strength variations for different level of silica fume (100% replacement by recycled aggregate)

Replacement level of silica fume (% weight of cement)	3 day compressive strength (% variation)	7 day compressive strength(% variation)	28 day compressive strength(% variation)
5	32.13(decrease)	38.12(decrease)	19.35(decrease)
10	36.80(decrease)	34.87(decrease)	10.83(decrease)
15	28.45(decrease)	30.37(decrease)	2.50(increase)

- At all stages for all the replacements levels of cement, there is decrease in strength except at 28 days for 15% replacement level of cement by silica fume.
- From above discussion, it is clear that optimum level is 15% of silica fume.

From all of the above discussion,

- It is clear that the strength of the concrete decreased with increase in replacement level of recycled coarse aggregate.
- Then we added supplementary materials in the form of fly ash and silica fume. It was out that by adding these materials; there was increase in strength for some proportions of fly ash and silica fume.
- The best results obtained were observed at 35% replacement level of fly ash and 15% of replacement level of silica fume for respective level of recycled coarse aggregate.

4.4 Split Tensile Strength Test

Split tensile strength studies were carried out at the age 28 days. Test results are given below in Table 4.3 and in figure 4.8:

Table 4.3:Split tensile strength at 28 days

Designation	Split Tensile strength 28 Day (N/mm^2)
R0	3.807
R0 F25	3.854
R0 F35	3.91
R0 F55	3.981
R0 SF5	3.915
R0 SF10	3.961
R0 SF15	4.045
R50	3.412
R50 F25	3.334
R50 F35	3.827
R50 F55	3.612
R50 SF5	3.386
R50 SF10	3.347
R50 SF15	3.882
R100	2.276
R100 F25	2.924
R100 F35	3.785
R100 F55	2.998
R100 SF5	2.665
R100 SF10	3.321
R100 SF15	3.875

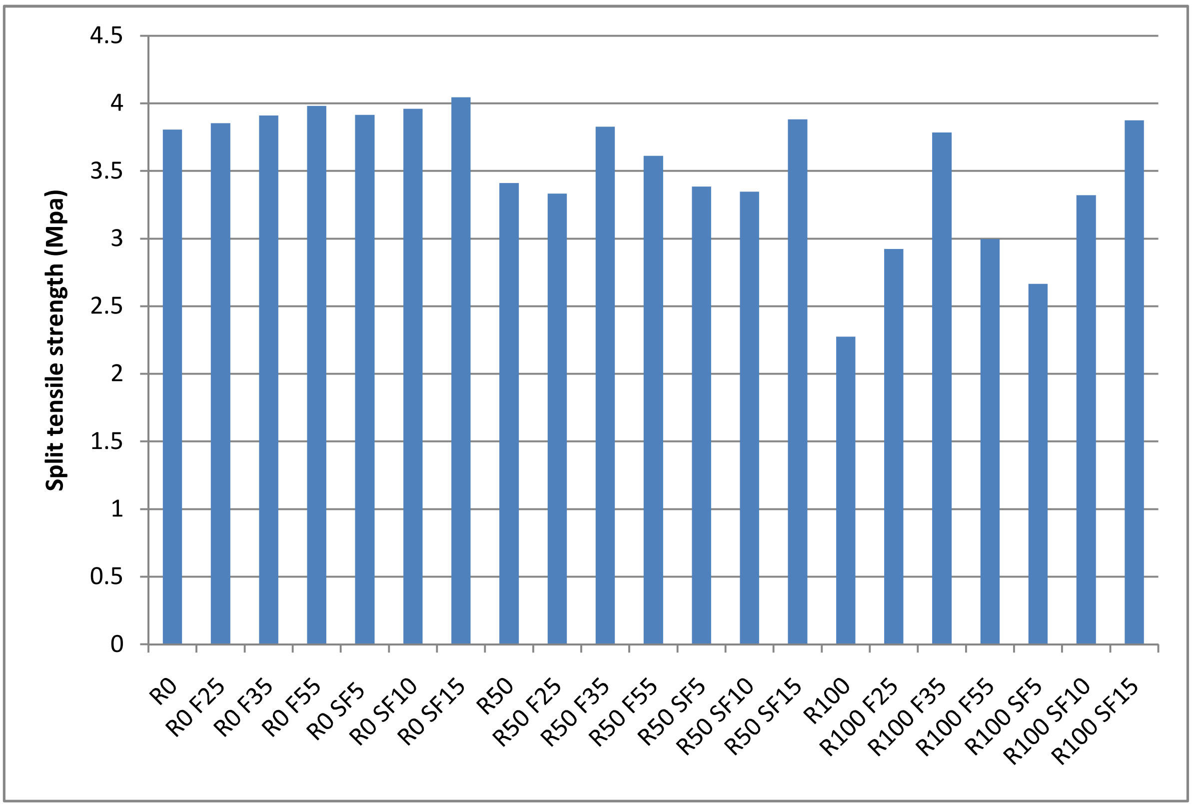

Fig. 4.8: 28 day split tensile strength

The variation in the value of splitting tensile strength has been shown in figure 4.9 and discussed later:

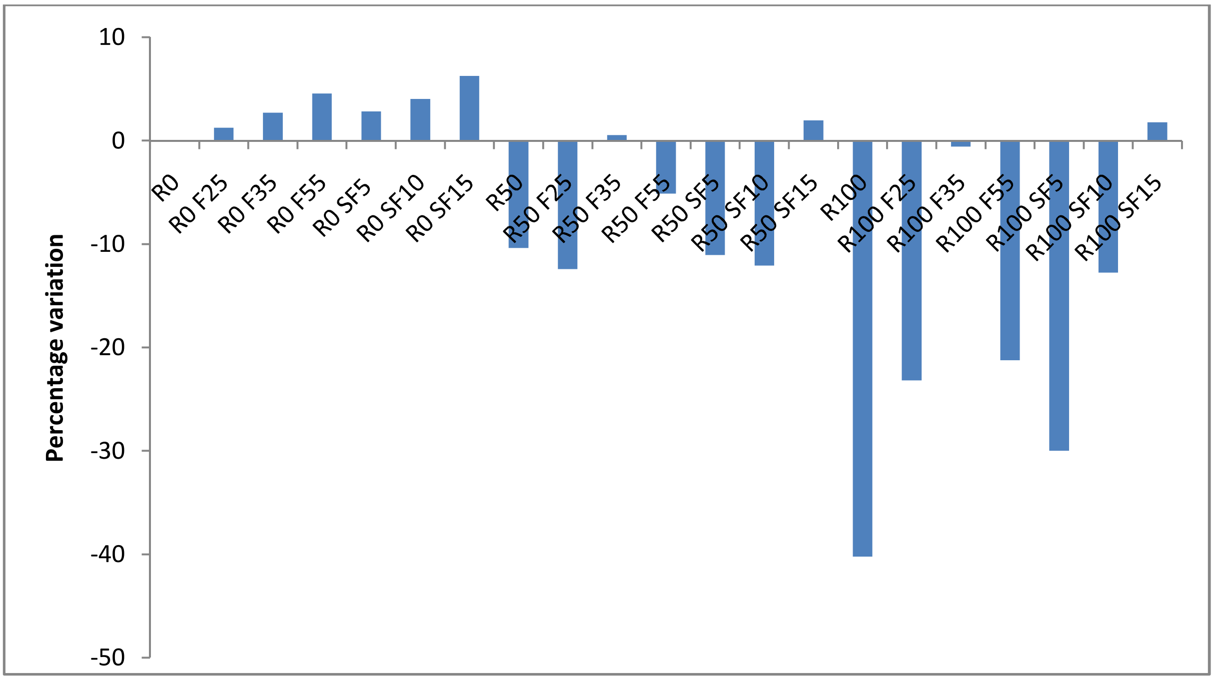

Fig 4.9: Percentage variation of 28 day split tensile strength

First natural coarse aggregate is simply replaced with recycled coarse aggregate. The variation in split tensile strength has been shown in discussed in table 4.4 (a):

Table 4.4 (a)Split tensile strength variation at different replacement level of natural coarse aggregate

Replacement level of natural coarse aggregate (% weight of coarse aggregate)	28 day split tensile strength variation (%)
0	-
50	10.3756(decrease)
100	40.2154(decrease)

- The split tensile strength decreases when recycled aggregate are used without any mineral admixture or other supplementary materials.
- With increase in replacement level of recycled aggregate, the decrease in split tensile strength is quite large.
- This may be due to the fact that recycled coarse aggregate have very less impact and crushing strength than the natural coarse aggregate.

Since the strength decreases, we add supplementary materials like fly ash and silica fume to study its effect on the split tensile strength. First we observe that when we add fly ash and silica fume, its effect on the split tensile strength is studied. At 0% replacements by recycled aggregate, in case of fly ash, the split tensile strength is shown in table 4.4 (b) below:

Table 4.4 (b):Split tensile strength variations for different level of fly ash (0% replacement by recycled aggregate)

Replacement level of fly ash (% weight of cement)	28 day split tensile strength variation (%)
25	+1.23
35	+2.71
55	+4.57

- Use of fly ash contributed to recover some strength losses of recycled aggregate concrete.
- The reason behind such behaviour is that the silica content is quite high as compared to that of cement.

At 0% replacement by recycled aggregate, in case of silica fume, the split tensile strength is shown in table 4.4 (c) below:

Table 4.4 (c):Split tensile strength variations for different level of silica fume (0% replacement by recycled aggregate)

Replacement level of silica fume (% weight of cement)	28 day split tensile strength variation (%)
5	+2.84
10	+4.05
15	+6.25

- Use of silica fume contributed to recover some strength losses of recycled aggregate concrete.
- The reason behind such behaviour is that silica content is high and particles are very fine leading to very high specific area. Due to this, there is increase in pozzolanic activity of silica fume.

At 50% replacement of recycled aggregate the amount of increase, in case of fly ash, the split tensile strength is shown in table 4.2 (d)

Table 4.4 (d)Split tensile strength variations for different level of fly ash (50% replacement by recycled aggregate)

Replacement level of fly ash (% weight of cement)	28 day split tensile strength variation (%)
25	-12.42
35	+0.53
55	-5.12

- When fly ash is added along with recycled coarse aggregate, there is decrease in split tensile strength except for 35% of fly ash.
- The reason behind such behaviour is that fly ash consists of alumina and iron oxide along with silica fume in high quantity. This decreases the pozzolanic activity of fly ash.

At 50% replacement of recycled aggregate the amount of increase, in case of silica fume, the split tensile strength is shown in table 4.2 (e).

Table 4.4(e):Split tensile strength variations for different level of silica fume (50% replacement by recycled aggregate)

Replacement level of silica fume (% weight of cement)	28 day split tensile strength variation (%)
5	-11.06
10	-12.08
15	+1.97

- When silica fume is added upto 10%, there is decrease in split tensile strength. But at 15% of silica fume, there is increase in strength.\
- The reason might due to the fact that silica fume consists of pure silica and fineness of particles is quite high. It means that surface available for pozzolanic activity is very large which contributes to a well packed matrix.

At 100% replacement of recycled aggregate the amount of increase, in case of fly ash, the split tensile strength is shown in table 4.4 (f):

Table 4.4 (f):Split tensile strength variations for different level of fly ash (100% replacement by recycled aggregate)

Replacement level of fly ash (% weight of cement)	28 day split tensile strength variation (%)
25	-23.19
35	-0.58
55	-21.25

- When fly ash is added in 100% recycled coarse aggregate, there is decrease in strength at all the levels. Only in case of 35% of fly ash, the value of split tensile strength is somewhat similar.
- It might be due to the fact that the decrease in split tensile strength due to 100% of recycled aggregate might not be able to compensate by fly ash.

At 100% replacement of recycled aggregate the amount of increase, in case of silica fume, the split tensile strength is shown in tabular form.

Table 4.4 (g)Split tensile strength variations for different level of silica fume (100% replacement by recycled aggregate)

Replacement level of silica fume (% weight of cement)	**28 day split tensile strength (% variation)**
5	-30.00
10	-12.77
15	+1.79

- When fly ash is added in 100% recycled coarse aggregate, there is decrease in strength at all the levels. Only in case of 15% of silica fume, the value of split tensile strength increases marginally.
- It might be due to the fact that the decrease in split tensile strength due to 100% of recycled aggregate is only compensated by 15% of silica fume.

4.5 Flexural Strength Test

Flexural strength studies were carried out at the age of 28 days. Test results are given below in Table 4.4.

Table 4.4: Flexural strength at 28 days

Designation	Flexural strength
R0 F25	5.944
R0 F35	5.974
R0 F55	5.992
R0 SF5	5.891
R0 SF10	6.107
R0 SF15	6.124
R50	4.674
R50 F25	4.715
R50 F35	4.582
R50 F55	4.653
R50 SF5	4.887
R50 SF10	5.154
R50 SF15	5.876
R100	3.798
R100 F25	3.816
R100 F35	5.543
R100 F55	5.231
R100 SF5	3.983
R100 SF10	5.126
R100 SF15	5.645

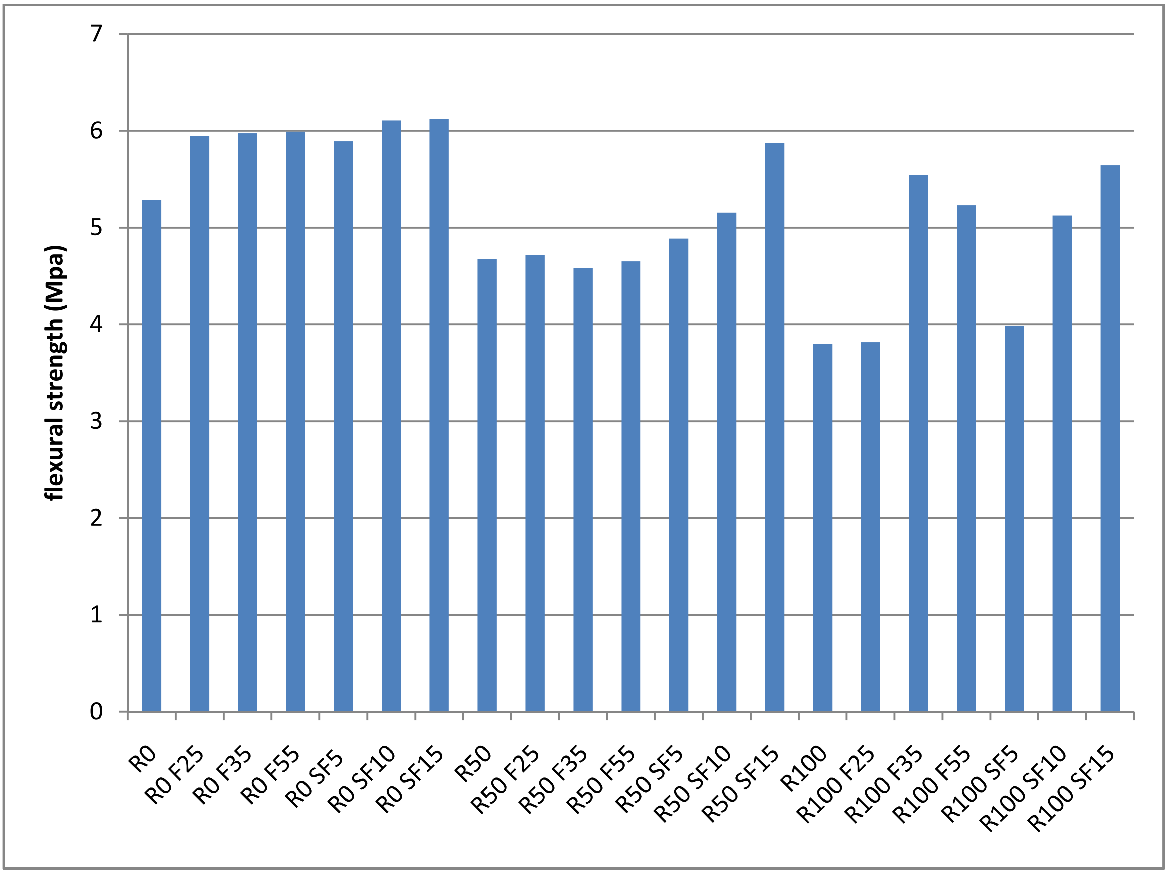

Fig 4.10: 28 day flexural strength

Figure 4.11 shows the percentage variation with respect to the control sample. The detailed discussion has been listed later on.

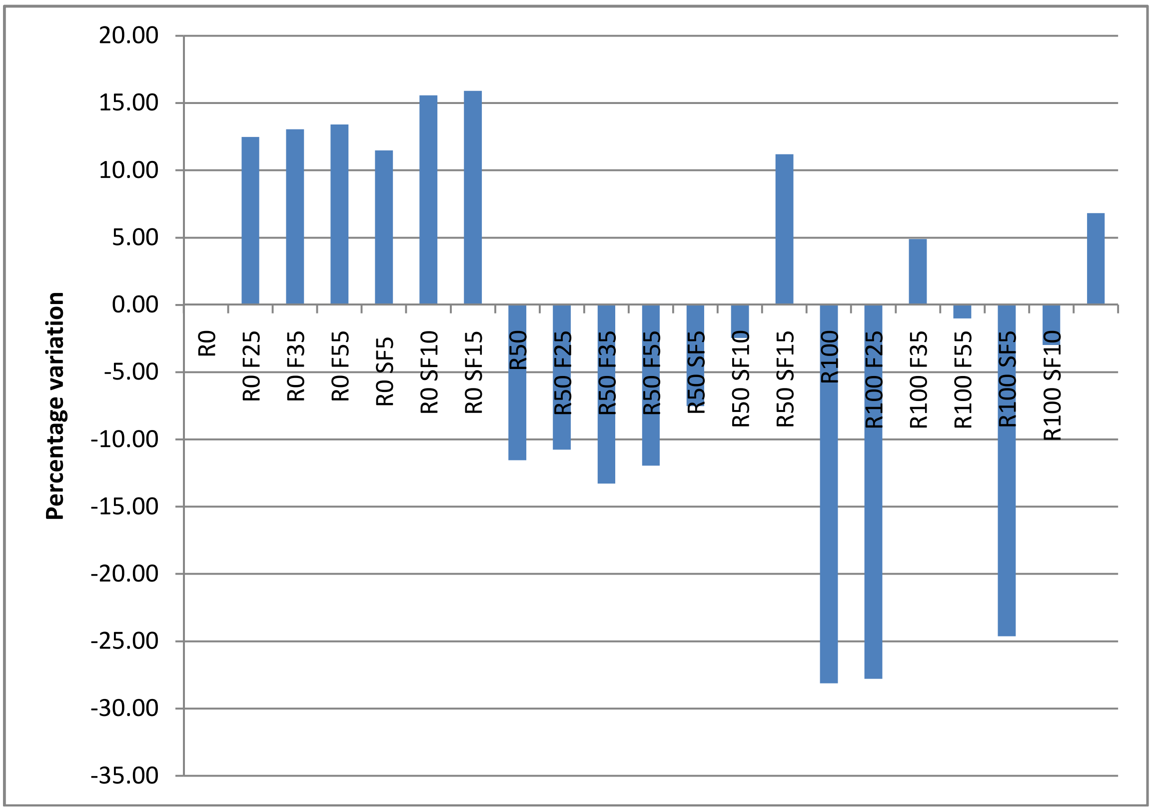

Fig. 4.11: percentage variation of 28 day flexural strength

When recycled coarse aggregate is used instead of natural coarse aggregate, the flexural strength decreases. This behaviour is clearly shown in the table 4.5 (a) below when natural coarse aggregate is replaced with 50% and 100% by recycle coarse aggregate.

Table 4.5 (a)flexural strength variation at different replacement level of natural coarse aggregate

Replacement level of natural coarse aggregate (% weight of coarse aggregate)	28 day flexural strength variation (%)
0	-
50	11.54(decrease)
100	28.12(decrease)

The flexural strength decreases when recycled aggregate are used without any mineral admixture or other supplementary materials. So we used fly ash and silica fume in order to recover some strength losses of recycled aggregate concrete. At 0% replacement by recycled aggregate, in case of fly ash, the flexural strength is shown in table 4.5 (b) below:

Table 4.5(b): flexural strength variations for different level of fly ash (0% replacement by recycled aggregate)

Replacement level of fly ash (% weight of cement)	28 day flexural strength variation (%)
25	12.49(increase)
35	13.06(increase)
55	13.40(increase)

- From above table, it is clear that flexural strength increased as level of fly ash is increased.
- It means fly ash can be used as a partial replacement of cement in recycled coarse aggregate.

At 0% replacement by recycled aggregates, in case of silica fume, the flexural strength is shown in table 4.5 (c) below:

Table 4.5(c): flexural strength variations for different level of silica fume (0% replacement by recycled aggregate)

Replacement level of silica fume (% weight of cement)	28 day flexural strength variation (%)
5	11.49(increase)
10	15.58(increase)
15	15.90(increase)

- From above table, it is clear that flexural strength increased as level of silica fume is increased.
- It means silica fume can be used as a partial replacement of cement in recycled coarse aggregate.

At 50% replacement of recycled aggregate the amount of increase, in case of fly ash, the flexural strength is shown in table 4.5 (d):

Table 4.5(d): flexural strength variations for different level of fly ash (50% replacement by recycled aggregate)

Replacement level of fly ash (% weight of	28 day flexural strength variation (%)
25	-10.77(decrease)
35	-13.29(decrease)
55	-11.94(decrease)

- When fly ash was added along with recycled coarse aggregate, there is decrease in strength at all the levels of replacement.

At 50% replacement of recycled aggregate, the amount of increase, in case of silica fume, the flexural strength is shown in table 4.5 (e):

Table 4.5(e) flexural strength variations for different level of silica fume (50% replacement by recycled aggregate)

Replacement level of silica fume (% weight of cement)	28 day flexural strength variation (%)
5	-7.51(decrease)
10	-2.46(decrease)
15	11.20(increase)

- The flexural strength increased at 15% replacement level of cement by silica fume.
- Silica fume showed more promising behaviour with increase in flexural strength of the recycled coarse aggregate concrete.

At 100% replacement of recycled aggregate the amount of increase, in case of fly ash, the flexural strength is shown in table 4.5 (f):

Table 4.5 (f): flexural strength variations for different level of fly ash (100% replacement by recycled aggregate)

Replacement level of fly ash (% weight of cement)	28 day flexural strength variation (%)
25	-27.78(decrease)
35	4.90(increase)
55	-1.00(decrease)

- When 100% recycled coarse aggregate is used, there was increase in strength at 35% of fly ash.

At 100% replacement of recycled aggregate, the amount of increase (in case of silica fume), the flexural strength is shown in table 4.5 (g):

Table 4.5 (g): flexural strength variations for different level of silica fume (100% replacement by recycled aggregate)

Replacement level of silica fume (% weight of cement)	**28 day flexural strength variation (%)**
5	-24.62(decrease)
10	-2.99(decrease)
15	6.83(increase)

- The flexural strength increased at 15% of silica fume content.

From all of the above discussion, it is clear that fly ash and silica fume indeed increased the flexural strength of recycled coarse aggregate. The optimum level of fly and silica fume that showed positive increase in strength was 35% and 15% respectively.

4.6 Air Content

For air content, optimum mix designs from each of the three series were selected and studied for the test. Table 4.5 and figure 4.12 shows a comparative of the air content values of the different types of concrete.

Table 4.5: Air content value

Designation	Air content (%)
R0	3.5
R0 F35	3.1
R0 SF15	2.5
R50	3.9
R50 F35	3.7
R50 SF15	2.9
R100	4.1
R100 F35	3.6
R100 SF15	2.8

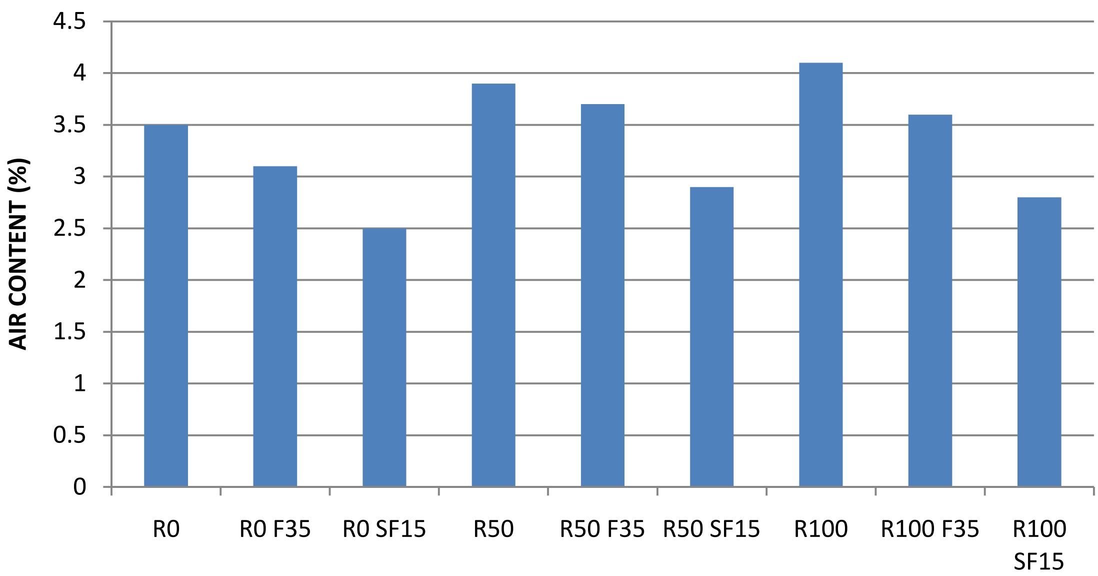

Fig.4.12: Air content

- It is seen from the data that the air content increases with increase in recycle aggregate substitution. A maximum of 4.1% was found for 100% RAC.
- As we add pozzolanic material like fly ash and silica fume the air content decreases which is quite clear from the graph.
- The above effect of fly ash and silica fume on the air content of the concrete might be due to the fact that both (silica fume and fly ash) have high specific areas and finer particles. These particles fill the voids in which the air is entrapped in the concrete matrix.
- Although the increased fineness in case of silica fume as compared to fly ash usually lowers the air content, the spherical shape of the silica fume lowers voids, particle friction and offsets such effects.

4.7 Bleeding Of Concrete.

For bleeding test, optimum design mix was selected from each of the parameter. The results of the various selected concrete mixtures selected are shown in table 4.6.The bleeding rate is defined as the volume of water in ml collected per cm^2 per second during the first 60 minutes of the test. The bleeding capacity is defined as the total volume of bleeding water collected over the entire course of the test, expressed as the fraction of the initial volume of the concrete.

The results of the various selected concrete mixtures selected are shown in table below:

Table 4.6: Bleeding rate and capacity for concrete mix

Designation	**Test started immediately after mixing**		**Test started immediately after 30 minutes**		**Test started immediately after 60 minutes**		**Test started immediately after 120 minutes**	
	bleeding capacity x10-	**bleeding rate x10-^{6} (ml/cm^2/sec)**	**bleeding capacity x10-^{3} (ml/ml)**	**bleeding rate x10-^{6} (ml/cm^2/sec)**	**bleeding capacity x10-**	**bleeding rate x10-^{6} (ml/cm^2/sec)**	**bleeding capacity x10-**	**bleeding rate x10-^{6} (ml/cm^2/sec)**

	^{3}(ml/ ml)				^{3}(ml/ ml)		^{3}(ml/ ml)	
R0	14.6	34.8	8.2	19.9	7.6	14.9	3.8	8.8
R0 F35	12.8	30.4	7.4	18.5	6.2	13.2	3.2	6.4
R0 SF15	10.3	26.4	6.2	16.6	4.3	10.8	2.2	3.2
R50	16.8	38.6	9.8	21.3	9.2	16.3	5.2	10.2
R50 F35	12.2	32.8	8.2	19.3	8.6	15.8	4.8	9.2
R50 SF15	8.6	28.6	5.3	26.8	4.3	12.9	2.9	4.9
R100	18.6	42.8	10.2	20.5	10.8	17.8	6.3	11.8
R100 F35	16.8	38.4	8.8	22.7	9.6	16.4	4.6	10.6
R100 SF15	12.6	32.9	6.4	20.5	7.6	12.3	2.9	8.2

- It is clear from the table that the bleeding increases with increase in substitution of the recycle coarse aggregate. Further reduction in bleeding capacity and bleeding rate was observed when the start of the bleeding test was delayed.
- With the use of fly ash and silica fume, the bleeding decreases as compared with the control sample.
- Due to the finer particles and high specific area of fly ash and silica fume, the voids in the concrete matrix gets filled and it blocks the path of the water channels inside. For this reason, the rate of bleeding in case of fly ash and silica fume is less.
- The effect of adding fly ash and silica fume has a beneficial effect on the concrete in case of bleeding of water.
- Due increased fineness in case of silica fume as compared to fly ash usually lowers the bleeding content, the spherical shape of the silica fume lowers air voids and particle friction and offsets such effects.
- Fly ash and silica fume act like a superplastizing admixture when used in concrete. The phenomenon is attributed to three mechanisms which are as follows:
- In case of fly ash and silica fume, the fine particles gets absorbed on the cement particles which tend to have an opposite charged surface. This leads to the prevention from flocculation. Doe to the opposite charge of the particles, the amount of water

entrapped will be large which ultimately leads to the reduction in the water requirement at given consistency.

- The inter particle friction is reduced due to the spherically smooth surface of silica fume and fly ash. This facilitates more mobility of the particles.
- The particles of silica fume and fly ash fills the void spaces present within the matrix. This also leads to reduced water demand in plasticizing the system.

4.8 Rapid Chloride Permeability Test (RCPT)

Rapid chloride permeability test were carried out at the age of 28 days. The results are presented in Table 5.7 and further in form of graphs Fig.4.13.

Table 5.7: RCPT values for concrete mix

Designation	Total charge passed (coulombs)	Permeability
R0	3820	moderate
R0 F35	1928	low
R0 SF15	893	very low
R50	4116	high
R50 F35	1286	low
R50 SF15	1112	low
R100	4458	high
R100 F35	2316	moderate
R100 SF15	1193	low

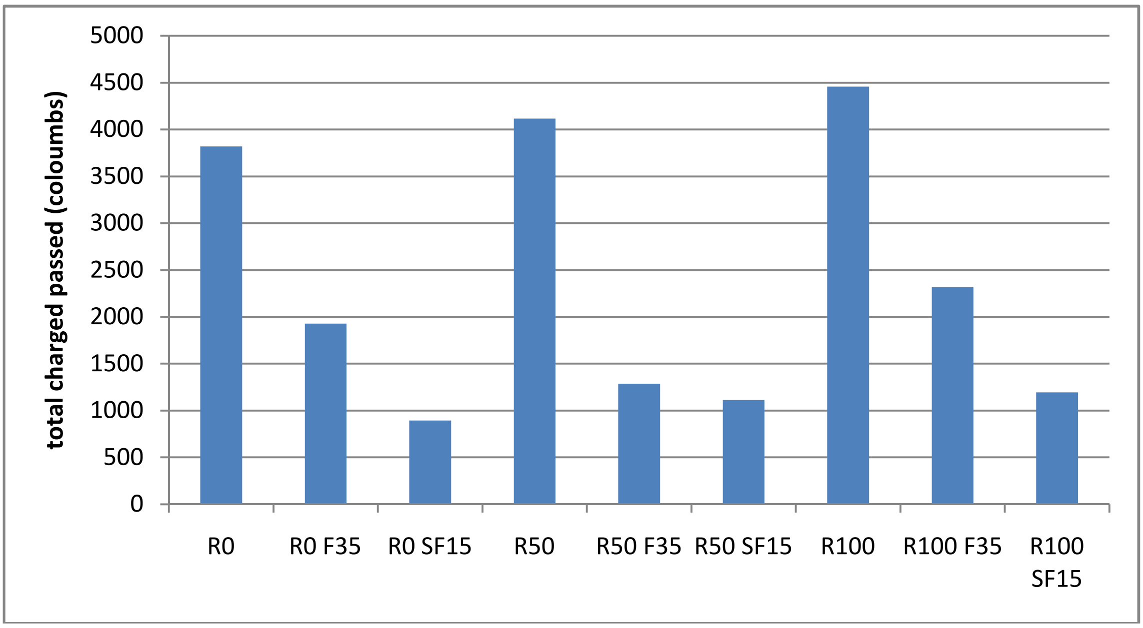

Fig.4.13: Rapid chloride permeability test

- As the level of recycled coarse aggregate increases the chloride permeability increases.
- With the addition of supplementary materials, the chloride permeability decreases.
- At 50% percent replacement level, with the addition of fly ash and silica fume, the permeability decreases. The behaviour is same in case of 100% replacement level.
- From the above table, it is clear that the resistance to chloride permeability decreases with the addition of more strong pozzolanic material. The permeability is moderate for fly ash which has silica with about 55% whereas the permeability of silica fume is low which has silica content up to 90%.

4.9 Carbonation Test

The carbonation test was carried out after 28 days of curing. Alkaline nature of the concrete was observed due to the change in colour of phenolphthalein. If no coloration occurs, carbonation has taken place and the depth of the carbonated surface layer can be measured.

Table 4.8: Carbonation depth values for concrete mix

Designation	Carbonation depth (mm)
R0	3.89
R0 F35	4.93
R0 SF15	6.52
R50	4.56
R50 F35	6.98
R50 SF15	7.33
R100	5.78
R100 F35	7.63
R100 SF15	8.56

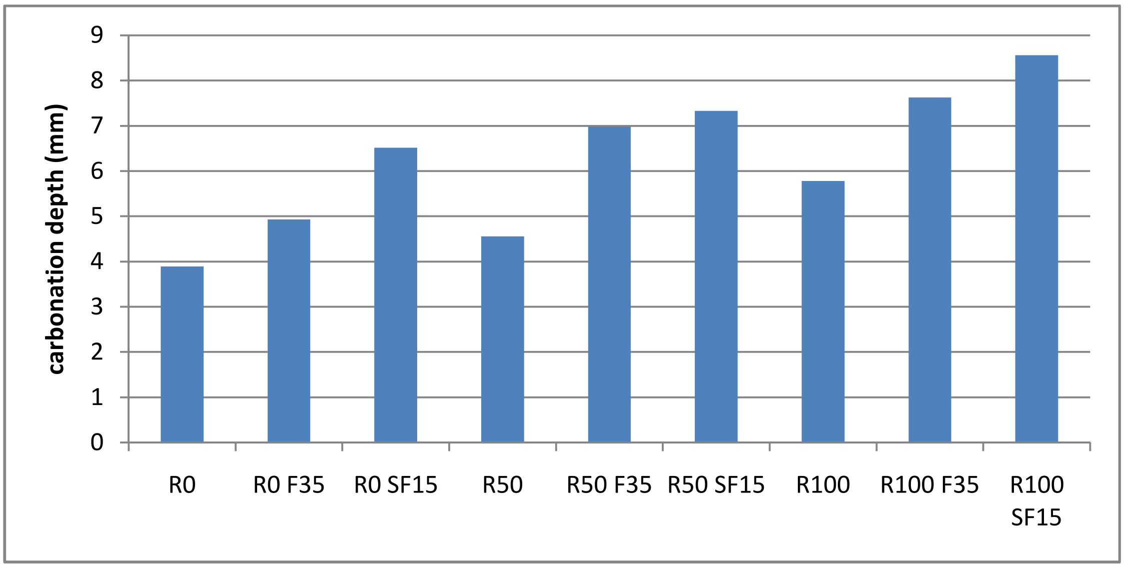

fig.4.14: Carbonation depth test

- From the table and graph it is clear that the carbonation resistance is lower with increase in replacement level.
- Carbonation of concrete is the process by which carbon dioxide from air penetrates into concrete through pores and reacts with calcium hydroxide to form calcium carbonates responsible for lower pH.
- The value of carbonation depth increases even with the addition of fly ash and silica fume.

4.10 Water Penetration Test

The test is carried out according to German Standard DIN 1048 on concrete specimens of size 150x150x150 mm, at an age of 28 days subjected to water under pressure of 3 bar for three days.

Table 4.9: Water penetration depth for concrete mix

DESIGNATION	WATER PENETRATION DEPTH (cm)
R0	15.46
R0 F35	18.13
R0 SF15	16.08
R50	32.56
R50 F35	34.13
R50 SF15	28.1
R100	36.92
R100 F35	38.02
R100 SF15	32.16

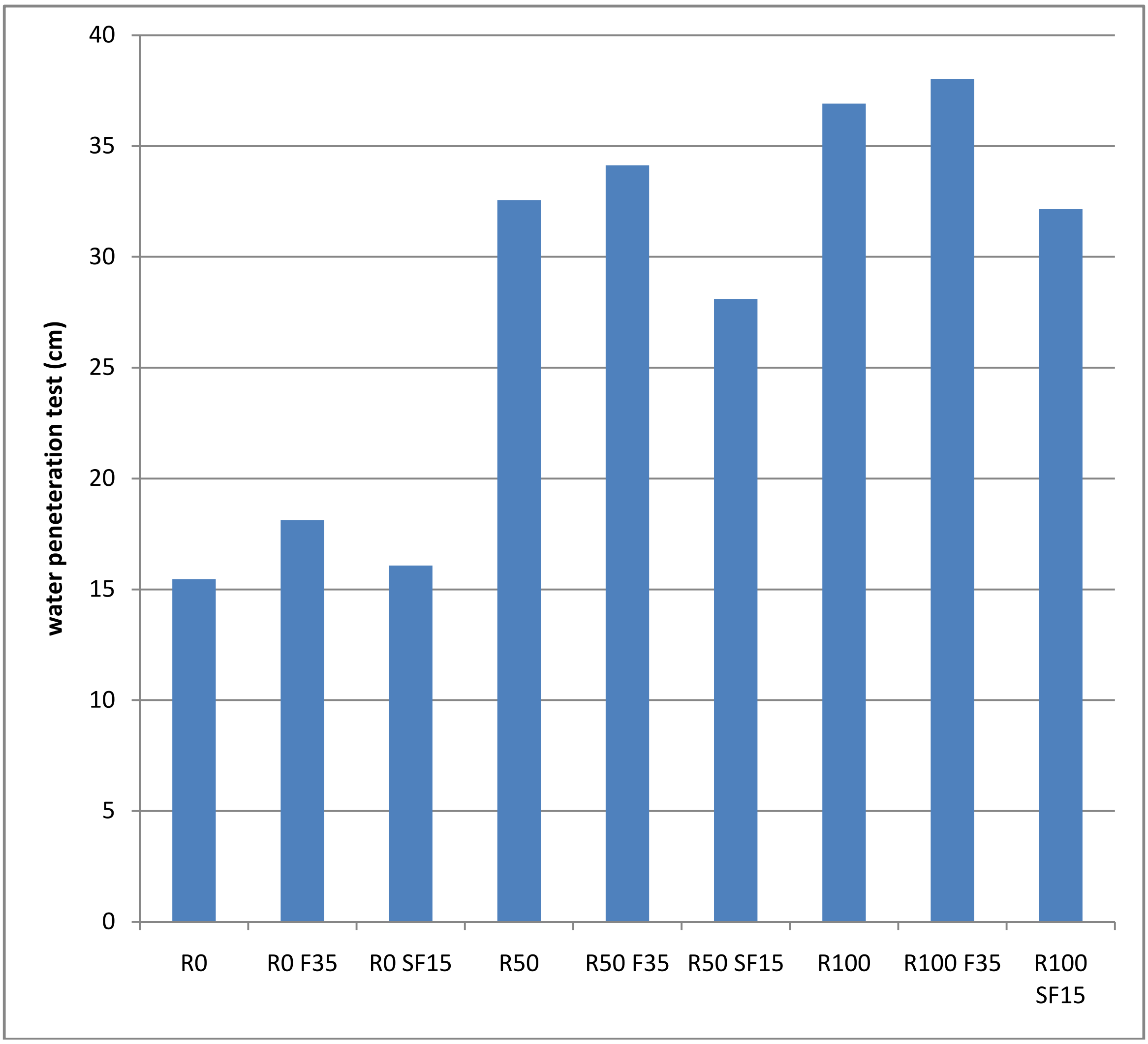

Fig. 4.15: water penetration test

- The table above shows the water penetration depth. With increase in replacement level of coarse aggregate, the water penetration depth increases.
- It is also observed that at the same replacement level, with the addition of external pozzolanic material, the depth decreases.
- It may due to the fact that pozzolanic material like silica fume have high and concentration of silicon oxide and are very much finer as compared to the cement particles. Since the voids gets filled with finer particles, the water penetration depth decreases.

4.11 Ultrasonic Guided Waves

This test was conducted on a beam specimen of size 150 mm x 150 mm x 300 mm with an embedded mild steel rod of 25 mm diameter and 600 mm length. Three optimum samples were selected to study the fresh concrete properties using ultrasonic guided waves for duration of 48 hours. One sample was control sample with natural coarse aggregate. Second sample selected was 50% recycled aggregate with fly ash. Third sample selected was 50% recycled aggregate with silica fume up to 15%.

For the comparison of the three levels, normalised peak to peak curves were used. Figure 4.16 shows the behaviour of three different levels.

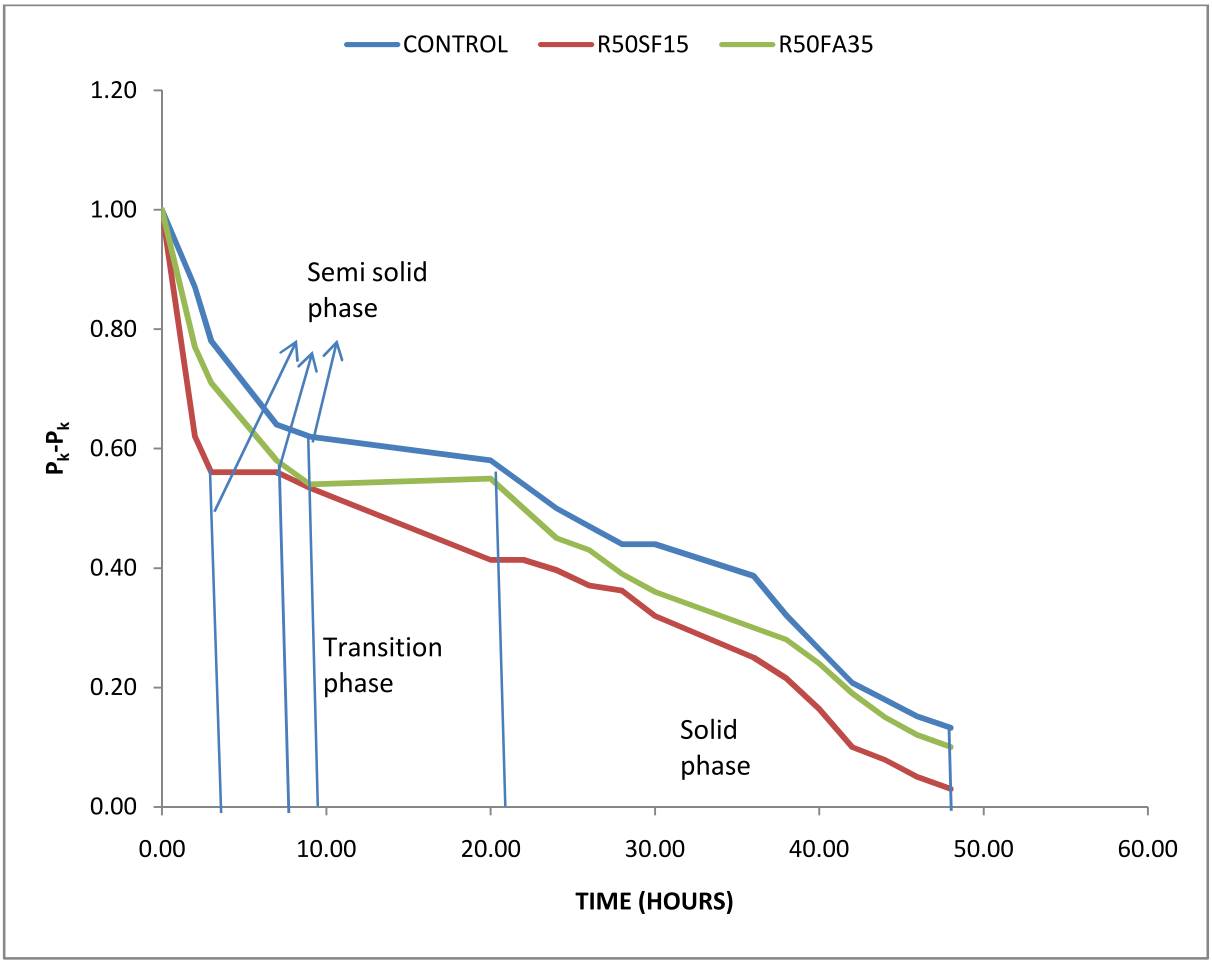

Fig. 4.16: Ultrasonic guided waves

- First a healthy signature i.e. voltage vs. time graph is captured and then compared with results signatures taken at different time intervals. Finally pk-pk voltage is measured and results are plotted as V-T (Voltage vs. Time) graphs.
- As concrete sets and hardens, Pk-Pk Voltage drops and hence the signature also drops. This is because of the surface seeking nature of the mode selected. This mode picks up the bond development between the reinforcing embedded mild steel and surrounding concrete.
- As the concrete sets, bond develops between steel and surrounding concrete indicating more energy leakage into the surrounding concrete thus causing drop in signal strength. Hence the fall in signal strength is a measure of development of bond and hence setting of concrete.
- Ultrasonic Guided Wave (UGV) readings are taken throughout 48 hrs of setting of concrete at regular time intervals. The ultrasonic measurements are made for concretes of control sample, sample with silica fume and sample containing fly ash.
- It is clear after seeing the UGV result graph that concrete was undergoing though three phases i.e. Semi-Solid, Transition & Solid Phase (Fig 4.16).
- The semi-solid Phase for the three different batches is different. In control sample, for the first 7 ½ hrs, the concrete is still in semi-liquid phase & there is heavy fall in Pk-Pk voltage.
- For sample with recycled aggregate with fly ash, the concrete is in semi solid state for first 6½hours whereas in recycled aggregate sample with fly ash, the fall is very rapid in peak to peak voltage in first 3 hours. The difference between the samples is that the two samples contain 50% recycled aggregates along with strong pozzolanic material like fly ash and silica fume.
- In case of silica fume, there is high concentration of silica along with recycled aggregates which starts the setting process immediately after mixing. The span of semi solid state in case of silica fume is relatively very small as compared to sample with fly ash and control sample.
- In Transition Phase for all the three different batches are mentioned below

1. Control sample: 7½ hour to 20 hour
2. R50FA55 (with fly ash): 6½ hour to 20 hour
3. R50SF15 (with silica fume): 3 hour to 20 hour

- In all the above span of time, the concrete is undergoing a change from semisolid to solid state or in other words we can say that the concrete is starting to set or making bond with the embedded mild steel bar. The maximum fall in Pk-Pk Voltage is observed in case of silica fume due to high concentration of silica content.
- Lastly in Solid Phase i.e. 20hrs to 48 hrs, there is fall in Pk-Pk voltage in case of both samples indicating the concrete has become almost solid. There is hardly any setting or bonding occurring in this phase which shows that the max setting or bonding occur up to 24 hrs after casting
- From the above graph, it is clear that silica fume increased the setting time very rapidly and the curve drops rapidly. It indicates the start of setting process of the concrete mix. In case of silica fume, the drop is more rapid which may be due to the strong pozzolanic action of silica fume. As the time increases, the drop is gradual indicating hardening of cement paste. The drop in amplitude is due to the fact that as the setting increases with time the signal decreases due to the leakage of signals. At initial time, the mix is in wet state, so the signal is transferred directly to and fro through 25mm bar. But as the time increases, mix becomes hard and signals starts to travel in lateral directions, thereby indicating the signal loss. So the signal received is weak which is indicated by the drop in the amplitude.

CHAPTER 5
CONCLUSIONS AND SCOPE OF FURTHER WORK

5.1 General

This chapter presents the conclusions derived after obtaining the results for all the mixes undergoing tests for hardened state and fresh state. The conclusions drawn are also in line with the literature work studied for this research.

a) With increase in the proportion of RCA in the mix, the slump value goes down. This means RAC might have problems in transportation, pump ability and/or workability during structural use in construction.

b) There is a significant difference in the compressive strength values obtained at 3 days , 7 days and 28 days for normal and recycled concrete mix. This may be due to the fact that recycled aggregate already have a mortar coating on it, which makes the new inter transitional zone weak.

c) As more supplementary materials are added along with recycled aggregate, there is still significant drop in 3 day and 7 day compressive strength, whereas for 28 days, the compressive strength in case of some RCA mix is more than the control sample. This may be due to the fact that supplementary materials like fly ash and silica fume are finer and have high pozzolanic action. During the initial stages (3 days and 7 days), pozzolanic action starts resulting in low strength. But at 28 days, mostly pozzolanic action is mostly at completion stage. So the new inter transitional zone formed over the old inter transitional zone is fairly strong resulting in high strength.

d) RCA with supplementary materials, i.e. fly ash and silica fume, in certain mixes exhibited more split tensile and flexure strength, at 28 days, than the control sample. The reason behind this behaviour is quite similar to that exhibited in case of 28 day compressive strength.

e) RAC requires higher quality control to ensure that waste concrete is free from impurities as much as possible, the mixing is done properly and ensure sufficient water availability for the hydration of cement.

f) The resistance to chloride decreases as the percentage of recycled aggregate in concrete increases. Use of silica fume and fly ash appreciably enhances the resistance to chloride attack at all replacement levels.

g)The carbonation resistance is lower with increase in replacement level of recycle coarse aggregate. With use of fly ash and silica fume the carbonation resistance decreases.

h) The water permeability increases rapidly with increase in replacement level of recycle aggregate. But with use of fly ash and silica fume along with recycle coarse aggregate the permeability decreases marginally. This due to the fact that alone recycle coarse aggregate contains high degree of water permeability due to the mortar film attached to the aggregates. As silica fume and fly ash is added, the pores get filled due to the fine size of both silica fume and fly ash, resulting in decreased porosity.

i) It is seen from the data that the air content increases with increase in recycle aggregate substitution. As we add pozzolanic material like fly ash and silica fume the air content decreases.

j) The bleeding increases with increase in substitution of the recycle coarse aggregate. Further reduction in bleeding capacity and bleeding rate was observed when the start of the bleeding test was delayed. With the use of fly ash and silica fume, the bleeding decreases as compared with the control sample.

From the above it can be concluded that recycle coarse aggregate can be used as an alternate to natural coarse aggregate. A substitute up to 50% of natural coarse aggregate with supplementary pozzolanic materials like fly ash and silica fume can be used in structural concrete as this mix exhibited best results for strength, durability and workability parameters. A replacement of complete 100% of natural coarse aggregate with some percent of fly ash and silica fume can also be used in structural concrete but some parameters like high level of bleeding, high permeability; low slump poses a problem for use at certain conditions and places.

5.2 Limitation of the Present Study and Suggestions for further Work.

The study carried out in this thesis dealt only with the mechanical and material aspect of recycled aggregate concrete. More efforts are required to be carried out in this field. Many aspects are still to be covered. The recycled aggregate procured from different sources can be used in the study. The response of recycled aggregate concrete to different conditions, resistance to freeze thaw cycles, behaviour under loading conditions like cyclic loading, reversal loading, torsion, etc. can be studied. More aspects may also include by recycling fine aggregate or by recycling cement and their concerned properties. More studies can be carried out on the recycled concrete response to torsion loading, bond properties, anchorage and its nature of failure properties. More NDT techniques can also be incorporated in the study to compare the recycled aggregate concrete with the conventional concrete.

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STANDARD CODES

1. ASTM C 1202-97 Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration
2. DIN 1048 (part-5): German Standard for determination of Permeability of Concrete.
3. IS : 1199 - 1959 Methods Of Sampling And Analysis Of Concrete
4. IS 10262-2009 Concrete Mix Proportioning - Guidelines
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6. IS 2386-1 (1983) Methods Of Test For Aggregates For Concrete Part I Particle Size And Shape

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8. IS 2386-5 (1963). Method Of Test For Aggregates For Concrete
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