# A Comparative Study of Concrete Incorporating Recycled Concrete Aggregates and Microsilica (Silica Fume) to Develop a Sustainable Construction Material

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***Abstract* - Environmental protection, shortage of land for waste disposal, and increasing costs of waste treatment prior to disposal are main reasons for increasing interest for the recycling of construction and demolition waste materials throughout the world. The use of recycled concrete aggregates is encouraged due to following three reasons: conservation of natural resources, minimization of overall construction cost, and reduction of pollution. Aggregates are produced by crushing and sieving of the waste concrete is known as recycled aggregates and basically, recycled aggregates are of two types: recycled coarse aggregate and recycled fine aggregate.**

**The present work addresses the behavior of concrete using recycled coarse aggregates and Microsilica (Silica Fume) to develop sustainable construction material. The physical and mechanical characteristics of recycled coarse aggregates obtained from field sources are determined as procedures of IS: 2386 (1963) and compared with those values with natural coarse aggregates. Furthermore, characterization of cement and Microsilica has been done by performing standard tests. In the present work, a total of 9 mixes were prepared. Mix having percentage of silica fume as 0%, 10% and 20% was designated as A, B and C respectively whereas replacement of natural aggregates with coarse aggregate by 0%, 30% and 70% were designated as R1, R2 and R3 respectively. Therefore each mix designated as A, B and C constitutes three different proportion of recycled coarse aggregates designated as R1, R2 and R3. In mix proportioning in each mix, 6 cubes, 6 cylinders and 2 beams were casted. However 3 cubes in each mix were tested after 7 days of moist curing to obtain the 7 days cube compressive strength of concrete. The remaining 3 cubes were tested after 28 days for each mix. In a similar manner cylindrical and prismatic specimens were tested for split tensile strength and flexural strength.**

**The study illustrates that behaviour of concrete mixes made with 100% recycled aggregates are inferior to that of concrete with natural aggregates. Furthermore, addition of Microsilica (Silica Fume) compensates the degradation in properties due to the substitution of natural coarse aggregates by recycled coarse aggregates.**

***Keywords- Recycled Concrete Aggregate, Microsilica (Silica Fume)***

## 1 .INTRODUCTION

Concrete's versatility, durability, sustainability, and economy have made it the world's most widely used construction material. About four tons of concrete are produced per person per year worldwide and about 1.7 tons per person in the United States. The increasing number of concrete buildings being demolished, the difficulties of disposing of concrete rubble produced together with a developing scarcity of aggregate need to the major urban areas has prompted an interest in the possibility of using concrete rubble as aggregate in concrete. Infrastructural development plays an important role in the growth and enhancement of any country or society. This facility is accompanied by construction, remoulding, maintenance and demolition of buildings, roads, subways and other structural establishments.. The concrete accounting for nearly 50% waste is not properly reused and recycled. Lately many countries like U.S, U.K, Germany and Japan have successfully utilised nearly 90% of their construction and demolition waste. However less insight and effort is reported regarding recycle of demolition waste in India. Due to the increase in the economic growth after development and redevelopment projects in the country and subsequent increase in the urbanization in the cities has made construction sector to increase drastically, but also environmental impacts from construction and demolition (C & D) waste are increasingly becoming a major issue in urban solid waste management. Environmental issues such as increase in the flood levels due to the illegal dumping of construction and demolition waste into the rivers, resource depletion, shortage of landfill and illegal dumping on hill slopes are evident in the metro cities. For the purpose of management of C&D Wastes in India, Construction and demolition waste has been defined as 'waste which arises from construction, renovation and demolition activities. Also included within the definition are surplus and damaged products and materials arising in the course of construction work or used temporarily during the course of on-site activities. Due to the increase in the economic growth after development and redevelopment projects in the country and subsequent increase in the urbanization in

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the cities has made construction sector to increase drastically, but also environmental impacts from construction and demolition (C & D) waste are increasingly becoming a major issue in urban solid waste management. Environmental issues such as increase in the flood levels due to the illegal dumping of construction and demolition waste into the rivers, resource depletion, shortage of landfill and illegal dumping on hill slopes are evident in the metro cities.

This thesis aims to provide an overview of recent studies that have been carried out to investigate the incorporation of recycled aggregates, hereafter referred to as RA, into the production of concrete. In particular, this thesis examines the results of those studies in regard to the compressive strength of concrete blocks made with RA, hereafter referred to as recycled aggregate concrete, or simply, RAC. The goal is to identify if RAC has achieved similar mechanical performances as normally expected from conventional concrete. Considerable amount of research has been carried out with different types of materials. This thesis presents the most widely researched waste material used as RA that is concrete waste. In addition other commonly used waste material is introduced that is silica fume to enhance the property of Recycled aggregate.

## 2. MATERIALS AND METHODS

2.1 General: The present chapter outlines the details of the material used, their physical properties and methodology adopted for experimental program. The basic properties of different constituents of concrete like cement, water, recycled aggregates, fine aggregates, coarse aggregate and silica fume are discussed in this chapter. Concrete mix design details using the properties of constituent materials are also presented in this chapter. The details of various tests conducted on recycled aggregate concrete containing silica fume have also been discussed in this chapter.

2.2 Test Programme: The test programme consisted of the following activities:-

Testing of the constituents materials of concrete i.e. cement, fine aggregates, coarse aggregate and recycled aggregate as per relevant Indian standard code of practice, wherever applicable.

(i) Design of concrete mix and casting of the test specimens.

(ii) Testing of specimens casted for compressive strength, split tensile strength, flexural strength and water permeability.

2.3 Physical Properties of Materials: The aim of studying various properties of the materials used in concrete is to check the conformance of codal requirements. The test specimens were cast using cement, fine and coarse aggregate, recycled aggregate, silica fume and water. The materials in general conformed to the specification laid down in the relevant Indian standard codes of practice wherever applicable. Laboratory test were conducted on these materials and their properties have been reported.

2.3.1 Cement: In the present investigation, 43 grade ordinary Portland cement conforming to IS 8112-2013 was used. The cement was tested in accordance with the methods of test specified in IS 8112-2013. The physical properties of the cement as determined from various test are listed in table 2.1.

Table 2.1 Physical properties of cement

| Sr. | Characteristics | Experimental | Specified value as per |
|---|---|---|---|
| 1 | Consistency Of Cement | 28.1% | |
| 2 | Specific Gravty | 3.12 | 3.15 |
| 3 | Initial Setting | 95 minutes | >30 minutes |
| 4 | Final Setting | 342 minutes | <600 minutes |
| 5 | Comp.Strength<br>(N/mm$^2$)<br>a) 3 days | 28.9<br>38.01 | >23<br>>33 |
| 6 | Fineness (Dry Sieving) | 1.6% | <10% |
| 7 | Soundness (Mm) | 1.2 | <10 |

2.3.2 Fine Aggregates: Washed sand obtained from a quarry at Pampore near Gas Agency was used as fine aggregate. The sand was sieved through IS sieve with a 10mm opening, then washed to remove dust and then dried. Sieve analysis and other tests for fine aggregates were performed in laboratory. The physical properties of fine aggregate are listed in table 2.3.

Table 2.2 Physical Properties of Fine Aggregates

| Characteristics | Results Obtained |
|---|---|
| Grading | Grading Zone III (IS: 383-2011) |
| Fineness Modulus | 2.18 |
| Specific Gravity | 2.62 |
| Water Absorption (%) | 0.48 % |
| Free Moisture Content (%) | Nil |

2.3.3 Coarse Aggregates: Two size fractions of coarse aggregates, 20 mm down and 10 mm down obtained from a stone crusher at Letpora Pampore were used for making concrete mixtures. The coarse aggregates fraction were washed to remove dust, dirt and then dried to surface dry condition. Sieve analysis and other test for coarse aggregates were performed in laboratory. Crushed stone aggregate of 20 mm and 10 mm size were mixed in 50:50 proportions to meet the requirements of IS 383-2011. The results of sieve analysis are listed in table 4.4 and 4.5.

- Cumulative %age retained = 164.2
- Fineness modulus = (500+164.2)/100

= 6.7

Table 2.3 Physical Properties of Coarse Natural Aggregates

| Characteristics | Value |
|---|---|
| Colour | Grey |
| Type | Crushed |
| Shape | Angular |
| Specific gravity | 2.66 |
| Water absorption | 0.50% |
| Fineness modulus | 6.7 |
| Moisture Content (%) | Nil |

2.3.4 Recycled Aggregates: The recycled coarse aggregate (>4.75mm) were collected from the PG structure laboratory of NIT Sgr. Typically, the already tested RCC beams were broken manually and the coarse aggregate were separated. Then, these separated aggregates were crushed in the crushing machine (> 4.75mm & <20mm). the aggregate was then washed thoroughly to remove dust and dirt adhered to the coarse aggregate and then dried to surface dry condition. The aggregate were tested for their physical properties and the test results are presented in table 4.6. These results conform to IS 383-2011. The sieve analysis for recycled aggregates was carried out and the results are reported in table 4.7.

- Cumulative %age retained= 162.3
- Fineness modulus of recycled aggregates= (500+162.3)/100

= 6.62

Table 2.4 Physical Properties of Recycled Aggregates

| Characteristics | Value |
|---|---|
| Colour | Grey |
| Type | Crushed |
| Shape | Angular |
| Specific gravity | 2.65 |
| Water absorption | 5.18% |
| Fineness modulus | 6.62 |
| Moisture Content (%) | Nil |

2.3.5 Silica Fume: Silica fume, also known as microsilica or condensed silica fume, is a pozzolanic admixture. When used in concrete it will fill the void space between cement particles resulting in a more impermeable concrete. Silica fume is replaced at 10% level with cement.. Silica fume is a byproduct resulting from the reduction of high-purity quartz with coal or coke and wood chips in an electric arc furnace during the production of silicon metal or ferrosilicon alloys. The silica fume which condenses from the gases escaping from the furnaces has a very high content of amorphous silicon dioxide and consists of very fine spherical particles (IS 15388-2003). The silica fume was supplied by ELKEM Company .It is known as "Silica -Fume 920D". Specific Gravity given by Elkem Company in the TDS is 2.2. Actual specific gravity calculated in RCC Lab is 2.15. So, Sp. Gravity = 2.15 was used for design of every mix. The physical properties of silica fume are presented in table 4.10

Table 2.5 Physical properties of Silica fume (source: from supplier)

| Characteristics | Value |
|---|---|
| Appearance | Grey Powder |
| Specific Gravity | 2.2 |
| Chloride Content | Nil |
| Toxicity | Non-Toxic |

2.3.6 Water: Water to be used for both mixing and curing of concrete should be free from injurious amount of deleterious materials. As per IS: 456-2000 potable water is generally considered satisfactory for making and curing of concrete. In the present study, potable tap water available in P.G. Structure Engg. Laboratory was used for casting the specimens and for curing purposes.

2.4 Design of Concrete Mix

The concrete mix was designed as per the codes IS 10262-2009. A summary of the mixture proportion is presented in table 4.11. Three trial mixes were prepared by making variations in the w/c ratio and tested for compressive strength. Finally, the trial mix which gave the strength close to the target strength was adopted for further investigation.

Table 2.6 Actual quantities required for mix of M 30 grade

| Water (litres) | Cement (Kg) | Fine Aggregates (Kg) | Coarse Aggregates (Kg) |
|---|---|---|---|
| 191.52 | 399 | 643 | 1157.60 |
| 0.48 | 1 | 1.61 | 3.05 |

2.4.1 Mix Designation

In the present work, a total of 9 mixes were prepared. Mix having percentage of silica fume as 0%, 10% and 20% was designated as A, B and C respectively whereas replacement of natural aggregates with coarse aggregate by 0%, 30% and 70% were designated as R1, R2 and R3 respectively. Therefore each mix designated as A, B and C constitutes three different proportion of recycled aggregates designated as R1, R2 and R3 are presented in table 4.12

Table 2.7 Mix Designation

| Mix Designation | Percentage of Silica Fume | Percentage of Recycled |
|---|---|---|
| AR1 | 0% | 0 |
| AR2 | 0% | 30 |
| AR3 | 0% | 70 |
| BR1 | 10% | 0 |
| BR2 | 10% | 30 |
| BR3 | 10% | 70 |
| CR1 | 20% | 0 |
| CR2 | 20% | 30 |
| CR3 | 20% | 70 |

2.4.2 Details of Concrete Mixes

The details of mix proportion of M 30 concrete having 0% (R1), 30% (R2) and 70% (R3) of recycled aggregates with 0% (A), 10% (B) and 20% (C) of cement replacement with silica fume is shown below.

**a)** Mix with 0% silica fume

Table 2.8 Mix proportion for 0%, 30% and 70% recycled aggregate with 0% silica fume

| Mix | AR1 | AR2 | AR3 |
|---|---|---|---|
| Cement | 399 | 399 | 399 |
| Silica fume | 0 | 0 | 0 |
| Fine aggregate | 643 | 643 | 643 |
| Coarse aggregate | 1157.6 | 810.32 | 347.3 |
| Recycled aggregate | 0 | 347.3 | 810.32 |
| Admixture | 0 | 0 | 0 |
| Water | 191.52 | 191.52 | 191.52 |
| Ratio | 1:1.61:3.05 | 1:1.61:3.05 | 1:1.61:3.05 |

(All units are in kg/m³)

**b)** Mix with 10% silica fume

Table 2.9 Mix proportion for 0%, 30% and 70% recycled aggregate with 10% silica fume

| Mix | BR1 | BR2 | BR3 |
|---|---|---|---|
| Cement | 359.1 | 359.1 | 359.1 |
| Silica fume | 17.95 | 17.95 | 17.95 |
| Fine aggregate | 643 | 643 | 643 |
| Coarse aggregate | 1157.6 | 810.32 | 347.3 |
| Recycled aggregate | 0 | 347.3 | 810.32 |
| Admixture | 0 | 0 | 0 |
| Water | 191.52 | 191.52 | 191.52 |
| Ratio | 1:1.61:3.05 | 1:1.61:3.05 | 1:1.61:3.05 |

(All units are in kg/m³)

c) Mix with 20% silica fume

Table 2.10 Mix proportion for 0%, 30% and 70% recycled aggregate with 20% silica fume

| Mix | CR1 | CR2 | CR3 |
|---|---|---|---|
| Cement | 319.2 | 319.2 | 319.2 |
| Silica fume | 39.9 | 39.9 | 39.9 |
| Fine aggregate | 643 | 643 | 643 |
| Coarse aggregate | 1157.6 | 810.32 | 347.3 |
| Recycled aggregate | 0 | 347.3 | 810.32 |
| Admixture | 0 | 0 | 0 |
| Water | 191.52 | 191.52 | 191.52 |
| Ratio | 1:1.61:3.05 | 1:1.61:3.05 | 1:1.61:3.05 |

(All units are in kg/m³)

*2.4.3 Mix Proportioning*

In this topic there is an overview of total number of cubes, beams, cylindrical specimens were casted during thesis work to show strength and durability characteristics of recycled aggregate concrete.

Table 2.11 Overview of Number of Specimen Casted

| SR NO | CUBE | CYLINDER | BEAM | COMMENT |
|---|---|---|---|---|
| 1 | 6 | 3 + 3 | 2 | Mix with 0 % silica fume with 0% recycle aggregates |
| 2 | 6 | 3 + 3 | 2 | Mix with 0 % silica fume with 30% recycled aggregates |
| 3 | 6 | 3 + 3 | 2 | Mix with 0% silica fume with 70% recycled Aggregates |
| 4 | 6 | 3 + 3 | 2 | Mix with 10% silica fume with 0% recycled Aggregates |
| 5 | 6 | 3 + 3 | 2 | Mix with 10% silica fume with 30% recycled aggregates |
| 6 | 6 | 3 + 3 | 2 | Mix with 10% silica fume with 70% recycled aggregate |
| 7 | 6 | 3 + 3 | 2 | Mix with 20% silica fume with 0% recycled aggregates |
| 8 | 6 | 3 + 3 | 2 | Mix with 20% silica fume with 30% recycle aggregates |
| 9 | 6 | 3 + 3 | 2 | Mix with 20% silica fume with 70% recycled aggregate |

In each mix, 6 cubes, 6 cylinders and 2 beams were casted. However 3 cubes in each mix were tested after 7 days of moist curing to obtain the 7 days cube compressive strength of recycled aggregate concrete. The remaining 3 cubes were tested after 28 days for each mix. In a similar manner cylindrical and prismatic specimens were tested for split tensile strength and flexural strength.

## 3. RESULTS AND DISCUSSION

3.1 General: The present study was undertaken to achieve the objectives of this investigation. In all, 126 specimens were casted and tested and the results obtained from experiments are presented and discussed in this chapter. Following aspects of concrete were investigated

- The effect of partial replacement of natural aggregate by recycled aggregate on compressive strength, split tensile strength, flexural strength and the effect of partial replacement of cement with silica fume on compressive strength, split tensile strength and flexural strength of concrete.

3.2 Test Results

3.2.1 Compressive Strength: The effect of silica fume on compressive strength of concrete with replacement of natural aggregate with recycled aggregate in different proportion was investigated under following conditions:

- Cement partially replaced by silica fume.
- Natural aggregate partially replaced by recycled aggregate in different proportions.

3.2.1.1 Effect of Percentage of Recycled Aggregate on Compressive Strength: The effect of recycled aggregate on compressive strength of concrete at the age of 7 days is presented in table 3.1 to 3.3.

Table 3.1 Compressive Strength of Recycled Aggregates Concrete with 0% Silica Fume

| Concrete Mix | Failure Load (kN) | Compressive Strength (N/mm²) | Average Compressive Strength (N/mm²) | Percentage Decrease In Compressive Strength |
|---|---|---|---|---|
| AR 1 | 568.1 | 25.2 | 24.2 | - |
| | 520.6 | 23.1 | | |
| | 543.3 | 24.1 | | |
| AR 2 | 523.6 | 23.3 | 23.5 | 2.9 |
| | 548.5 | 24.4 | | |
| | 515.2 | 22.9 | | |
| AR 3 | 543.4 | 24.2 | 22.2 | 8.3 |
| | 473.5 | 21.0 | | |
| | 482.2 | 21.4 | | |

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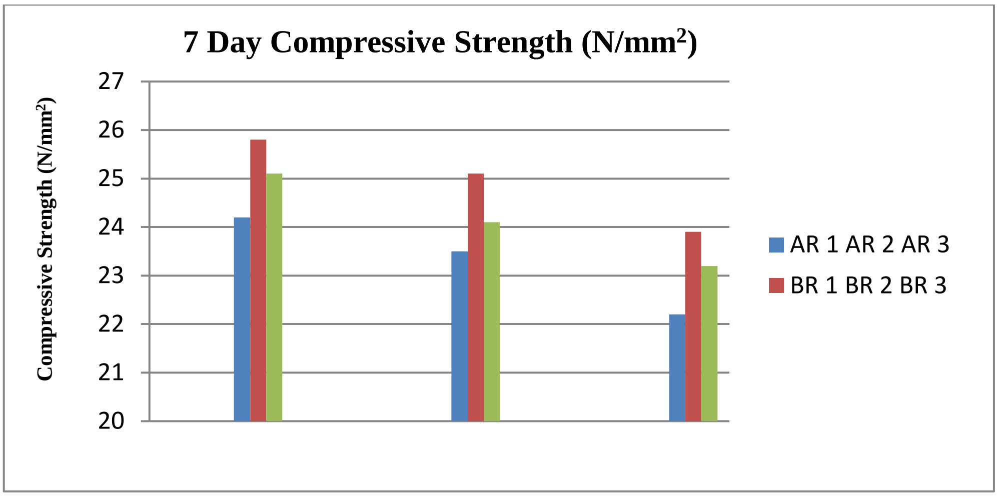
Table 3.2 Compressive Strength of Recycled Aggregates Concrete with 10% Silica Fume

| Concrete Mix | Failure Load (kN) | Compressive Strength (N/mm²) | Average Compressive Strength (N/mm²) | Percentage Decrease In Compressive Strength |
|---|---|---|---|---|
| BR 1 | 598.5 | 26.6 | 25.8 | -6.6 |
| | 573.8 | 25.5 | | |
| | 567.0 | 25.2 | | |
| BR 2 | 564.8 | 25.1 | 25.1 | -3.7 |
| | 553.5 | 24.6 | | |
| | 578.3 | 25.1 | | |
| BR 3 | 549.0 | 24.4 | 23.9 | 1.2 |
| | 528.8 | 23.5 | | |
| | 533.3 | 23.7 | | |

Table 3.3 Compressive Strength of Recycled Aggregates Concrete with 20% Silica Fume

| Concrete Mix | Failure Load (kN) | Compressive Strength (N/mm²) | Average Compressive Strength (N/mm²) | Percentage Decrease In Compressive Strength |
|---|---|---|---|---|
| CR 1 | 573.8 | 25.5 | 25.1 | -3.7 |
| | 558.0 | 24.8 | | |
| | 564.8 | 25.1 | | |
| CR 2 | 555.4 | 24.6 | 24.1 | 0.42 |
| | 535.5 | 23.8 | | |
| | 555.8 | 24.7 | | |
| CR 3 | 533.3 | 23.7 | 23.2 | 4.1 |
| | 515.3 | 22.9 | | |
| | 519.8 | 23.1 | | |

- Graph Showing Variation Of 7 Days Compressive Strength Of Concrete With Different Replacements Of Cement And Coarse Aggregates




It is clear from above tables and graph that increase in percentage of recycled aggregate results in decrease in compressive strength of concrete. For mix AR2 and AR3 containing 30% and 70% recycled aggregate, the compressive strength decreased by 2% and 8.3% respectively and compressive strength of these mixes was 23.5 N/mm$^2$ and 22.2 N/mm$^2$ respectively, it is pertain to mention here that the reference mix achieved compressive strength 24.2 N/mm$^2$ at 7 days. The reduction in compressive strength is attributed to the additional interfacial transition zone between the old adhered mortar to the original aggregate and the new mortar. For mix BR1 containing 10% SF, achieved compressive strength of 25.8 N/mm$^2$ at 7 days as compared to the compressive strength of 24.2 N/mm$^2$ for reference mix AR1. The mixes BR2 and BR3 containing 10 SF and 30%, 70% recycled aggregate achieved compressive strength of 25.1 N/mm$^2$ and 23.9 N/mm$^2$ respectively. So it can be clearly seen that the compressive strength of concrete increased by 3.7% for mix BR2. However the compressive strength of mix BR3 marginally decreased by 1.2%. For mix CR1 containing 20% SF, achieved compressive strength of 25.1 N/mm$^2$ at 7 days as compared to the compressive strength of 24.2 N/mm$^2$ for reference mix AR1. The mixes CR2 and CR3 containing 20% SF and 30%, 70% recycled aggregate achieved compressive strength of 24.1 N/mm$^2$ and 23.2 N/mm$^2$ respectively. So it can be clearly seen that the compressive strength of concrete increased by 0.42% for mix CR2 as compared to reference mix. However the compressive strength of mix CR3 decreased by 4.1%. The increase in compressive strength of concrete with addition of silica fume is due to the reason that surplus lime released from hydration of cement becomes source of pozzolanic reaction for additional secondary hydration mineralogy this reaction contributes for the mechanism of pore refinement and grain refinement, resulting in enhanced strength and strong transition zone. The mechanism of primary and secondary hydrated mineralogy is as follows:

Fast

OPC +H ⟶ Primary hydrated mineralogy +CH

Slow

Pozzolona + CH + H ⟶ Secondary hydrated mineralogy.

The effect of recycled aggregate on compressive strength of concrete at the age of 28 days is presented in table 3.4 to 3.6. The variation of compressive strength of concrete with different replacement level of silica fume after moist curing of 28 days is shown in figures below.

Table 3.4 Compressive Strength of Recycled Aggregates Concrete with 0% Silica Fume

| Concrete Mix | Failure Load (kN) | Compressive Strength ($N/mm^2$) | Average Compressive Strength ($N/mm^2$) | Percentage Decrease In Compressive Strength |
|---|---|---|---|---|
| AR 1 | 852.3 | 37.9 | 37.3 | - |
| | 825.8 | 36.7 | | |
| | 841.5 | 37.4 | | |
| AR 2 | 843.8 | 37.5 | 36.7 | 1.6 |
| | 821.3 | 36.5 | | |
| | 812.3 | 36.1 | | |
| AR 3 | 814.5 | 36.2 | 35.6 | 4.6 |
| | 801.0 | 35.6 | | |
| | 785.3 | 34.9 | | |

Table 3.5 Compressive Strength of Recycled Aggregates Concrete with 10% Silica Fume

| Concrete Mix | Failure Load (kN) | Compressive Strength ($N/mm^2$) | Average Compressive Strength ($N/mm^2$) | Percentage Decrease In Compressive Strength |
|---|---|---|---|---|
| BR 1 | 886.5 | 39.4 | 38.7 | -3.8 |
| | 859.5 | 38.2 | | |
| | 866.3 | 38.5 | | |
| BR 2 | 864.0 | 38.4 | 38.1 | -2.1 |
| | 859.5 | 38.2 | | |
| | 850.5 | 37.8 | | |
| BR 3 | 841.5 | 37.4 | 36.8 | 1.3 |
| | 816.8 | 36.3 | | |
| | 823.5 | 36.6 | | |

Table 3.6 Compressive Strength of Recycled Aggregates Concrete with 20% Silica Fume

| Concrete Mix | Failure Load (kN) | Compressive Strength ($N/mm^2$) | Average Compressive Strength ($N/mm^2$) | Percentage Decrease In Compressive Strength |
|---|---|---|---|---|
| CR 1 | 850.5 | 37.8 | 37.9 | -1.6 |
| | 843.8 | 37.5 | | |
| | 861.8 | 38.3 | | |
| CR 2 | 846.0 | 37.6 | 37.2 | 0.27 |
| | 821.3 | 36.5 | | |
| | 837.0 | 37.2 | | |
| CR 3 | 823.5 | 36.6 | 36.0 | 3.5 |
| | 803.3 | 35.7 | | |
| | 805.5 | 35.8 | | |

- Graph Showing Variation Of 28 Days Compressive Strength Of Concrete With Different Replacements Of Cement And Coarse Aggregates

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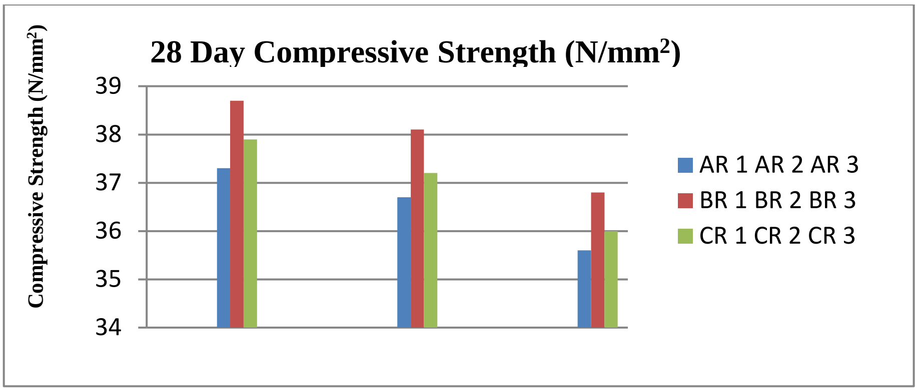


It is clear from above tables and figures that increase in percentage of recycled aggregate results in decrease in compressive strength of concrete. For mix AR2 and AR3 containing 30% and 70% recycled aggregate, the compressive strength decreased by 1.6% and 4.6% respectively and compressive strength of these mixes was 36.7 N/mm$^2$ and 35.6 N/mm$^2$ respectively it is pertain to mention here that the reference mix achieved the compressive strength of 37.3 N/mm$^2$ at 28 days. The reduction in compressive strength is attributed to the additional interfacial transition zone between the old adhered mortar to the original aggregate and the new mortar. For mix BR1 containing 10% SF, achieved compressive strength of 38.7 N/mm$^2$ at 28 days as compared to the compressive strength of 37.3 N/mm$^2$ for reference mix AR1 and shows increase in strength by 3.8%. The mixes BR2 and BR3 containing 10% SF and 30%, 70% recycled aggregate achieved compressive strength of 38.1 N/mm$^2$ and 36.8 N/mm$^2$ respectively. So it can be clearly seen that the compressive strength of concrete increased by 2.1% for mix BR2. However the compressive strength of mix BR3 marginally decreased by 1.3%. For mix CR1 containing 20% SF, achieve compressive strength of 37.9 N/mm$^2$ at 7 days as compared to the compressive strength of 37.3 N/mm$^2$ for reference mix AR1. The mixes CR2 and CR3 containing 20% SF and 30%, 70% recycled aggregate achieved compressive strength of 37.2 N/mm$^2$ and 36.0 N/mm$^2$ respectively. So it can be clearly seen that the compressive strength of concrete increase by 0.27% for mix CR2 as compare to reference mix. However the compressive strength of mix CR3 decreased by 3.5%.It is clear from above discussions that the trend of variation of compressive strength with percentage replacement of recycled aggregates is similar to variation shown by various mixes at the age of 7 days.

3.2.2 Split Tensile Strength:- The effect of silica fume on split tensile strength of concrete with replacement of natural aggregate with recycled aggregate in different proportion was investigated under following conditions:

- Cement partially replaced by silica fume
- Natural aggregate replaced by recycled aggregate in different proportions.

3.2.2.1 Effect of Percentage of Recycled Aggregate on Split Tensile Strength:- The effect of recycled aggregate on split tensile strength of recycled aggregate concrete at the age of 28 days is presented in table 5.7 to 5.9. The variation of compressive strength of concrete with different replacement level of silica fume after moist curing of 28 days is shown in figures below.

Table 3.7 Split Tensile Strength of Recycled Aggregates Concrete with 0% Silica Fume

| Concrete Mix | Failure Load (kN) | Split Tensile Strength (N/mm²) | Average Split Tensile Strength (N/mm²) | Percentage Decrease In Split Tensile Strength |
|---|---|---|---|---|
| AR 1 | 297.4 | 4.21 | 4.06 | - |
| | 278.2 | 3.94 | | |
| | 284.2 | 4.02 | | |
| AR 2 | 272.8 | 3.86 | 3.95 | 2.7 |
| | 277.8 | 3.93 | | |
| | 286.3 | 4.05 | | |
| AR 3 | 264.5 | 3.74 | 3.75 | 7.6 |
| | 273.6 | 3.87 | | |
| | 254.2 | 3.67 | | |

Table 3.8 Split Tensile Strength Of Recycled Aggregates Concrete with 10% Silica Fume

| Concrete Mix | Failure Load (kN) | Split Tensile Strength (N/mm²) | Average Split Tensile Strength (N/mm²) | Percentage Decrease In Split Tensile Strength |
|---|---|---|---|---|
| BR1 | 310.4 | 4.39 | 4.25 | -4.7 |
| | 297.4 | 4.21 | | |
| | 292.7 | 4.14 | | |
| BR2 | 292.2 | 4.13 | 4.15 | -2.2 |
| | 284.6 | 4.03 | | |
| | 303.9 | 4.29 | | |
| BR3 | 279.2 | 3.89 | 3.95 | 2.7 |
| | 272.9 | 3.86 | | |
| | 289.8 | 4.10 | | |

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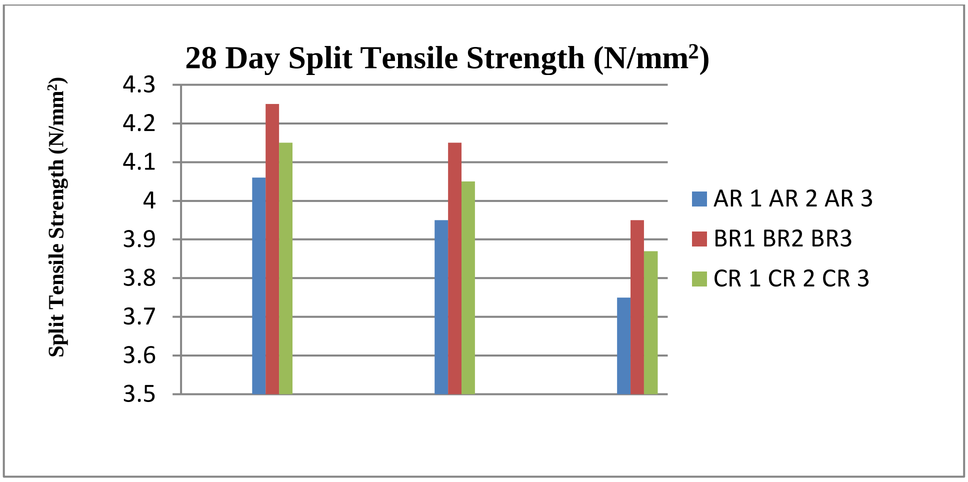
Table 3.9 Split Tensile Strength of Recycled Aggregates Concrete with 20% Silica Fume

| Concrete Mix | Failure Load (kN) | Split Tensile Strength (N/mm²) | Average Split Tensile Strength (N/mm²) | Percentage Decrease In Split Tensile Strength |
|---|---|---|---|---|
| CR 1 | 306.9 | 4.34 | 4.15 | -2.2 |
| | 284.6 | 4.08 | | |
| | 289.7 | 4.09 | | |
| CR 2 | 279.2 | 3.95 | 4.05 | 0.25 |
| | 289.1 | 4.09 | | |
| | 291.2 | 4.12 | | |
| CR 3 | 280.3 | 3.97 | 3.87 | 4.7 |
| | 272.5 | 3.85 | | |
| | 267.8 | 3.79 | | |

- Graph Showing Variation Of 28 Days Split Tensile Strength Of Concrete With Different Replacements Of Cement And Coarse Aggregates




It is clear from above tables and figures that increase in percentage of recycled aggregate results in decrease in split tensile strength of concrete. For mix AR2 and AR3 containing 30% and 70% recycled aggregate, the split tensile strength decreased by 2.7% and 7.6% respectively and split tensile strength of these mixes was 3.95 N/mm² and 3.75 N/mm² respectively, it is pertain to mention here that the reference mix achieved the split tensile strength of 4.06 N/mm² at 28 days. The reduction in split tensile strength is attributed to the additional interfacial transition zone between the old adhered mortar to the original aggregate and the new mortar. For mix BR1 containing 10% SF, achieved split tensile strength of 4.25 N/mm² at 28 days as compared to the split tensile strength of 4.06 N/mm² for reference mix AR1 and shows increase in strength by 4.7%. The mixes BR2 and BR3 containing 10% SF and 30%, 70% recycled aggregate achieved split tensile strength of 4.15 N/mm² and 3.95 N/mm² respectively. So it can be clearly seen that the split tensile strength of concrete increased by 2.2% for mix BR2. However the split tensile strength of mix BR3 marginally decreased by 2.7%. For mix CR1 containing 10% FA+10% SF, achieved split tensile strength of 4.15 N/mm² at 28 days as compared to the split tensile strength of 4.06 N/mm² for reference mix AR1. The mixes CR2 and CR3 containing 20% SF and 30%, 70% recycled aggregate achieved split tensile strength of 4.05 N/mm² and 3.87 N/mm² respectively. So it can be clearly seen that the split tensile strength of concrete increased by 0.25% for mix CR2 as compared to reference mix.. However the split tensile strength of mix CR3 decreased by 4.7%.

So it can be seen from the above discussions the variation of split tensile strength of concrete for various mixes containing different percentage of recycled aggregate is similar to the compressive strength achieved by various mixes in 7 and 28 days. The reason for increase in split tensile strength is due to addition of silica fume and decrease in split tensile strength with the increase in recycled aggregate is already explained in case of compressive strength.

3.2.3 Flexural Strength:- The effect silica fume on flexural strength of concrete with replacement of natural aggregate with recycled aggregate in different proportion was investigated under following condition:

- Cement partially replaced by silica fume.
- Natural aggregate replaced by recycled aggregate in different proportion.

3.2.3.1 Effect of Percentage of Recycled Aggregate on Flexural Strength:- The effect of recycled aggregate on split tensile strength of recycled aggregate concrete at the age of 28 days is presented in table 5.10 to 512. The variation of compressive strength of concrete with different replacement level silica fume after moist curing of 28 days is shown in figure 5.7 and 5.8

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Table 3.10: Flexural Strength of Recycled Aggregates Concrete with 0% Silica Fume

| Concrete Mix | Failure Load (Tonne) | Flexural Strength (N/mm²) | Average flexural Strength (N/mm²) | Percentage Decrease In flexural Strength |
|---|---|---|---|---|
| AR 1 | 1.55 | 6.2 | 6.0 | - |
| | 1.45 | 5.8 | | |
| AR 2 | 1.50 | 6.0 | 5.8 | 3.3 |
| | 1.40 | 5.6 | | |
| AR 3 | 1.45 | 5.8 | 5.7 | 5.0 |
| | 1.40 | 5.6 | | |

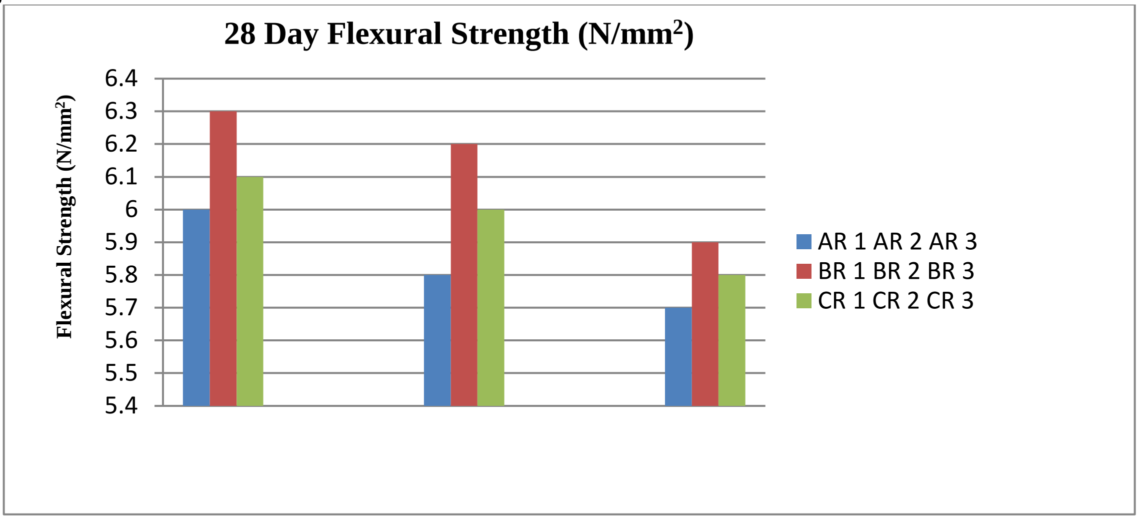
Table 3.11: Flexural Strength of Recycled Aggregates Concrete with 10% Silica Fume

| Concrete Mix | Failure Load (Tonne) | Flexural Strength (N/mm²) | Average flexural Strength (N/mm²) | Percentage Decrease In flexural Strength |
|---|---|---|---|---|
| BR 1 | 1.60 | 6.4 | 6.3 | -5.0 |
| | 1.55 | 6.2 | | |
| BR 2 | 1.60 | 6.4 | 6.2 | -3.3 |
| | 1.50 | 6.0 | | |
| BR 3 | 1.45 | 5.8 | 5.9 | 1.7 |
| | 1.50 | 6.0 | | |

Table 3.12: Flexural Strength of Recycled Aggregates Concrete with 20% Silica Fume

| Concrete Mix | Failure Load (Tonne) | Flexural Strength (N/mm²) | Average flexural Strength (N/mm²) | Percentage Decrease In flexural Strength |
|---|---|---|---|---|
| CR 1 | 1.55 | 6.2 | 6.1 | -1.7 |
| | 1.50 | 6.0 | | |
| CR 2 | 1.50 | 5.8 | 6.0 | 0 |
| | 1.50 | 6.0 | | |
| CR 3 | 1.50 | 6.0 | 5.8 | 3.3 |
| | 1.40 | 5.6 | | |

- Graph Showing Variation Of 28 Days Flexural Strength Of Concrete With Different Replacements Of Cement And Coarse Aggregates.




It is clear from above tables and figures that increase in percentage of recycled aggregate results in decrease in flexural strength of concrete. For mix AR2 and AR3 containing 30% and 70% recycled aggregate, the flexural strength decreased by 3.3% and 5.0% respectively and flexural strength of these mixes was 5.8 N/mm$^2$ and 5.7 N/mm$^2$ respectively, it is to pertain to mention here that the reference mix achieved the flexural strength of 6.0 N/mm$^2$ at 28 days. The reduction in flexural strength is attributed to the additional interfacial transition zone between the old adhered mortar to the original aggregate and the new mortar. For mix BR1 containing 10% SF, achieved flexural strength of 6.3 N/mm$^2$ at 28 days as compared to the flexural strength of 6.0 N/mm$^2$ for reference mix AR1 and shows increase in strength by 5.0%. The mixes BR2 and BR3 containing 10% SF and 30%, 70% recycled aggregate achieved flexural strength of 6.3 N/mm$^2$ and 6.2 N/mm$^2$ respectively. So it can be clearly seen that the flexural strength of concrete increased by 3.3% for mix BR2. However the flexural strength of mix BR3 marginally decreased by 1.7%. For mix CR1 containing 20% SF, achieved flexural strength of 6.1 N/mm$^2$ at 28 days as compared to the flexural strength of 6.0 N/mm$^2$ for reference mix AR1. The mixes CR2 and CR3 containing 20% SF and 30%, 70% recycled aggregate achieved flexural strength of 6.0 N/mm$^2$ and 5.8 N/mm$^2$ respectively. So it can be clearly seen that the flexural strength of concrete increased by 0% for mix CR2 as compared to reference mix . However the flexural strength of mix CR3 decreased by 3.3%.

So it can be seen from the above discussions the variation of flexural strength of concrete for various mixes containing different percentage of recycled aggregate is similar to the compressive strength achieved by various mixes in 7 and 28 days. The reason for increase in flexural strength is due to addition of silica fume and decrease in flexural strength with the increase in recycled aggregate is already explained in case of compressive strength.

3.2.4 Permeability of Concrete

Permeability of cement mortar or concrete is of particular significance in structures which are intended to retain water or which come into contact with water. Besides functional considerations, permeability is also intimately related to the durability of concrete, specially its resistance, against progressive deterioration under exposure to severe climate, and leaching due to prolonged seepage of water, particularly when it contains aggressive gases or minerals in solution. The effect of silica fume on flexural strength of concrete with replacement of natural aggregate with recycled aggregate in different proportion was investigated under following condition:

- Cement partially replaced by silica fume.
- Natural aggregate replaced by recycled aggregate in different proportion

3.2.4.1Effect of Percentage of Recycled Aggregate on Permeability of Concrete:- The effect of recycled aggregate on durability of concrete is presented in table 5.13 to table 5.15 and plotted in figure 5.8 to 5.10 which show the variation of permeability of concrete with different replacement level of silica fume at various stages of moist curing for 28 days. Two cylindrical specimens of each mix containing 0%, 30% and 70% recycled aggregate were tested after 28 days of moist curing with partial replacement of cement with silica fume as 0%, 10% and 20%.

Table 3.13: Permeability of Concrete Containing Recycled Aggregate for Concrete with 0% Silica Fume

| Mix Sample | Discharge Q (ml) | Time T (hrs) | Head H (m) | Coefficient of Permeability, K (m/s) x10-ll | Percentage Increase in K value |
|---|---|---|---|---|---|
| AR1 | 15 | 12 | 50 | 5.89 | - |
| AR2 | 17.4 | 12 | 50 | 6.84 | 16.1 |
| AR3 | 19.9 | 12 | 50 | 7.82 | 32.8 |

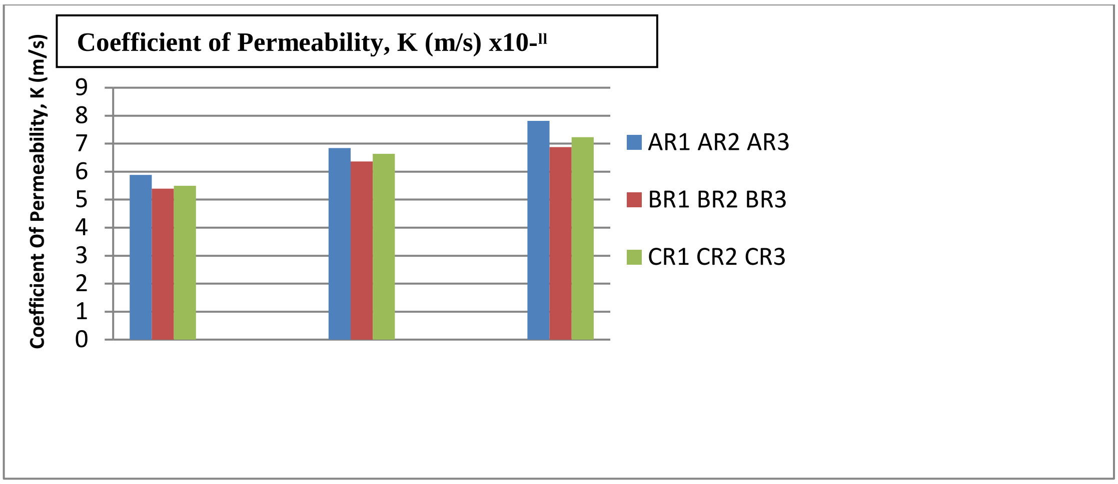
Table 3.14: Permeability of Concrete Containing Recycled Aggregate for Concrete with 10% Silica Fume

| Mix Sample | Discharge Q (ml) | Time T (hrs) | Head H (m) | Coefficient of Permeability, K (m/s) x10-ll | Percentage Increase in K value |
|---|---|---|---|---|---|
| BR1 | 13.7 | 12 | 50 | 5.39 | -8.4 |
| BR2 | 16.2 | 12 | 50 | 6.37 | 8.1 |
| BR3 | 17.5 | 12 | 50 | 6.88 | 16.8 |

Table 3.15: Permeability of Concrete Containing Recycled Aggregate Concrete with 20% Silica Fume

| Mix Sample | Discharge Q (ml) | Time T (hrs) | Head H (m) | Coefficient of Permeability, K (m/s) x10-ll | Percentage Increase in K value |
|---|---|---|---|---|---|
| CR1 | 14 | 12 | 50 | 5.50 | -6.6 |
| CR2 | 16.9 | 12 | 50 | 6.64 | 12.7 |
| CR3 | 18.4 | 12 | 50 | 7.23 | 22.6 |

- Graph Showing Variation Of Permeability Of Concrete With Different %age Replacements Of Cement And Coarse Aggregates




It is clear from above tables and figures that increase in percentage of recycled aggregate results in increase in permeability of concrete. For mix AR2 and AR3 containing 30% and 70% recycled aggregate, the permeability increased by 16.1% and 32.8% respectively and permeability of these mixes was 6.84 X $10^{-11}$ m/sec and 7.82 X $10^{-11}$ m/sec respectively it is pertain to mention here that the reference mix achieved the permeability of 5.89. X $10^{-11}$ m/sec at 28 days. Increase in permeability is attributed to the additional interfacial transition zone between the old adhered mortar to the original aggregate and the new mortar. For mix BR1 containing 10% SF, achieved permeability of 5.39 X $10^{-11}$ m/sec at 28 days as compared to the permeability of 5.89 X $10^{-11}$ m/sec for reference mix AR1 and shows decrease in permeability by 8.4%. The mixes BR2 and BR3 containing 10% SF and 30%, 70% recycled aggregate achieved flexural strength of 6.37 X $10^{-11}$ m/sec and 6.88 X $10^{-11}$ m/sec respectively. So it can be clearly seen that the permeability of concrete increased by 8.1% for mix BR2. However the permeability of mix BR3 marginally increased by 16.8%. For mix CR1 containing 20% SF, achieved permeability of 5.50 X $10^{-11}$ m/sec at 28 days as compared to the permeability of 5.89 X $10^{-11}$ m/sec for reference mix AR1. The mixes CR2 and CR3 containing 20% SF and 30%, 70% recycled aggregate achieved permeability of 6.64 X $10^{-11}$ m/sec and 7.23 X $10^{-11}$ m/sec respectively. So it can be clearly seen that the permeability of concrete increased by 12.7% for mix CR2 as compared to reference mix. However the permeability of mix CR3 increased by 22.6%.It is clear from above discussion that the permeability of concrete decreases with addition of silica fume. This is due to the fact that addition of silica fume results in pozzolanic reaction to form more densely calcium silicate hydrate gel. The increase in percentage of recycled aggregate results in increase in permeability which is attributed to fact that recycled aggregate get adhered mortar on the surface of recycled aggregates which results in formation of additional transition zone and increase in permeability of concrete.The above results show that the permeability of concrete increases with the increase in replacement of recycled aggregate in a mix and decreases with addition of supplementary cementing material i.e silica fume in different proportions.

## 4. CONCLUSIONS

4.1 General:- The present work was undertaken to investigate the effects of recycled aggregate (0%, 30% and 70%) on mechanical behaviour of concrete. Cement was replaced by silica fume whereas, natural aggregate were replaced by recycled aggregate in different proportions. In all, 126 specimens were cast and tested to investigate the effect of these replacements on compressive strength, split tensile strength, flexural strength and permeability of concrete. On the basis of results obtained in this investigation the conclusion have been drawn and included in this chapter.

4.2 Conclusions:- On the basis of results and discussions, the following conclusions are drawn:

- Water absorption of recycled aggregates was found to be greater than natural aggregates. This is due to the fact that the mortar adhered with recycled aggregate was weak and porous which lead to the increase in water absorption.
- The replacement of natural aggregate by recycled aggregate resulted in decrease in all strength parameter i.e. compressive strength, split tensile strength and flexural strength of concrete however, the permeability of concrete increases with the replacement of natural aggregate by recycled aggregate. Further, increased in percentage of recycled aggregate resulted in decrease in strength parameter and increase in permeability. The compressive strength of concrete containing 30% and 70% recycled aggregate decreased by 1.6% and 4.6% respectively for 28 days. Similar trend was obtained for split tensile strength and flexural strength. The permeability of concrete containing 30% and 70% recycled aggregate increased by 16.1% and 32.8% respectively at 28 days.
- The replacement of cement by silica fume in concrete resulted in increase in all strength parameter and decrease in permeability. The compressive strength of concrete containing 30% and 70% recycled aggregate and 10% silica fume increased by 3.8% and 3.4% respectively at 28 days. Similar trend was obtained for split tensile strength and flexural strength of concrete, the permeability of concrete containing 30% and 70% recycled aggregate, 10% silica fume decreased by 12% and 2.1% respectively.
- The compressive strength of concrete containing 30% and 70% recycled aggregate and 20 silica fume increased by 1.3% and 1.1% respectively at 28 days. Similar trend was obtained for split tensile strength and flexural strength of concrete, the permeability of concrete containing 30% and 70% recycled aggregate, 10% silica fume decreased by 12% and 2.1% respectively. No significant gains in strength parameter were obtained when the silica fume was increased to 10% each. Similar trend was obtained for split tensile, flexural strength and permeability of concrete,
- The mix containing 30% recycled aggregate, 10% silica fume exhibited compressive strength of 38.1N/mm$^2$ at 28 days which is 2.1% higher than the compressive strength exhibited by reference mix. Hence it can be recommended for field application.

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