A COMPARATIVE STUDY OF CONTROL AND RECYCLED AGGREGATE CONCRETE CONTAINING SILICA FUME AND STEEL FIBRES

A Thesis Submitted

In Partial Fulfillment of the Requirements for

the award of degree of

Master of Engineering (M.E.)

In

Structural Engineering

Submitted by

SALMAN SIDDIQUE

(ROLL NO. 801222016)

THAPAR UNIVERSITY

UNDER THE GUIDANCE OF

Dr. Gurbir Kaur

(Assistant Professor)

DEPARTMENT OF CIVIL ENGINEERING

THAPAR UNIVERSITY, PATIALA – 147004

JULY 2014

DECLARATION

I, Salman Siddique, hereby declare that this thesis report entitled **"A comparative study of control and recycled aggregate concrete containing silica fume and steel fibres"** submitted in the partial fulfilment of the requirements for the award of degree of Master of Engineering in Structural Engineering, in the Civil Engineering Department, Thapar University, Patiala, is my own work. This 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.

Salman

Date: 14-7-14

Place: Patiala

Salman Siddique

801222016

CERTIFICATE

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

14/07/14

Dr. Gurbir Kaur
Assistant Professor
Civil Engineering Department
Thapar University, Patiala

Countersigned by

Dr. Naveen Kwatra
Professor and Head
Civil Engineering Department
Thapar University, Patiala

Dr.S.K.Mohapatra
Dean Academic Affairs
Thapar University, Patiala

i

ACKNOWLEDGMENT

First of all, praise is due to almighty ALLAH who taught humankind everything they knew not and giving me the opportunity to step in the excellent world of technology.

It gives me immense pleasure to express my sincere regards and deep sense of gratitude to my supervisor, **Dr Gurbir Kaur** Assistant Professor Department of Civil Engineering Thapar University, Patiala, for her thoughtful guidance, continuous enthusiasm, and warm encouragement throughout the course of work. Apart from the subject of my work, I learnt a lot from her, which I am sure, will be useful in different stages of my life.

Sincere gratitude to **Dr. Naveen Kwatra,** HOD, Civil engineering department, for having made available the requisite facilities during the course of study.

My deepest gratitude goes to my parents for their unflagging love, constant encouragement, helpful advice, and a constant support during my study program and this thesis would certainly not have existed without them.

I would like to convey my sincere gratitude to my friends, colleagues and all the staff member of Civil Engineering Department.

.

Salman Siddique

(801222016)

ABSTRACT

The growing environmental concerns and proper disposal of construction and demolition waste is a challenge for construction industry. The use of demolition waste as a resource for recycling or recovery is gaining grounds in many countries. The proper selection and processing of demolition waste can be helpful in producing concrete. Production of concrete using recycled aggregate concrete has many benefits, such as, proper management of demolition waste, natural aggregates shortage is addressed, reduction in transport cost of raw materials.

This thesis, aims to find the possibility of the structural usage of recycled aggregate concrete as alternative or mixed with natural aggregates, by conducting a comprehensive laboratory investigation for better understanding of mechanical and durability properties of recycled aggregate concrete.

A mix proportion was established to produce twelve different concrete mixtures using 0%, 50% and 100% of recycled coarse aggregate with and without silica fume and steel fibre. The water-cement ratio of 0.42 is used.

Control mixture using natural aggregate showed better results compared with the mixture of using recycled aggregate. Results shows that more recycled aggregate is used, the compressive strength of concrete decreases. However, recycled aggregate used with silica fume and steel fibres showed improved strength and durability. By using supplementary materials it was possible to achieve higher mechanical properties of the RAC containing 100% recycled aggregate than that of control mixture concrete.

CONTENTS

CHAPTER PAGE NO.	DESCRIPTION	
	DECLARATION	i
	CERTIFICATE	i
	ACKNOWLEDGEMENTS	ii
	ABSTRACT	iii
	CONTENTS	iv
	LIST OF TABLES	vii
	LIST OF FIGURES	ix
	LIST OF PLATES	xiii
CHAPTER 1	**INTRODUCTION**	
	1.1 General	1
	1.2 Classification of Recycled Aggregate	1
	1.3 Current position of RCA in India and World	2
	1.4 Example of Structural Application of RCA	3
	1.5 Production of RCA	4
	1.6 Properties of RCA	5
	1.7 Specifications to be Considered While Using RCA	6
	1.8 Use of Additional Materials	6
	1.8.1 Silica fume	7
	1.8.2 Steel fibres	8
	1.9 Challenges and Scope of RCA	8
	1.10 Research Objectives	9
	1.11 Organization of the Thesis	9
CHAPTER 2	**LITREATURE REVIEW**	
	2.1 General	11
	2.2 Effect of RCA on Fresh Properties of Concrete	11
	2.2.1 Initial slump	11

2.3 Effect of RCA on Hardened Properties of Concrete 11
2.3.1 Compressive strength 11
2.3.2 Splitting tensile strength 22
2.3.3 Flexural strength 30
2.4 Effects of RCA on Durability Properties of Concrete 32
2.4.1 Chloride ion test 32
2.5 Need for Present Investigation 34
2.6 Closing Remarks 34
CHAPTER 3 EXPERIMENTAL WORK
3.1 General 35
3.2 Material Properties 35
3.2.1 Cement 35
3.2.2 Fine Aggregates 36
3.2.3 Natural Coarse Aggregates 37
3.2.4 Recycled Coarse Aggregates 37
3.2.5 Silica fume 39
3.2.6 Steel fibre 39
3.2.7 Water 40
3.2.8 Superplasticizer 40
3.3 Mix Combinations 40
3.4 Casting of specimens 43
3.4.1 Casting for Compressive strength test 43
3.4.2 Casting for Splitting tensile strength test 43
3.4.3 Casting for Flexural strength test 43
3.4.4 Casting for Rapid chloride permeability test 44
3.5 Testing of specimens 44
3.5.1 Setup for static compressive strength test 44
3.5.2 Setup for splitting tensile strength test 45
3.5.3 Setup for flexural strength test 47
3.5.4 Setup for rapid chloride permeability test 48

	3.6 Closing remarks	50
CHAPTER 4	**RESULTS AND DISCUSSION**	
	4.1 General	51
	4.2 Compressive Strength Test	51
	4.3 Splitting Tensile Strength Test	58
	4.4 Flexural Strength Test	64
	4.5 Rapid Chloride Permeability Test	70
	4.6 Effect of Recycled Aggregate, Silica Fume and Steel Fibre on Properties of Concrete	72
CHAPTER 5	**CONCLUSIONS**	
	5.1 General	74
	5.2 Compressive Strength	74
	5.3 Splitting Tensile Strength	75
	5.4 Flexural Strength	75
	5.5 Rapid Chloride Permeability	76
	5.6 Future Scope of Study	76
REFERENCES		78

LIST OF TABLES

Table no.	Description	Page no.
1.1	Specifications for the properties of recycled aggregates for concrete (RILEM, 1994)	5
1.2	Physical requirements of Silica fume (IS 15388, 2003)	7
1.3	Chemical requirements of Silica fume (IS 15388, 2003)	7
2.1	Compressive strength of concrete *(Kou et al. 2012)*	14
2.2	Cube compressive strength of concrete for each curing time (*Lima et al. 2013*)	15
2.3	Compressive strength of various mixes *(Surya et al. 2013)*	17
2.4	Compressive strength of concrete mixtures (*Andreu and Miren 2014*)	18
2.5	Compressive strength of mixes at 28 days *(Carneiro et al. 2014)*	19
2.6	Compressive Strength at 28 days (*Dibas et al. 2014)*	19
2.7	Compressive strength of concrete mixtures *(Kou and Poon 2013)*	21
2.8	Splitting tensile results *(Butler et al. 2013)*	24
2.9	Splitting tensile strength of various mixes *(Surya et al. 2013)*	25
2.10	Splitting tensile strength of mixes at 28 days *(Carneiro et al. 2014)*	26
2.11	Splitting tensile strength at 28 days (Dilbas *et al. 2014)*	27
2.12	Splitting tensile strength of concrete mixtures *(Kou and Poon 2013)*	29
2.13	Flexural strength of various mixes *(Surya et al. 2013)*	30
2.14	Flexural strength of mixes at 28 days *(Carneiro et al. 2014)*	31
3.1	Physical properties of ordinary Portland cement	35

3.2	Sieve analysis of fine aggregates	36
3.3	Physical properties of fine aggregates	37
3.4	Sieve analysis of natural coarse aggregates	37
3.5	Sieve analysis of recycled coarse aggregates	39
3.6	Physical properties of the recycled and natural course aggregate	39
3.7	Technical data of superplasticizer	40
3.8	Mix proportion of control sample	41
3.9	Mix proportions for different samples	42
3.10	Chloride ion penetrability based on charge passed (ASTM 1202-97)	49
4.1	Compressive strength of specimen at 7 and 28 days	51
4.2	Splitting tensile strength of concrete mixes at 7 and 28 days	58
4.3	Flexural strength of concrete mixes at 28 days	64
4.4	Rapid chloride permeability of samples at 28 days	70

LIST OF FIGURES

Figure no.	Description	Page no.
1.1	Vilbeler Weg office building (*www.b-i-m.de/projekte/projframe)*	3
1.2	The BRE office building (Collins, R. 2000)	3
1.3	Enterprise Park (www.concreterecycling.org)	4
2.1	Development of compressive strength of concrete mixtures (*Kou et al. 2011*)	13
2.2	Development of compressive strength of concrete mixtures (*Kou et al. 2011*)	13
2.3	The compressive strength development of RAC with fly ash (*Radonjanin et al. 2013*)	16
2.4	The compressive strength development of RAC with milled limestone (*Radonjanin et al. 2013*)	16
2.5	Compressive strength of recycled aggregate concrete compared with conventional concrete (*Andreu and Miren 2014*)	18
2.6	Tensile splitting strength of concrete mixtures (Kou *et al. 2011)*	23
2.7	Splitting Tensile and compressive strength of different mixes *(Radonjanin et al. 2013)*	25
2.8	Total charge passed in coulombs of concrete mixtures *(Kou et al 2011)*	32
2.9	Total charge passed in coulombs *(Kou and Poon 2013)*	33
4.1	Compressive strength value of control mixture and recycled aggregate concrete	53
4.2	Compressive strength value of control mixture and recycled aggregate concrete containing silica fume	53
4.3	Compressive strength value of control mixture and recycled aggregate concrete containing steel fibre	54

4.4	Compressive strength value of control mixture and recycled aggregate concrete containing silica fume and steel fibre	54
4.5	Compressive strength value of control mixture and recycled aggregate concrete with and without silica fume and steel fibre	55
4.6	Percentage variation of compressive strength of recycled aggregate concrete with respect to control mixture	55
4.7	Percentage variation of compressive strength of recycled aggregate concrete containing silica fume with respect to control mixture	56
4.8	Percentage variation of compressive strength of recycled aggregate concrete containing steel fibre with respect to control mixture	56
4.9	Percentage variation of compressive strength of recycled aggregate concrete containing silica fume and steel fibre with respect to control mixture	57
4.10	Splitting tensile strength value of control mixture and recycled aggregate concrete	59
4.11	Splitting tensile strength value of control mixture and recycled aggregate concrete containing silica fume	60
4.12	Splitting tensile strength value of control mixture and recycled aggregate concrete containing steel fibre	60
4.13	Splitting tensile strength value of control mixture and recycled aggregate concrete containing silica fume and steel fibre	61
4.14	Splitting tensile strength value of control mixture and recycled aggregate concrete with and without silica fume and steel fibre	61
4.15	Percentage variation of splitting tensile strength of recycled aggregate concrete with respect to control mixture	62
4.16	Percentage variation of splitting tensile strength of recycled aggregate concrete containing silica fume with respect to control mixture	62

4.17	Percentage variation of splitting tensile strength of recycled aggregate concrete containing steel fibre with respect to control mixture	63
4.18	Percentage variation of splitting tensile strength of recycled aggregate concrete containing silica fume and steel fibre with respect to control mixture	63
4.19	Flexural strength value of control mixture and recycled aggregate concrete	65
4.20	Flexural strength value of control mixture and recycled aggregate concrete containing silica fume	66
4.21	Flexural strength value of control mixture and recycled aggregate concrete containing steel fibre	66
4.22	Flexural strength value of control mixture and recycled aggregate concrete containing silica fume and steel fibre	67
4.23	Flexural strength value of control mixture and recycled aggregate concrete with and without silica fume and steel fibre	67
4.24	Percentage variation of flexural strength of recycled aggregate concrete with respect to control mixture	68
4.25	Percentage variation of flexural strength of recycled aggregate concrete containing silica fume with respect to control mixture	68
4.26	Percentage variation of flexural strength of recycled aggregate concrete containing steel fibre with respect to control mixture	69
4.27	Percentage variation of flexural strength of recycled aggregate concrete with and without steel fibre with respect to control mixture	69
4.28	Total charge passed in coulombs of control mixture and recycled aggregate concrete	71
4.29	Total charge passed in coulombs of control mixture and recycled aggregate concrete containing silica fume	71

4.30	Total charge passed in coulombs of control mixture and recycled aggregate concrete with and without silica fume	72

LIST OF PLATES

Plate no.	Description	Page no.
3.1	Waste concrete rubble for obtaining RCA	38
3.2	Jaw crusher to obtain RCA	38
3.3	Testing for compressive strength	45
3.4	Testing for splitting tensile strength	47
3.5	Testing for flexural strength	48
3.6	Vacuum desiccator’s bowl	49
3.7	Rapid chloride permeability test	50

CHAPTER 1

INTRODUCTION

1.1 General

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 buildings which are over their serviceability state are demolished for safety reasons. The waste generated from demolition was earlier used for landfills of ditches and trenches. But with time the amount of construction and demolition waste generated increased exponentially. It consists mostly of inert and non-biodegradable materials such as wood, concrete, glass, plastic and steel. Many large project sites have heaps and piles of construction and demolition waste lying around on roads and highways causing inconvenience and accidents to traffic movement. It is estimated that in India construction industry generates nearly 10-12 million ton of waste annually *(Thomas and Wilson 2013)*. Future predictions for use of aggregates in building and road construction indicate of shortage of 55,000 million cu.m and 750 million cu.m. Recycling of aggregates from construction and demolition waste may be helpful to bridge some of the gap. While wood, plastic, glass and glass is individually recycled. 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.

1.2. Classification of Recycled Aggregates:

- Recycled Concrete Aggregate (RCA) - Crushed sound and clean waste concrete of at least 95% by weight of concrete with total contamination lower than 1% of the bulk mass
- Recycled Concrete and Masonry (RCM) - Graded aggregate produced from sorted and clean waste concrete and masonry
- Reclaimed Aggregate (RA) - Coarse aggregates reclaimed from rejected concrete by separating the aggregates from the water-cement slurry.
- Reclaimed Asphalt Pavement (RAP) - Old asphalt concrete.

- Reclaimed Asphalt Aggregate (RAA) - Reclaimed coarse aggregate and recycled asphalt granules from waste asphalt concrete.
- Glass Cullet - Glass cullet pulverised into a sand-like product.
- Scrap Tyres - Processed scrap tyres as tyre chips and crumb rubber aggregate.
- Used Foundry Sand - Spent foundry sand.

1.3 Current Position of RCA in India and World.

Work on recycling of aggregates has been done at Central Building Research Institute (CBRI), Roorkee, and Central Road Research Institute (CRRI), New Delhi. Realising the future & national importance of recycled aggregate concrete in construction, Science and Engineering Research Council (SERC), Ghaziabad had taken up a pilot R&D project on recycling and reuse of demolition and construction wastes in concrete for low rise and low cost buildings in mid-nineties with the aim of developing techniques/ methodologies for use recycled aggregate concrete in construction. The experimental investigations were carried out to evaluate the mechanical properties and durability parameters of recycled aggregate concrete made with recycled coarse aggregate collected from different sources. Also, the suitability in construction of buildings has been studied. The properties of RAC were established and demonstrated through several experimental and field projects successfully. It has been concluded that RCA can be readily used in construction of low rise buildings, concrete paving blocks & tiles, flooring, retaining walls, approach lanes, sewerage structures, sub base course of pavement, drainage layer in highways, dry lean concrete (DLC) etc. in Indian scenario. Use of RCA will further ensure the sustainable development of society with environment (*Shah and Pitroda, 2011*).

Germany is the largest producer of recycled aggregates (60 million tonne) followed by United Kingdom (49 million tonne). Even smaller countries like Netherlands produce about 20 tonnes of recycled aggregates. Australia recycles nearly 50% of its construction and demolition waste while rest is used for landfills. Japan has the highest rate (98%) in processing of concrete waste to recycled aggregates. (*Ismail and Ramli, 2013*)

1.4 Example of Structural Application of RCA

The Vilbeler Weg office building in Darmstadt, Germany (1998) is one of the early application of RCA in construction. It has a built in of 480 cubic metre of RAC.

Fig 1.1: Vilbeler Weg office building (www.b-i-m.de/projekte/projframe.htm)

Another early example of RAC is the BRE office building in Watford, UK (1996). Over 1500 m^3 of RAC supplied for foundations, floor slabs, structural columns and waffle floors.

Fig 1.2: The BRE office building (www.projects.bre.co.uk)

In 2008, ReCrete Materials, Inc. of Arvada, Colo. provided approximately 7,900 cubic yards of ready mixed concrete containing recycled concrete aggregate for use in foundations and tilt-up panels at the Enterprise Park at Stapleton project in Denver, Colo. In a unique effort, Etkin Johnson Group, general contractor Murray and Stafford, Inc., concrete contractor CAL Construction, Inc. and Forest City Development utilized the recycled mix designs for their office and industrial development which is located within the borders of what was once Denver's Stapleton International Airport *(www.concreterecycling.org).*

Fig 1.3: Enterprise Park (www.concreterecycling.org)

1.5 Production of RCA

A number of methods are available for crushing and sieving of the construction and demolition waste for production of quality RCA meeting appropriate standards and specifications. Extensive research and process have been developed to demonstrate that both plain and reinforced concrete can be used to produce RCA with acceptable quality to conforming BS 882 standards. It is clear that such material often contains foreign matter in the form of metals, wood, hardboard, plastics, papers etc. Therefore, a process scheme is adopted to remove large pieces of these materials, mechanically and/or manually, before crushing and thorough cleaning of the crushed product. In many European countries, as well in the USA, methods have been developed to improve quality of recycled aggregate to suit individual circumstances and applications. Dry processing of CDW is a common practice that includes crushing, screening, magnetic separation and dry separation. During the past few years, wet processing has been adopted with local variations in some countries, e g, Austria, Netherlands and USA. It could incur a marginally higher cost but it is claimed that the products from the wet process are cleaner and better in quality.

After successful batching of RCA, the next step is to carry out mix design process. Water absorption and adhered mortar content should be kept in mind in order to get appreciable results.

1.6 Properties of RCA

Particles of RCA consist of natural aggregate partially coated with mortar or cement paste. The amount of surrounding mortar will vary depending on the method by which the RCA was produced; for example, an increasing number of cycles in a ball crusher can reduce the amount of mortar present. However there are other more efficient processing methods available, but the aim should still be to remove as much of the mortar as possible. The mortar, which is lighter and more porous than natural aggregate, affects the physical properties of the recycled material notably with respect to water absorption and density. Table 1.1 lists the specifications of RCA as per RILEM technical code.

Table 1.1 Specifications for the properties of recycled aggregates for concrete (RILEM, 1994)

Composition	Type 1	Type 2	Type 3
	Aggregates from masonry rubble	Aggregates from concrete rubble	Mixture of natural (80%) and RCA (20%)
Oven dry density (kg/m^3)	1500	2000	2400
Maximum content of foreign matter (glass, bitumen.) (%)	5	1	1
Maximum content of metal (%)	1	1	1

Maximum content of organic materials (%)	1	0.5	0.5
Maximum content of fines (<0.063 mm) (%)	3	2	2
Maximum content of sand (%)	5	5	5
Maximum content of sulfate (%)	1	1	1

1.7 Specifications to be Considered While using RCA

The major effects on the quality of RCA is the large amount of adhered cement mortar that remains on the surface of the aggregate, resulting in higher porosity, water absorption rates and weaker interfacial zone between new cement mortar and aggregates, which weakens the strength and mechanical performance of concrete made from RA *(Tam et al 2007)*.

The following methods can be used to enhance the quality of RCA

1. Two stage RAC mixing approach
2. Heat treatment
3. Microwave decontamination
4. Pre-soaking treatment
5. Washing and chloride treatment

1.8 Use of Additional Materials

From the viewpoint of sustainability and durability partial replacement of Portland cement with various mineral admixtures has been studied with RCA. Supplementary cementitious materials such as fly ash, blast furnace slag, silica fume, nano-silica and lime powder were used. Satisfactory properties of RAC has been reported, depending on the replacement of cement and natural aggregates and type of mineral admixtures used.

1.8.1 Silica fume

Silica fume, also known as micro-silica, is an amorphous (non-crystalline) polymorph of silicon dioxide, silica. It is an ultrafine powder collected as a by-product of the silicon and ferrosilicon alloy production and consists of spherical particles with an average particle diameter of 150 nm. The main field of application is as pozzolanic material for high performance concrete. The pozzolanic reactions take place when silica fume is added to the concrete mixture, and the amorphous silica, which is the major component of the pozzolana, reacts with calcium hydroxide formed from the hydration of the calcium silicates with the resulting product being a calcium silicate hydrate (C-S-H). Usually after micro silica is added to the concrete mix, the matrix of micro silica concrete becomes very dense. This denseness effect has been attributed to the extreme fineness of micro silica, due to the fact that 50,000 to 100,000 microspheres exist for every cement grain, allowing micro silica hydration products to infill the water spaces usually left within the cement hydrates. Silica fume is used in amounts between 5% and 10% by mass of the total cementitious material, in applications where high degree of impermeability and high compressive strength are needed in concrete.

The physical and chemical properties of silica fume as per Indian standards are given in Table 1.2 and 1.3

Table 1.2 Physical requirements of Silica fume (IS 15388, 2003)

Characteristic	Requirement
Specific Surface (m^2/g) [Minimum]	15
Oversize percent retained on 45 micron IS sieve [Maximum]	10
Oversize percent retained on 45 micron IS sieve, variation from average percent [Maximum]	5
Compressive strength at 7 days as percent of control sample [Minimum]	85

Table 1.3 Chemical requirements of Silica fume (IS 15388, 2003)

Characteristic	Requirements
SiO_2, Percent by mass, [Minimum]	85
Moisture Content, Percent by mass, [Maximum]	3
Loss on Ignition, Percent by mass, [Maximum]	4
Alkalis as NaO_2, percent, [Maximum]	1.5

1.8.2 Steel fibres

Steel fibres are filaments of wire, deformed and cut to lengths, for reinforcement of concrete, mortar and other composite materials. It is a cold drawn wire fibre with corrugated and flatted shape.

Steel fibre are generally available in two types

1. Corrugated Steel Fibre: - The cold-rolled strip steel products are made from cutting. Stainless steel fibre has high tensile strength and it can be easily dispersed, and can be easily integrated with the concrete.
2. Hooked End Steel Fibre: - Steel fibre with hooked ends is made using high-quality low-carbon steel wire. A kind of high-performance steel fibre, with the characteristics of the high tensile strength and good toughness.

When the fibre reinforcement is in the form of short discrete fibres, they act effectively as rigid inclusions in the concrete matrix. Physically, they have thus the same order of magnitude as aggregate inclusions; steel fibre reinforcement cannot therefore be regarded as a direct replacement aggregates. However, because of the inherent material properties of fibre concrete, the presence of fibres in the body of the concrete can be expected to improve the resistance of conventional structural members to cracking, deflection and other serviceability conditions.

1.9 Challenges and Scope of RCA

The use of recycled aggregate in concrete is relatively rare. There are three main reasons for that:

1. Overall economics – direct costs can also be unfavourable
2. Situation of steady supply of suitable aggregates - aggregate producers do not want to build up large stock of recycled aggregate for concrete since there is no market.
3. Other end uses are far more tolerant than concrete of the inevitable contaminants in RA.

Technical problems may include:

- High content of cement paste/mortar

- Weak interfacial transition zones between cement paste and aggregate
- Porosity and traverse cracks within demolished concrete
- High level of sulphate
- High level of chlorides
- Impurity
- Poor grading
- High variations in quality

1.10 Research Objectives

The principle objective of this thesis is to study the possible techniques of improving the properties of recycled aggregate concrete that is made up with 50% or higher percentages of recycled aggregates. This study is conducted to compare the fresh and hardened properties of RAC made with different recycled coarse aggregate (RCA) replacement levels with those of natural aggregate concrete (NAC). Evaluate the durability performance of RAC made with different RCA replacement levels. Investigate the potential of silica fume and steel fibres in recycled aggregate concrete.

1.11 Organisation of the Thesis

This thesis has been organized in five chapters as follows:

Chapter- 1. Introduction- It presents various aspects of RCA concrete.

Chapter- 2. Literature Review- It introduces the review of 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 (durability assessment)

Chapter- 3. Experimental Programme- It describes the material characteristics (physical/chemical), mixture proportions, specimen size, test methods and associated instruments.

Chapter- 4. Results and Discussions- Deals with the presentation, analysis and discussion of different results.

Chapter-5.Conclusion- Summarises the main conclusions and recommendations for future scope of study is presented.

References are listed at the end for the convenience of the readers.

CHAPTER 2

LITERATURE REVIEW

2.1 General

In this chapter a review of the literature related to mineral admixtures in RAC is presented. A brief review of the published work on material and structural characteristic of RCA concrete is presented and finally the need of the present investigation is identified.

2.2. Effect of RCA on Fresh Properties of Concrete

Some of the required fresh properties of fresh concrete are workability characteristics of concrete, which include slump, loss of slump and bleeding. All these aspects are discussed in the following section.

2.2.1. Initial slump

Poon et al. (2004) studied the moisture condition of the aggregate on initial slump, showed that the initial slump of recycled aggregate concrete was significantly affected by the moisture condition of aggregates.

Butler et al. (2013) graded the aggregates as per 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.

Ismail and Ramli (2013) pre-soaked the RCA in acid of different molarity and studied 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.

2.3 Effect of RCA on Hardened Properties of Concrete

Some of the important hardened properties of concrete are compressive strength, splitting tensile strength and flexural strength. They are discussed in the following sections.

2.3.1. Compressive strength

Poon et al. (2004) studied influence of moisture states of natural and recycled aggregates on the compressive strength of concrete. Concrete mixtures prepared with the incorporation of recycled aggregates, the air dried (AD) aggregate concretes exhibited the highest compressive strength. The surface dried density (SSD) recycled aggregates seemed to impose the largest negative effect on the concrete strength, which might be attributed to ‘‘bleeding’’ of excess water in the pre-wetted aggregates in the fresh concrete. Air dried RCAs when used at 50% replacement level to NAs give optimum strength.

Tangchirapat et al. (2008) examined concrete containing 100% coarse recycled aggregate and recycled fine aggregate at 0%, 50% and 100% replacement along with rice husk-bark ash. The rice husk-bark ash was used to replace cement at rate of 20%, 35% and 50%. It has been concluded that higher amount of fine and coarse recycled aggregates resulted in lower compressive strength values. Though concrete having 100% coarse recycled aggregate and river sand showed higher strength than conventional concrete at 35% rice husk-bark ash.

Corinaldesi and Moricioni (2009) presented the study on influence of mineral additions on the performance of 100% recycled coarse aggregate and 26% recycled fine aggregate concrete. Silica fume and fly ash were mixed and recycled aggregates consists of 70% old concrete and 30% bricks. Mineral additions were replaced at 15% and 30% by weight of cement and added as fine aggregate replacement. The W/C ratio was kept at 0.40. The compressive strength of concrete with silica fume was appreciable as compared to fly ash concrete. The compressive strength of fly ash concrete was nearly equal to control mixture concrete.

Kou et al. (2011) compared the compressive strength recycled aggregate concrete prepared with different mineral admixtures including silica fume (10%), metakaolin (15%), fly ash (35%), ground granulated blast slag (55%) used as cement replacement. The recycled aggregates were replaced at 50% and 100%. The recycled aggregate concrete with addition of silica fume and meatkaolin exhibited positive effects on compressive strength at both replacement levels when compared to control concrete. Fly ash and ground granulated blast slag had a detrimental effect on the compressive strength. Fig 2.1 and 2.2 shows the compressive strength of control mixture and recycled aggregates.

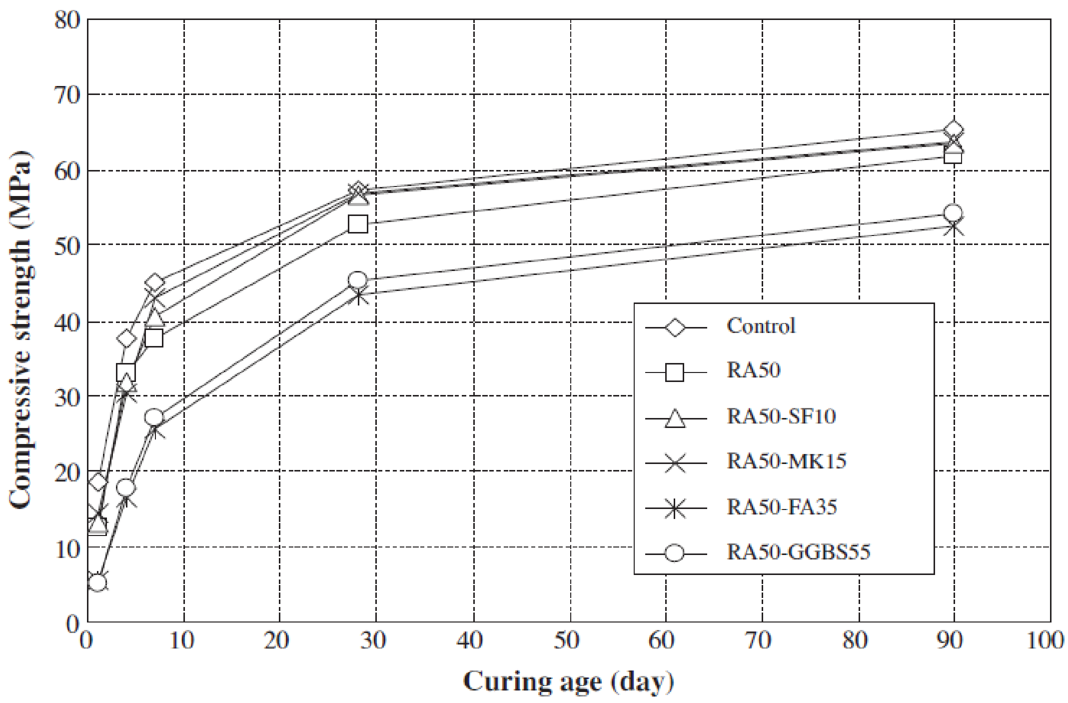

Fig 2.1: Development of compressive strength of concrete mixtures (*Kou et al. 2011*)

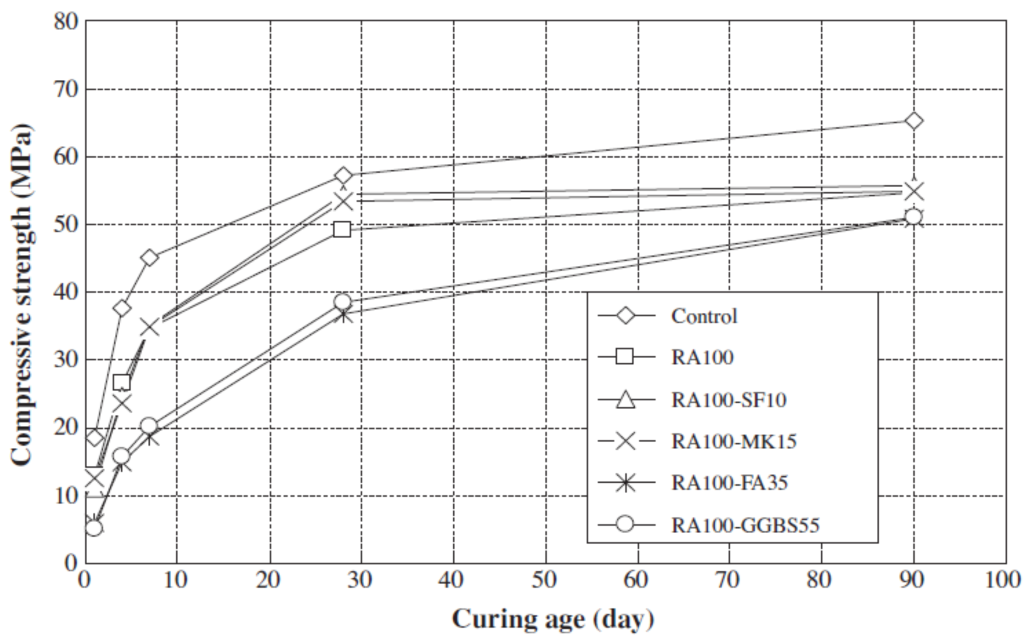

Fig 2.2: Development of compressive strength of concrete mixtures (*Kou et al. 2011*)

Kou et al. (2012) used commercial recycled aggregates at 0%, 25%, 50% and 100% replacement levels on natural aggregates. At 28 days the compressive strength of 100% recycled aggregate concrete was 12.2% lower than natural aggregate concrete. After 90 days the values of recycled aggregate concrete was better and even more at 20% replacement level of natural aggregate. Table 2.1 gives the compressive strength.

Table 2.1: Compressive strength of concrete *(Kou et al. 2012)*

Concrete mixes	Recycled aggregates (%)	Compressive Strength (MPa)	
		28-day	90-day
RA0	0	43.4	47.8
RA20	20	45.3	49.1
RA50	50	42.5	47.5
RA100	100	38.1	45.5

Butler et.al. (2013) concluded compressive strength of recycled aggregate concrete can be equivalent to that of conventional concrete if basic mixture proportions can be adjusted properly and the quality of recycled aggregates are of fine quality. The source of the recycled aggregate played an important role in achieving the desired compressive strength. To achieve adequate batch to batch compatibility the aggregates were pre-soaked. The recycled aggregate was procured from three different sources such as decommissioned curbs and sidewalks, demolished terminals from airport and returned ready-mix concrete. The aggregates were replaced at 100% level.

Ismail and Ramli (2013) observed the compressive strength of treated recycled aggregate. The recycled aggregates were pre-soaked in acids of different of molarity for 1, 3 and 7 days. The compressive strength values of treated recycled aggregate was higher than normal recycled aggregates. The acid removed the loose adhered mortar on the aggregate surface. The replacement levels were at 15%, 30%, 45% and 60%. At 60% replacement level the compressive strength showed improvement when compared to non-treated aggregate. Though on higher side 45% achieves the optimum strength.

Kou and Poon (2013) observed long term compressive strength of recycled aggregate concrete prepared with incorporation of fly ash. The recycled aggregate concrete was prepared by using 25%, 35% and 55% fly ash whereas recycled aggregate used were substituted as 0%, 50% and 100%. Two types of curing conditions were imposed water and air curing. It was concluded that even after 10 years the compressive strength recycled aggregate concrete was lower than conventional concrete.

Lima et al. (2013) presented the compressive strength property of concrete made with recycled aggregate and fly ash. The percentage of recycled aggregates was 30, 60 and

100. Both coarse and fine recycled aggregates were used in concrete mixtures. To keep the water available for chemical reaction constant, extra amount of water was added in various mixes calculated from water absorption capacity of aggregates. The content of fly ash was kept as "Low", "Medium" and "High". Medium content of fly ash at 30% recycled aggregates showed higher values than traditional concrete. Fly ash was beneficial in long run when using recycled aggregates. They concluded that fly ash can be used in specific proportions to get positive results. Table 2.2 depicts the cube compressive strength.

Table 2.2: Cube compressive strength of concrete for each curing time (*Lima et al. 2013*)

Time	N	LN	LR30	LR60	LR100	MN	MR30	MR60	MR100	HN	HR30	HR60	HR100
2 days	25	24.06	22.12	14.43	3.33	20.11	24.26	12,76	6.70	6.59	8.66	7.71	5.12
7 days	30.04	29.90	28.89	22.57	8.49	26.81	28.81	23.05	15.20	20.59	17.53	13.78	10.74
28 days	34.46	37.39	33.20	26.86	12.06	39.48	37.91	26.20	20.52	35.04	30.77	28.32	18.17
60 days	39.10	39.40	36.56	29.17	14.61	56.96	47.95	42.36	27.10	48.73	39.93	36.63	23.84
90 days	39.29	44.39	36.63	33.54	13.04	53.79	55.46	40.31	31.69	56.14	42.39	40.32	29.04

Radonjanin et al. (2013) replaced 50% cement with different mineral admixtures such as milled limestone, fly ash, whereas fixed amount of 10% silica fume, metakaolin was used. The concrete mixtures consisted of 50% recycled aggregates. Seven concrete mixes were prepared. Chemical admixtures were added in some mixtures to achieve desired consistency. Different unconventional combinations such as 40% fly ash or milled limestone + 10% silica fume or metakaolin were also prepared. Concrete with Fly ash in combination with metakaolin or silica fume significantly improved the performance. Milled limestone in combination with metakaolin can also be used for low level structural work.

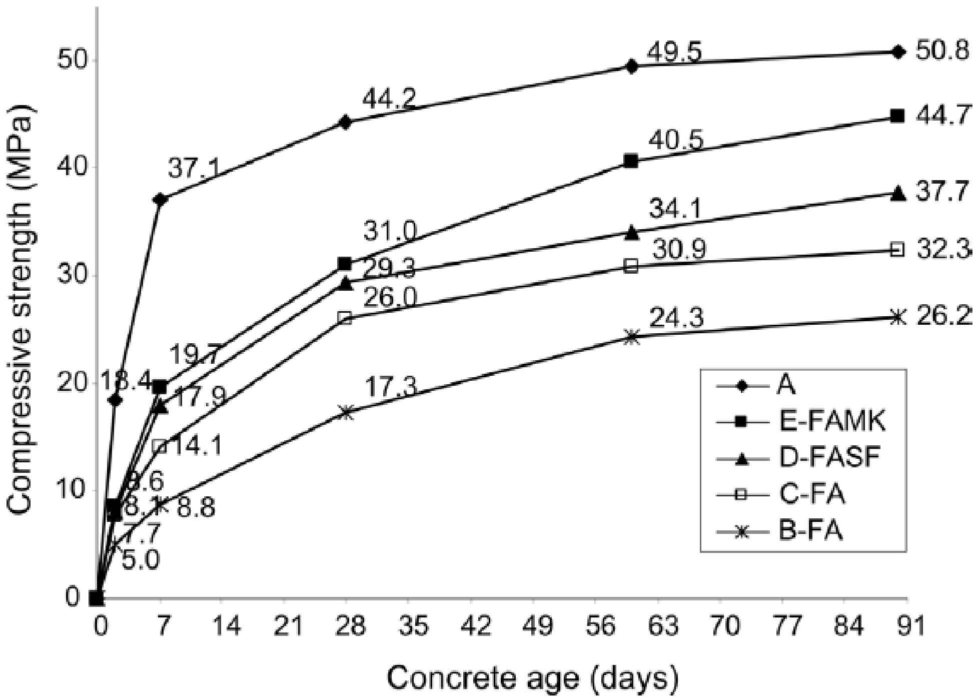

Fig 2.3: The compressive strength development of RAC with fly ash (*Radonjanin et al. 2013*)

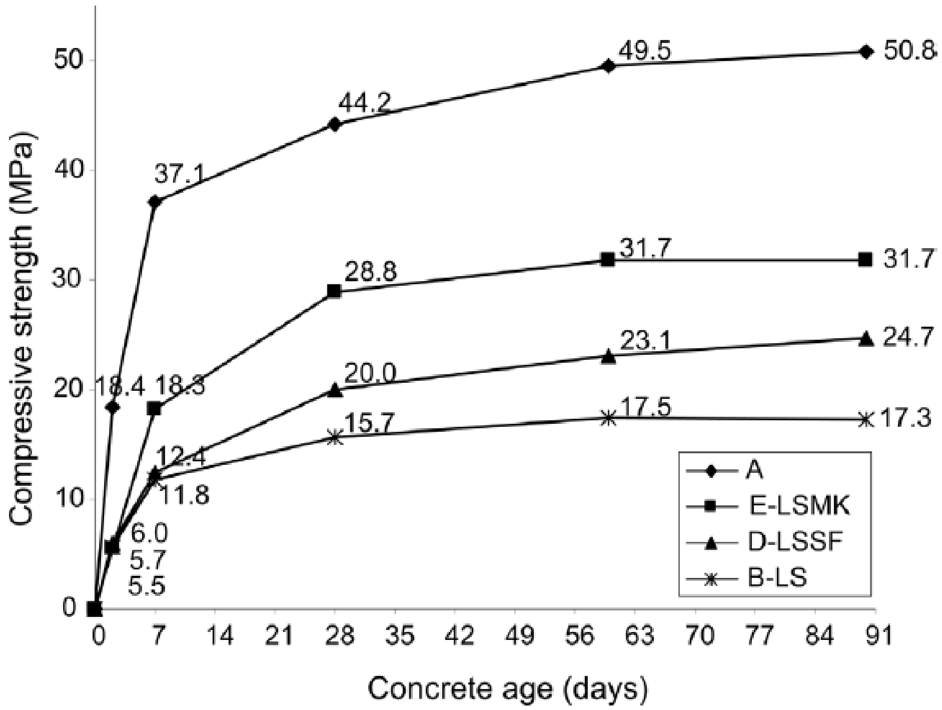

Fig 2.4: The compressive strength development of RAC with milled limestone (*Radonjanin et al. 2013*)

Surya et al. (2013) observed five different concrete mixes with and without class F Fly ash. Three mixes containing recycled aggregate at 50%, 75% and 100% replacement of natural aggregate were prepared containing fly ash, and two natural aggregate concrete mixes with and without fly ash. Recycled aggregates were generated by crushing waste dump of lab samples. Water-cement ratio was kept constant at 0.4. The compressive strength exhibited by recycled aggregate concrete was better than traditional concrete. The concrete containing 100% recycled aggregate exhibited maximum compressive strength. The transition zone of recycled aggregate concrete improved due to addition of fly ash making its strength parallel or greater than control mixture.

Table 2.3: Compressive strength of various mixes *(Surya et al. 2013)*

Mix Designation	Compressive strength (MPa)			
	3 days	7 days	28 days	56 days
NAC	33.85	43.85	45.63	53.19
NAF	33.33	41.03	47.25	57.77
R50	28.89	37.49	47.40	54.02
R75	30.67	34.96	46.61	54.22
R100	30.15	43.11	48.89	57.33

Thomas et al. (2013) used different water to cement ratios (0.45, 0.50, 0.55 and 0.65) to study samples. Substitution of recycled aggregates was 20%, 50% and 100% and were used in both dry and saturated states. The compressive strength test were carried out at 28, 180 and 365 days. At 20% replacement level no significant decrease was noted. Whereas at higher replacement levels there is significant loss of compressive strength. Study concluded that to achieve higher strength W/C has to be reduced.

Andreu and Miren (2014) analysed the properties of high performance recycled aggregate concrete. The recycled aggregates were sourced from high strength concrete and were replaced as 20%, 50% and 100%. The recycled were produced from 40, 60 and 100 MPa concrete. When 100 MPa recycled aggregates were used the compressive was higher than control mixture. High quality of cement paste was capable to develop a better bond with recycled aggregates. Only 40 MPa recycled aggregates at 100% replacement performed poorly. The negative influence was because of inferior adhered mortar content on the aggregates. The low water-cement ratio of 0.285 was used, to compensate for this in recycled aggregate concrete overly saturated fine aggregates were used.

Table 2.4: Compressive strength of concrete mixtures (*Andreu and Miren 2014*)

Concrete Reference	Compressive Strength (MPa)		
	1-day	7-day	28-day
CC	57.36	91.19	102.09
RC-20-100	73.79	88.51	108.03
RC-50-100	79.24	94.76	104.80
RC-100-100	78.73	93.43	108.51
RC-20-60	73.55	102.1	102.48
RC-50-60	72.38	98.77	103.10
RC-100-60	79.42	100.1	100.78
RC-20-40	67.06	91.73	104.28
RC-50-40	60.69	84.39	96.84
RC-100-40	56.62	79.88	91.23

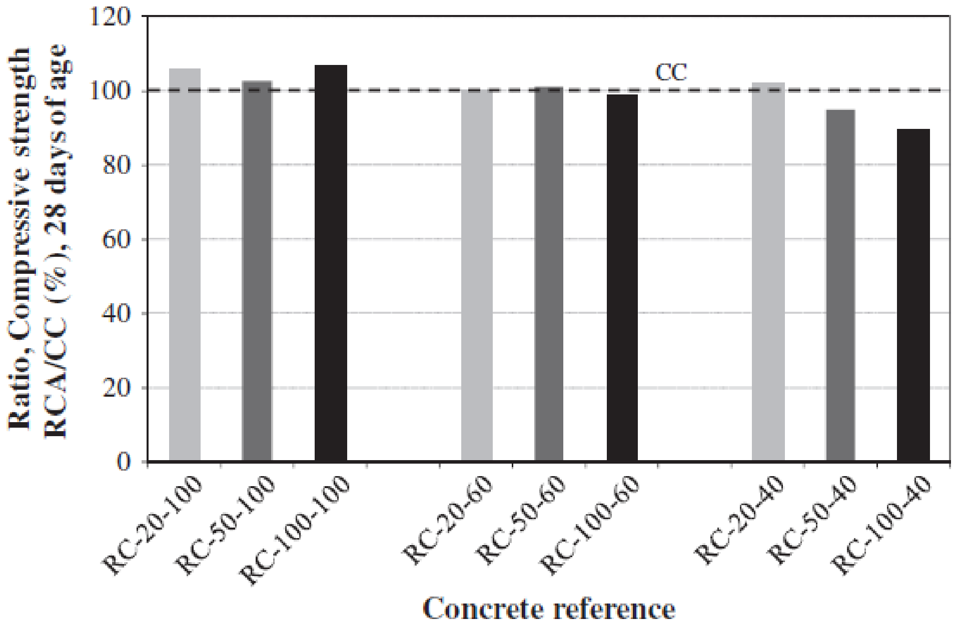

Fig 2.5: Compressive strength of recycled aggregate concrete compared with conventional concrete (*Andreu and Miren 2014*)

Carneiro et al. (2014) used steel fibres to reinforce recycled concrete, both recycled fine and coarse aggregates were used in mixes. The replacement being 25% by volume for RFA and RCA and 50% of both. The steel fibres substituted in volume fraction of 0.75% were both end hooked having 35 mm and 0.55 mm of length and diameter respectively. The compressive strength of mixtures increased 10-19% with the addition of steel fibres. In plain concrete low replacement levels showed positive results.

Table 2.5: Compressive strength of mixes at 28 days *(Carneiro et al. 2014)*

MIX	Compressive Strength (MPa)
	Plain Concrete
REF	29.9
RCA	32.6
RFA	34.1
RFCA	37.7
	Steel Fibre Reinforced Concrete
SF-REF	34.3
SF-RCA	36.9
SF-RFA	40.5
SF-RFCA	41.5

Dibas et al. (2014) investigated recycled aggregate concrete with silica fume for compressive strength. Two types of recycled aggregates were used, composed of concrete, tiles and bricks. The replacement levels of aggregates was 30% and 40%, later both types were used simultaneously taking replacement of 70%. Silica fume replaced was 5% and 10% by weight of cement. The results showed that impurities in recycled aggregates can reduce the effect of silica fume. Despite that concrete containing separate recycled aggregates exhibited good results using 5% and 10% silica fume when compared with traditional concrete.

Table 2.6: Compressive Strength at 28 days (*Dibas et al. 2014)*

Notation	Silica fume (%)	Recycled Aggregates (%)	Compressive Strength (MPa)
1st Group			
NAC	0	0	35.8
RA1C	0	40	33.0
RA2C	0	30	34.1
RA12C	0	70	29.1
2nd Group			
NACSF5	5	0	39.9

RA1CSF5	5	40	34.8
RA2CSF5	5	30	35.2
RA12CSF5	5	70	33.2
3rd Group			
NACSF10	10	0	45.5
RA1CSF10	10	40	37.2
RA2CSF10	10	30	38.5
RA12CSF10	10	70	28.9

Gayarre et al. (2014) reported that different curing environment, open air curing and standard curing conditions (20°C and 95% humidity) have evident impact on the properties of recycled aggregates. The aggregates were replaced at 20, 50 and 100%. The open air cured recycled aggregate concrete lost up to 20% of their compressive strength. This can be attributed that use of recycled aggregate concrete reduces concrete density and if not cured properly it can accelerate water loss.

Koenders et al. (2014) observed different water to cement ratio and initial moisture condition of recycled aggregates. The aggregates were batched in dry and saturated state. The concrete containing saturated recycled aggregate exhibited losses up to 60%. The aggregates were replaced at 30% and W/C was kept at 0.45 and 0.60. The 28 day compressive strength decreased when W/C ratio was 0.60 and saturated aggregates exhibited a loss in strength as compared to dry aggregates.

Kanellopoulos et al. (2014) used recycled lime powder to study the compressive strength of recycled aggregate concrete. The recycled aggregates were substituted at 10%, 30%, 50% and 100% of natural aggregates. Cement was gradually replaced by 5%, 8%, 10% and 20% by volume. The average strength drop recorded was 10%. No serious decrease was found in compressive strength of mixes.

Mukharjee and Barai (2014) studied the properties of concrete containing 100% recycled aggregate and nano- silica at 0.75%, 1.5% and 3% cement replacement levels. Additional 10% water was added to mitigate requirement of recycled aggregates. Mixture containing 3% nano-silica exhibited similar strength as traditional concrete.

Table 2.7: Compressive strength of concrete mixtures *(Kou and Poon 2013)*

Notation	Fly ash (%)	Recycled aggregates (%)	Compressive strength (MPa)									
			28-day		1-year		3-year		5-year		10- year	
			Water cured	Air cured	Water cured	Air cured	Water cured	Air cured	Water cured	Air cured	Water cured	Air cured
R0	0	0	48.6	46.7	56.5	53.3	60.8	55.9	64.2	58.4	67.5	61.3
R50	0	50	42.5	41.3	51.2	47.1	55.6	50.6	61.4	55.1	65.3	57.5
R100	0	100	38.1	36.5	46.6	43.1	51.1	46.2	56.3	50.8	62.7	52.2
R0F25	25	0	43.6	42.3	60.3	57.5	64.5	61.2	68.4	63.4	71.1	65.9
R50F25	25	50	41.7	39.8	55.2	52.4	59.2	56.8	65.8	59.4	70.2	63.1
R100F25	25	100	36.8	35.2	51.2	47.6	55.3	52.6	60.3	55.5	68.5	59.1
R0F35	35	0	40.7	38.9	50.3	46.6	61.2	55.9	66.5	59.8	69.2	63.4
R50F35	35	50	37.1	35.9	47.6	42.3	57.2	51.1	62.3	56.7	67.5	58.8
R100F35	35	100	32.2	29.7	42.4	37.5	53.1	48.3	59.3	52.3	65.9	56.3
R0F55	55	0	36.2	34.9	48.6	41.2	57.6	52.2	62.3	55.1	67.1	60.4
R50F55	55	50	31.4	29.9	43.9	38.6	52.1	46.4	57.6	50.3	62.9	54.8
R100F55	55	100	26.6	25.6	35.1	32.5	43.9	41.1	50.8	45.8	55.6	49.4

2.3.2. Splitting tensile strength

Tangchirapat et al. (2008) examined concrete containing 100% coarse recycled aggregate and recycled fine aggregate at 0%, 50% and 100% replacement along with rice husk-bark ash. The rice husk-bark ash was used to replace cement at rate of 20%, 35% and 50%. The splitting tensile strength of concrete is presented as a percentage of its compressive strength. The results indicated that splitting tensile strength of the recycled aggregate concrete was not much different from the concrete made from normal aggregates. The addition of rice husk-bark ash did not change the characteristic of splitting tensile strength of recycled aggregate concrete.

Corinaldesi and Moricioni (2009) presented the study on influence of mineral additions on the performance of 100% recycled aggregate and 26% fine recycled aggregate concrete. Fly Ash was mixed and recycled aggregates consists of 70% old concrete and 30% bricks. Mineral additions were replaced at 38% by weight of cement and added as fine aggregate replacement. The water cement ratio used were 0.56 for control mix, 0.35 for plain recycled aggregate concrete and 0.40 for concrete containing both recycled aggregate and mineral admixtures. The differences were very small in the tensile strength values. The failure pattern suggested that recycled aggregates were the weakest component of the concrete system.

Kou et al. (2011) compared the splitting tensile strength of recycled aggregate concrete prepared with different mineral admixtures including silica fume (10%), metakaolin (15%), fly ash (35%), ground granulated blast slag (55%) used as cement replacement. The recycled aggregates were replaced at 50% and 100%. The splitting tensile strength of natural and recycled aggregate concrete containing silica fume and metakaolin were better than traditional concrete. The use of fly ash and GGBS decreased the splitting tensile values, especially at the early ages due to their delayed binding action. The strength gains of the concrete mixtures with fly ash and GGBS were higher than that of mixtures containing silica fume and metakaolin.

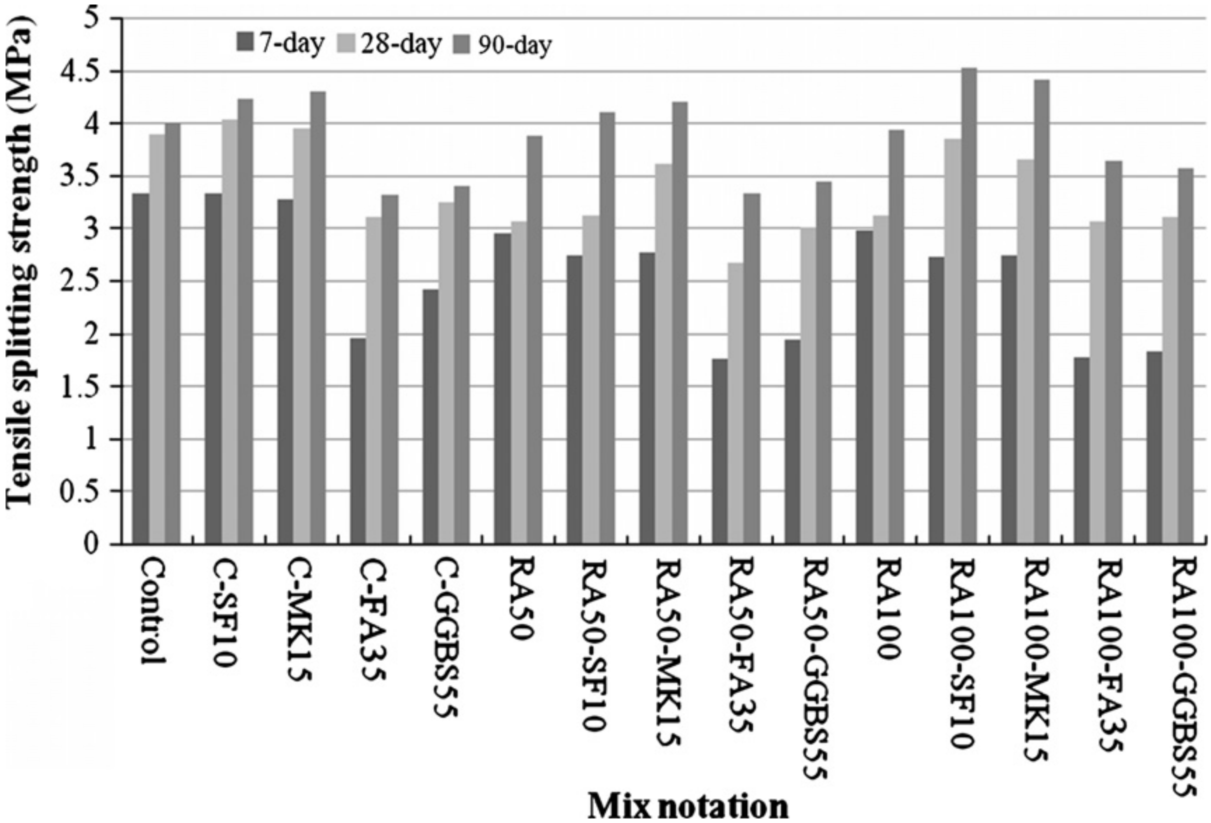

Fig 2.6: Tensile splitting strength of concrete mixtures (Kou *et al. 2011)*

Kou et al. (2012) used commercial recycled aggregates at 0%, 25%, 50% and 100% replacement levels of natural aggregate in concrete mixtures. The values of splitting tensile strength was lower than that of control mixture at 28 days. At 90 days the gain percentage of recycled aggregate concrete was higher than conventional concrete. This can be attributed to microstructure of the interfacial transition zone and increased bond strength between new cement paste and aggregates.

Butler et al. (2013) analysed three types of recycled aggregates. Different water cement ratios were used to obtain 100% recycled aggregate concrete. The splitting tensile values were higher for low compressive strength specimen and lower for higher compressive strength. For higher concrete compressive strength, the strength of coarse recycled aggregate influenced the splitting tensile strength of concrete.

Table 2.8: Splitting tensile results *(Butler et al. 2013)*

Mix	Splitting Tensile Strength (MPa)
NAC-40	3.18
RAC1-40	3.51
RAC2-40	3.11
RAC3-40	3.30
NAC-60	4.38
RAC1-60	3.84
RAC2-60	3.70
RAC3-60	3.72

Kou and Poon (2013) presented long term splitting tensile strength of recycled aggregate concrete prepared with incorporation of fly ash. The recycled aggregate concrete was prepared by using 25%, 35% and 55% fly ash whereas recycled aggregate used were substituted as 0%, 50% and 100%. Two types of curing conditions were imposed water and air curing. At 28 days the splitting tensile strength of control mixture was higher than the concrete incorporating recycled aggregates. However, comparison of the longer duration test results shows continuous and significant improvement in the splitting tensile strength of recycled aggregate concrete. The values of concrete mixtures prepared with 100% recycled aggregates were higher than traditional concrete. Moreover, the splitting tensile strength of concrete mixtures exposed to air curing was lower than the corresponding concrete mixtures with standard water curing. The data is presented in Table 2.12

Lima et al. (2013) presented the splitting tensile strength property of concrete made with recycled aggregate and fly ash. The percentage of recycled aggregates was 30, 60 and 100. Both coarse and fine recycled aggregates were used in concrete mixtures. To keep the water available for chemical reaction constant, extra amount of water was added in various mixes calculated from water absorption capacity of aggregates. The content of fly ash was kept as “Low”, “Medium” and “High”. The specimens containing 60% and 100% recycled aggregates showed strong reduction in tensile strength. Addition of medium level of fly ash at 30% recycled aggregates gave the best values in recycled aggregate concrete mix.

Radonjanin et al. (2013) replaced 50% cement with different mineral admixtures such as milled limestone, fly ash whereas fixed amount of 10% silica fume and metakaolin was used. The concrete mixtures consisted of 50% recycled aggregates. Seven concrete mixes were prepared. Chemical admixtures were added in some mixtures to achieve desired consistency. Different unconventional combinations such as 40% fly ash or milled limestone + 10% silica fume or metakaolin were also prepared. Concrete mixtures containing 10% silica fume and metakaolin exhibited higher values of split tensile when compared to conventional concrete. Use of fly ash and milled limestone even with silica fume and metakaolin exhibited low values of split tensile strength.

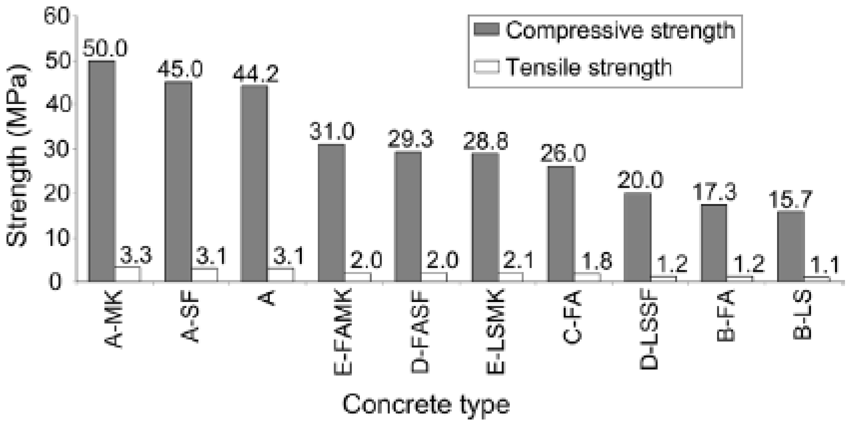

Fig 2.7: Splitting Tensile and compressive strength of different mixes *(Radonjanin et al. 2013)*

Surya et al. (2013) produced five different concrete mixes with and without class F Fly ash. Three mixes containing recycled aggregate at 50%, 75% and 100% replacement of natural aggregate were prepared containing fly ash, and two natural aggregate concrete mixes with and without fly ash. Recycled aggregates were generated by crushing waste dump of lab samples. Water-cement ratio was kept constant at 0.4. The splitting tensile strength exhibited by recycled aggregate concrete was better than traditional concrete. In case of recycled aggregate concrete the failure pattern was through transition zone and aggregates. The concrete containing 100% recycled aggregate exhibited maximum splitting tensile strength. The transition zone of recycled aggregate concrete improved due to addition of fly ash making its strength parallel or greater than control mixture. The splitting tensile values are shown in table 2.9.

Table 2.9: Splitting tensile strength of various mixes *(Surya et al. 2013)*

Mix Designation	Splitting tensile strength (MPa)	
	28 days	56 days
NAC	3.49	3.96
NAF	3.74	4.15
R50	3.49	3.53
R75	3.11	3.63
R100	3.68	4.15

Thomas et al. (2013) prepared total of 24 mixtures with different water-cement ratios, substitution of coarse aggregate with recycled aggregate was 20%, 50% and 100%. Clear tendency of lower tensile splitting strength of recycled aggregate concrete than conventional concrete was found. In case of 100% recycle aggregates loss was around 20%.

Andreu and Miren (2014) procured recycled aggregates from high strength concrete. Substitution of recycled aggregates was 20%, 50% and 100%. All concrete mixtures showed good performance except aggregates with 100% replacement of lower strength concrete. All other series achieved more than 4.5 MPa of tensile strength. The splitting tensile strength did not seemed to be very influenced by recycled aggregates.

Carneiro et al. (2014) used steel fibres to reinforce recycled concrete, both recycled fine and coarse aggregates were used in mixes. The replacement being 25% by volume for RFA and RCA and 50% of both. The steel fibres substituted in volume fraction of 0.75% were both end hooked having 35 mm and 0.55 mm of length and diameter respectively. The splitting tensile strength shows very little influence of type of recycle aggregate, on the other hand the addition of steel fibres shows significant effect on the splitting tensile strength of the mixtures. The splitting tensile strength of the recycled aggregate concrete increased by about 20-26%. Table 2.10 shows the splitting tensile strength values.

Table 2.10: Splitting tensile strength of mixes at 28 days *(Carneiro et al. 2014)*

MIX	Splitting tensile Strength (MPa)
	Plain Concrete
REF	3.21

RCA	3.17
RFA	3.28
RFCA	3.53
Steel Fibre Reinforced Concrete	
SF-REF	3.96
SF-RCA	3.87
SF-RFA	3.91
SF-RFCA	4.48

Dilbas et al. (2014) investigated recycled aggregate concrete with silica fume for compressive strength. Two types of recycled aggregates were used, composed of concrete, tiles and bricks. The replacement levels of aggregates was 30% and 40%, later both types were used simultaneously taking replacement of 70%. Silica fume replaced was 5% and 10% by weight of cement. The tensile strength of low grade recycled aggregates was slightly lower than control mixture. Besides, the mixture containing better coarse recycled aggregates with and without silica fume was were higher than traditional concrete. This shows that usage of silica fume has very marginal increasing effect on the splitting tensile strength. A severe decrease was noted when both quality of recycled aggregates were used simultaneously. Table 2.11 shows the splitting tensile strength reported.

Table 2.11: Splitting tensile strength at 28 days (Dilbas *et al. 2014)*

Notation	Silica fume (%)	Recycled Aggregates (%)	Splitting tensile strength (MPa)
1st Group			
NAC	0	0	2.25
RA1C	0	40	2.24
RA2C	0	30	2.41
RA12C	0	70	1.58
2nd Group			
NACSF5	5	0	2.62
RA1CSF5	5	40	2.52
RA2CSF5	5	30	2.97

RA12CSF5	5	70	1.92
3rd Group			
NACSF10	10	0	3.40
RA1CSF10	10	40	2.46
RA2CSF10	10	30	2.63
RA12CSF10	10	70	1.62

Mukharjee and Barai (2014) used Nano-silica on concrete containing 100% recycled aggregate. The doses of Nano-silica used were 0.75%, 1.5% and 3%. The split tensile values of recycled aggregate concrete without Nano-silica was 12% lower than that of control concrete. This may be attributed to weaker interfacial transition zone compared to natural aggregate concrete. The split tensile values increases with increase of Nano-silica percentage and recycled aggregate concrete with 3% Nano-silica is almost equal to that control concrete.

Table 2.12: Splitting tensile strength of concrete mixtures *(Kou and Poon 2013)*

Notation	Fly ash (%)	Recycled aggregates (%)	Splitting tensile strength (MPa)									
			28-day		1-year		3-year		5-year		10- year	
			Water cured	Air cured	Water cured	Air cured	Water cured	Air cured	Water cured	Air cured	Water cured	Air cured
R0	0	0	3.32	3.21	3.45	3.31	3.76	3.54	4.23	4.01	4.61	4.25
R50	0	50	3.16	3.09	3.51	3.41	3.92	3.62	4.41	4.14	4.71	4.32
R100	0	100	3.06	2.98	3.56	3.44	4.12	3.78	4.45	4.18	4.83	4.41
R0F25	25	0	3.28	3.14	3.65	3.42	3.89	3.58	4.25	3.92	4.69	4.27
R50F25	25	50	3.09	3.01	3.62	3.46	3.94	3.85	4.41	4.15	4.75	4.32
R100F25	25	100	2.96	2.91	3.75	3.54	4.12	3.91	4.40	4.21	4.81	4.49
R0F35	35	0	2.90	2.81	3.14	3.02	3.36	3.18	3.68	3.42	4.18	3.77
R50F35	35	50	2.78	2.72	3.24	3.11	3.38	3.21	3.72	3.53	4.24	3.88
R100F35	35	100	2.56	2.48	3.31	3.12	3.47	3.26	3.77	3.55	4.28	3.91
R0F55	55	0	2.66	2.58	2.89	2.73	3.04	2.91	3.22	3.01	3.72	3.30
R50F55	55	50	2.42	2.36	2.93	2.80	3.12	2.96	3.28	3.05	3.75	3.36
R100F55	55	100	2.23	2.19	3.01	2.89	3.24	3.11	3.41	3.14	3.81	3.48

2.3.2. Flexural strength

Surya et al. (2013) produced five different concrete mixes with and without class F Fly ash. Three mixes containing recycled aggregate at 50%, 75% and 100% replacement of natural aggregate were prepared containing fly ash, and two natural aggregate concrete mixes with and without fly ash. Recycled aggregates were generated by crushing waste dump of lab samples. Water-cement ratio was kept constant at 0.4. The flexural strength exhibited by recycled aggregate concrete was better than traditional concrete. The concrete containing 100% recycled aggregate exhibited maximum flexural strength. The transition zone of recycled aggregate concrete improved due to addition of fly ash making its strength parallel or greater than control mixture. Table 2.13 represents the flexural strength of various mixes.

Table 2.13: Flexural strength of various mixes *(Surya et al. 2013)*

Mix Designation	Flexural strength (MPa)
	56 days
NAC	5.35
NAF	5.46
R50	4.78
R75	4.77
R100	5.72

Andreu and Miren (2014) analysed the properties of high performance recycled aggregate concrete. The recycled aggregates were sourced from high strength concrete and were replaced as 20%, 50% and 100%. The recycled were produced from 40, 60 and 100 MPa concrete. All the recycled aggregates concrete exhibited similar strength as control mixture. Concrete comprising of maximum 50% of recycled aggregates improved by 10-20%. Even using medium strength concrete aggregates as total replacement the flexural strength achieved was similar to conventional concrete.

Carneiro et al. (2014) used steel fibres to reinforce recycled concrete, both recycled fine and coarse aggregates were used in mixes. The replacement being 25% by volume for RFA and RCA and 50% of both. The steel fibres substituted in volume fraction of 0.75% were both end hooked having 35 mm and 0.55 mm of length and diameter respectively. The flexural strength values indicate that type of recycled aggregate have very less influence. The values of mixtures containing coarse recycled aggregates are better than conventional mix. The addition of steel fibre, shows significant influence on the flexural strength of the mixtures. The steel fibre increased the flexural strength by 8-36%. Flexural strength are shown in Table 2.14.

Table 2.14: Flexural strength of mixes at 28 days *(Carneiro et al. 2014)*

MIX	Flexural Strength (MPa)
	Plain Concrete
REF	3.62
RCA	3..34
RFA	3.92
RFCA	4.09
	Steel Fibre Reinforced Concrete
SF-REF	3.92
SF-RCA	4.62
SF-RFA	4.21
SF-RFCA	5.57

Kanellopoulos et al. (2014) used recycled lime powder to study the mechanical property of recycled aggregate concrete. The recycled aggregates were substituted at 10%, 30%, 50% and 100% of natural aggregates. Cement was gradually replaced by 5%, 8%, 10% and 20% by volume. The flexural strength of beams containing recycled aggregates reduces due to weak interfacial transition zone between adhered mortar and new cement paste. The highest drop occurs when total replacement of natural aggregates is done by recycled aggregates.

Mukharjee and Barai (2014) used Nano-silica on concrete containing 100% recycled aggregate. The doses of Nano-silica used were 0.75%, 1.5% and 3%. The flexure strength increases with the increasing percentage of Nano silica irrespective of type of concrete. There is an improvement of 15% in flexural strength of conventional concrete. When recycled aggregates are used the flexural strength reduces though some improvement is achieved when higher doses of Nano silica are used.

2.4 Effect of RCA on Durability Properties of Concrete

2.4.1 Chloride ion test

Kou et al. (2011) compared the recycled aggregate concrete prepared with different mineral admixtures including silica fume (10%), metakaolin (15%), fly ash (35%), ground granulated blast slag (55%) used as cement replacement. The recycled aggregates were replaced at 50% and 100%. The total charge passed increased with use of recycled aggregates. However, the use of mineral admixtures improved the chloride ion penetration. The order of improvement is highest in GGBS and fly ash then metakaolin and silica fume. The values of total charges passed are showed in Fig 2.8.

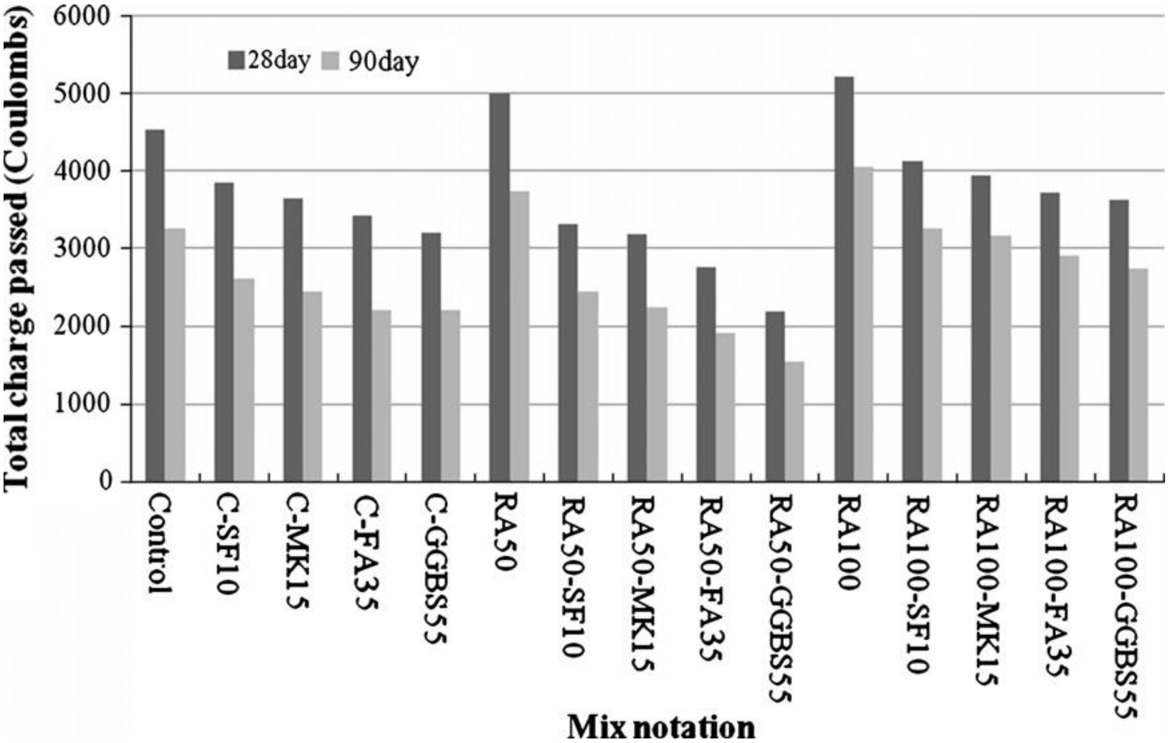

Fig 2.8: Total charge passed in coulombs of concrete mixtures *(Kou et al 2011)*

Kou et al. (2012) used commercial recycled aggregates at 0%, 25%, 50% and 100% replacement levels of natural aggregate in concrete mixtures. The resistance to chloride ion penetration was significantly reduced when recycled aggregates were incorporated in concrete. Though concrete containing better quality of recycled aggregates exhibited better resistance to chloride ion penetration.

Kou and Poon (2013) presented long term resistance to chloride ion penetration of recycled aggregate concrete prepared with incorporation of fly ash. The recycled aggregate concrete was prepared by using 25%, 35% and 55% fly ash whereas recycled aggregate used were substituted as 0%, 50% and 100%. Two types of curing conditions were imposed water and air curing. Recycled aggregates decreased the resistance to chloride ion penetration of concrete. The addition of fly ash increased the resistance to chloride ion penetration of both natural and recycled aggregate. This is due to reduction in average pore size of the paste and the improvement of interfacial transition zone. After 10 years further reductions in amount of charge passed was observed. Fig 2.9 represents the total charge passed.

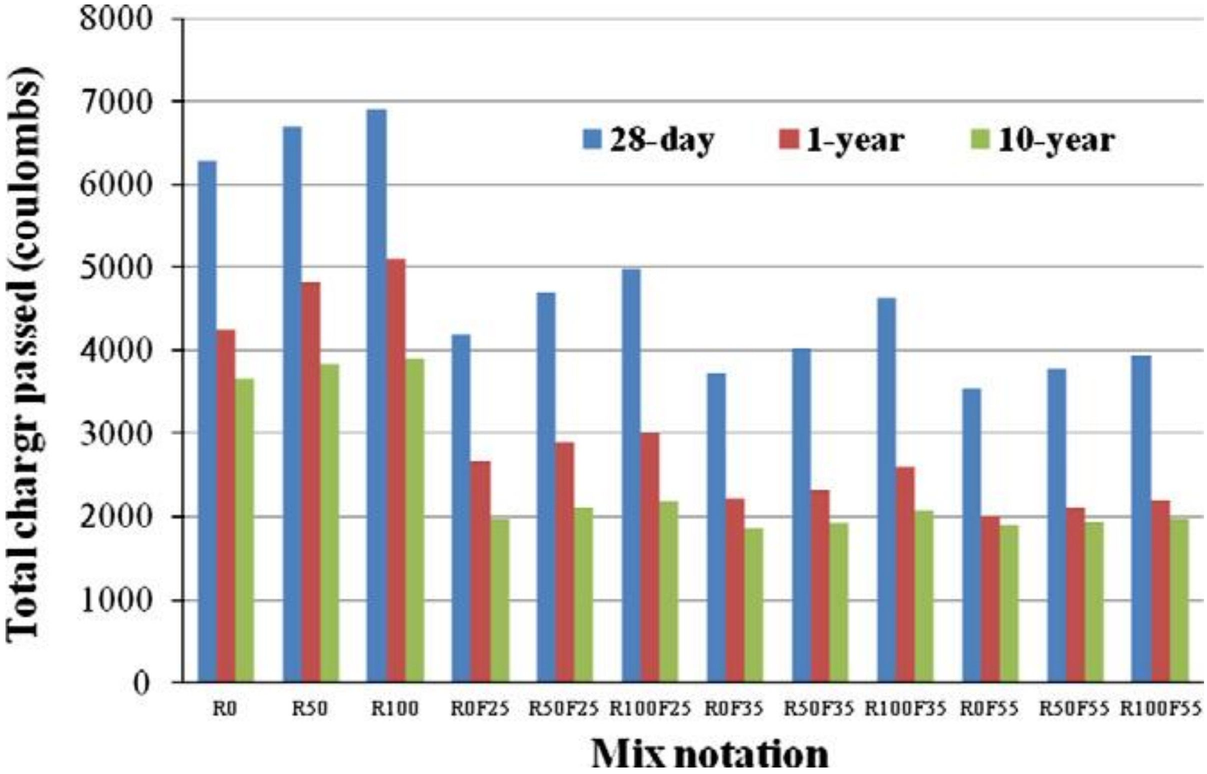

Fig 2.9: Total charge passed in coulombs *(Kou and Poon 2013)*

Lima et al. (2013) presented the chloride resistant property of concrete made with recycled aggregate and fly ash. The percentage of recycled aggregates was 30, 60 and 100. Both coarse and fine recycled aggregates were used in concrete mixtures. To keep the water available for chemical reaction constant, extra amount of water was added in various mixes calculated from water absorption capacity of aggregates. The content of fly ash was kept as “Low”, “Medium” and “High”. The use of recycled aggregates worsens the resistance to chloride ion penetration, higher the percentage of recycled aggregates lower is the resistance to chloride ion penetration. Adding fly ash considerably improves the anti-chloride performance of concrete.

Andreu and Miren (2014) analysed the properties of high performance recycled aggregate concrete. The recycled aggregates were sourced from high strength concrete and were replaced as 20%, 50% and 100%. The recycled were produced from 40, 60 and 100 MPa concrete. The resistance to chloride ion penetration decreased as the content of recycled aggregates increased in concrete. Low replacement level such as 20 and 50% obtained results of very low whereas total replacement level achieved values of moderate level corrosion.

Kanellopoulos et al. (2014) used recycled lime powder to study the mechanical property of recycled aggregate concrete. The recycled aggregates were substituted at 10%, 30%, 50% and 100% of natural aggregates. Cement was gradually replaced by 5%, 8%, 10% and 20% by volume. The poor quality of natural and recycled aggregates caused decreased chloride ion penetration.

2.5 Need of the Present Investigation

A review of literature presented shows that recycled aggregates are being investigated for proper use in concrete. The total use of recycled aggregates in concrete with positive results has been done in very few studies. Moreover the use of mineral admixtures and supplementary materials have not been examined completely on all properties of concrete.

2.6 Closing Remarks

A review of recent literature on behaviour of natural coarse aggregate and recycled coarse aggregate concrete has been presented on the basis of which the need of the present investigation has been identified.

CHAPTER 3

EXPERIMENTAL WORK

3.1 General

The details of experiment programme in terms of material properties, test set-up for measuring different parameters and the testing procedure discussed in this chapter.

3.2 Material Properties

Cement, fine aggregates, coarse aggregates, recycled coarse aggregate, silica fume, steel fibre super-plasticizer and water is used for present investigation. The properties of these materials are discussed in the following sections.

3.2.1 Cement

Cement is a fine, grey powder. It is mixed with water and materials such as sand, gravel, and crushed stone to make concrete. The ordinary cement contains two basic ingredients namely argillaceous and calcareous. In argillaceous materials, clay predominates and in calcareous materials calcium carbonate predominates. Ordinary Portland cement of grade – 43 (J.K cement) conforming to Indian standard IS: 8112-1989 has been used in the present study. The results of the various tests on cement properties are given in Table 3.1.

Table 3.1 Physical properties of ordinary Portland cement

Sr. No.	Characteristics	Values obtained	Values as per IS 8112:1989
1.	Consistency	28.2%	-
2.	Initial setting time	127 minutes	Not less than 30 minutes
3.	Final setting time	183 minutes	Not greater than 600 minutes
4.	Fineness	281.3 m^2/kg	Not less than 225 m^2/kg
5.	Specific gravity	3.01	-
6.	Compressive strength (MPa) 3 days 7 days 28 days	 33.4 42.5 49.9	 23 33 43

3.2.2 Fine aggregates

The material which passes through 4.75 mm sieve is termed as fine aggregate. Usually natural sand is used as a fine aggregate at places where natural sand is not available crushed stone is used as a fine aggregate. The sand used for the experimental works is locally procured and conformed to grading zone III. The sieve analysis of fine aggregates is shown in Table 3.2. The physical properties are provided in Table 3.3

Table 3.2: Sieve analysis of fine aggregates

Sr. No.	Sieve No.	Weight retained (Grams)	Percentage retained (%)	Percentage Passing (%)	Cumulative percentage retained (%)
1.	4.75 mm	5	0.50	99.50	0.50
2.	2.36 mm	59	5.90	93.60	6.40
3.	1.18 mm	136	13.60	80.00	20.00
4.	600 mm	243	24.30	55.70	44.30
5.	300 mm	415	41.50	14.20	85.80
6.	150 mm	122	12.20	2.00	98.00
7.	Pan	20	2.00	-	-
					ΣF = 255

Table 3.3: Physical properties of fine aggregates

Sr. No.	Characteristics	Value
1.	Type	Natural sand
2.	Specific Gravity	2.58
3.	Fineness Modulus	2.55
4.	Grading Zone	Type III

3.2.3 Natural coarse aggregate

The broken stone is generally used as a coarse aggregate. The nature of work decides the maximum size of the coarse aggregate. Locally available coarse aggregate having the maximum size of 20 mm was used in the present work. The properties of natural aggregate are presented in Table 3.4 and 3.6.

Table 3.4: Sieve analysis of natural coarse aggregates

Sr. No.	Sieve size	Weight retained (kg)	% retained	% passing For NCA	Cumulative % weight retained
1.	20 mm	0	0	100	0
2.	12.5 mm	2.1865	72.883	27.117	72.833
3.	10 mm	0.6745	22.483	4.634	95.366
4.	4.75 mm	0.1390	4.633	0.01	99.99

3.2.4 Recycled coarse aggregate

Tested concrete specimens e.g. cubes, cylinders and beams lying in the dump yard of concrete laboratory at Thapar University has been used as a source of RCA. To make RCA, the specimens without reinforcement were manually broken down into small pieces and then crushed using jaw crusher as shown in Fig. 3.1 and 3.2. The larger fraction, passing through 20 mm sieve but retained on 12.5 mm sieve was designated RCA20 – 12.5 mm. The fraction passing through 12.75 mm sieve was discarded. The properties of natural aggregate are presented in Table 3.5 and 3.6.

Plate 3.1: Waste concrete rubble for obtaining RCA

Plate 3.2: Jaw crusher to obtain RCA

Table 3.5: Sieve analysis of recycled coarse aggregates

Sr. No.	Sieve size	Weight retained (kg)	% retained For RCA	%passing For RCA	Cumulative % weight retained
1.	20 mm	0	0	100	0
2.	12.5 mm	2.355	78.5	21.5	78.5
3.	10 mm	0.615	20.5	1	99
4.	4.75 mm	0.03	1	0	100

Table 3.6: Physical properties of the recycled and natural course aggregate

Sr. No.	Properties	Natural aggregates	Recycled aggregates
1.	Specific gravity	2.31	2.67
2.	Water absorption (%)	1.8	3.4
3.	Fineness modulus (%)	7.6	7.8

3.2.5 Silica fume

Silica fume, also known as micro silica 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 was provided by Corniche India Pvt Ltd.

3.2.6 Steel fibre

Fibres made from mild steel drawn wire conforming to IS: 280-1976 with the diameter of wire varying from 0.3 to 0.5 mm have been practically used in India. The efficiency of Fibre distribution depends on the geometry of the fibre, the fibre content, the mixing and compaction technique, the size and shape of the aggregates inclusion and the mix proportions. Both end hooked steel fibres (30mm long, 0.6mm dia) supplied by Stewols India Pvt Ltd.; Nagpur was employed at a constant volume fraction of 1.5%.

3.2.7 Water

Water is an important ingredient of concrete as it actively participates in the chemical reaction with cement. Since it helps to form the strength giving cement gel, the quantity and quality of water is required to be looked into very carefully. Potable water is generally considered satisfactory. In the present investigation, tap water is used for both mixing and curing purposes.

3.2.8 Superplasticizer

Conplast SP430, the superplasticizer supplied by Fosroc India Pvt. Limited has been used in the investigations. It is a highly effective superplasticizer for concrete and mortar. It meets the requirements for superplasticizer according to BS 5075 Part 3, ASTM C-494Type A and Type F and IS: 9103-1999 (amended 2003). The technical data related to the superplasticizer used is provided in Table 3.8. This data is supplied by the manufacturers.

Table 3.7: Technical data of superplasticizer

Sr. No.	Characteristics	Value
1.	Colour	Brown
2.	Specific gravity	1.20
3.	Air entrainment	Minimum 1%
4.	pH	7 to 8

3.3 Mix Combinations

A total of twelve mix combinations were prepared in the laboratory. To compensate for additional water requirement of RA the aggregates were pre-soaked for 24 hrs and were sun dried before use. The slump test for workability of the mix was done by cone method and a desired slump of 80-90 mm was achieved. To achieve the required workability of concrete mix, water reducing admixture i.e. superplasticizer, namely conplast SP430 is added to the matrix at a desired dosage rate. Concrete mixture proportion and superplasticizer dosage rate is presented in Table 3.9. The mix proportion of corresponding mixes is prepared by replacing natural aggregate by recycled coarse aggregate. In this, mixture proportions for the natural coarse aggregate and the recycled coarse aggregate concretes were kept the same, except for replacement of NCA with recycled coarse aggregate, depending upon the desired recycled coarse aggregate replacement percentage. The recycled coarse aggregate replacement percentage is defined as the weight ratio of recycled coarse aggregate to the total coarse aggregates in the concrete mixture and depending upon the selected replacement percentage, direct substitution of NCA with an equal weight of recycled coarse aggregate particles is carried out. The following weight combinations of NCA and recycled coarse aggregate adopted are: 100 % NCA (control mixture), 50 % NCA + 50 % recycled coarse aggregate, 100 % RCA. Silica fume is added as cement replacement (10%). Both end hooked steel fibre are added as 1.5% of volume fractions. The fractions were selected as per previous reports and research work which specified the optimum replacement level. The concrete mixture proportions and the corresponding mix designations are presented in Table 3.10. The notations for mix combinations are as CC (control concrete), NASF10 (100% natural aggregate + 10% silica fume), NASTF1.5 (100% natural aggregate + 1.5% steel fibres), NASA10 + STF1.5 (100% natural aggregate + 10% silica fume + 1.5% steel fibres), RA50 (50% recycled aggregates), RA100 (100% recycled aggregates), RA50SF10 (50% recycled aggregates + 10% silica fume), RA100SF10 (100% recycled aggregates + 10% silica fume), RA50STF1.5 (50% recycled aggregates + 1.5% steel fibres), RA100STF1.5 (100% recycled aggregates + 1.5% steel fibres), RA50SF10+STF1.5 (50% recycled aggregates + 10% silica fume + 1.5% steel fibres) and RA100SF10+STF1.5 (50% recycled aggregates + 10% silica fume + 1.5% steel fibres).

Table 3.8: Mix proportion of control sample

w/c ratio	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Natural coarse aggregate (kg/m^3)	Water (kg/m^3)	Superplasticizer (% by weight of cement)
0.42	491.8	762.3	939.3	206.5	0.1%

Table 3.9: Mix proportions for different samples

Designation	Replacement (%)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Recycled coarse aggregate (kg/m^3)	Silica fume (kg/m^3)	Steel fibre (kg/m^3)	Water (kg/m^3)
CC	-	491.8	762.3	939.3	-	-	-	206.5
NASF10	-	442.62	762.3	939.3	-	49.18	-	206.5
NASTF1.5	-	491.8	762.3	939.3	-	-	36	206.5
NASF10+STF1.5	-	442.62	762.3	939.3	-	49.18	36	206.5
RA50	50	491.8	762.3	469.65	469.65	-	-	206.5
RA100	100	491.8	762.3	-	939.3	-	-	206.5
RA50SF10	50	442.62	762.3	469.65	469.65	49.18	-	206.5
RA100SF10	100	442.62	762.3	-	939.3	49.18	-	206.5
RA50STF1.5	50	491.8	762.3	469.65	469.65	-	36	206.5
RA100STF1.5	100	491.8	762.3	-	939.3	-	36	206.5
RA50SF10+STF1.5	50	442.62	762.3	469.65	469.65	49.18	36	206.5
RA100SF10+STF1.5	100	442.62	762.3	-	939.3	49.18	36	206.5

3.4. Casting of Specimens

In this section casting procedure for compressive strength test, splitting tensile strength and flexural strength test are discussed.

3.4.1 Casting for compressive strength test

Three cube specimens of size 150×150×150mm were casted for static compressive strength. The quantities of cement, coarse aggregate, fine aggregate, silica fume, steel fibre and water for each batch replacement was weighed separately. The cement, silica fume and steel fibre 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 in mixer. 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. Three cubes are casted for each parameter. The compressive strength test is carried out for 7 days and 28 days.

3.4.2 Casting for splitting tensile strength test

Four cylindrical specimens of 150Ømm diameter and 300mm height were casted for splitting tensile strength. The quantities of cement, coarse aggregate, fine aggregate, silica fume, steel fibre and water for each batch replacement was weighed separately. The cement, silica fume and steel fibre 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 in mixer. The moulds were filled with fresh concrete and were vibrated properly. After casting the cylinders were covered to prevent evaporation of water. Four cylinders were casted for each mix. The test were carried out on 7 day and 28 day.

3.4.3 Casting for flexural strength test

Four beams of size 700×150×150mm were casted for flexural strength. The quantities of cement, coarse aggregate, fine aggregate, silica fume, steel fibre and water for each batch replacement was weighed separately. The cement, silica fume and steel fibre 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 in mixer. The moulds were filled with fresh concrete and were vibrated properly. After casting the cylinders were covered to prevent evaporation of water. Four beams were casted for each mix. The test were carried out on 28 day.

3.4.4 Casting for 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, steel fibre and water for each batch replacement was weighed separately. The cement, silica fume and steel fibre 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 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 were carried out on 28 day.

3.5 Testing of Specimens

In this section test setup for the tests (compressive strength test, splitting tensile strength test, flexural strength test and rapid chloride permeability test) are discussed.

3.5.1 Setup for static compressive strength test

Three specimens are crushed at 7 and 28 days. 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. The compressive strength test machine which used in all tests is shown in Figure 3.3. 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

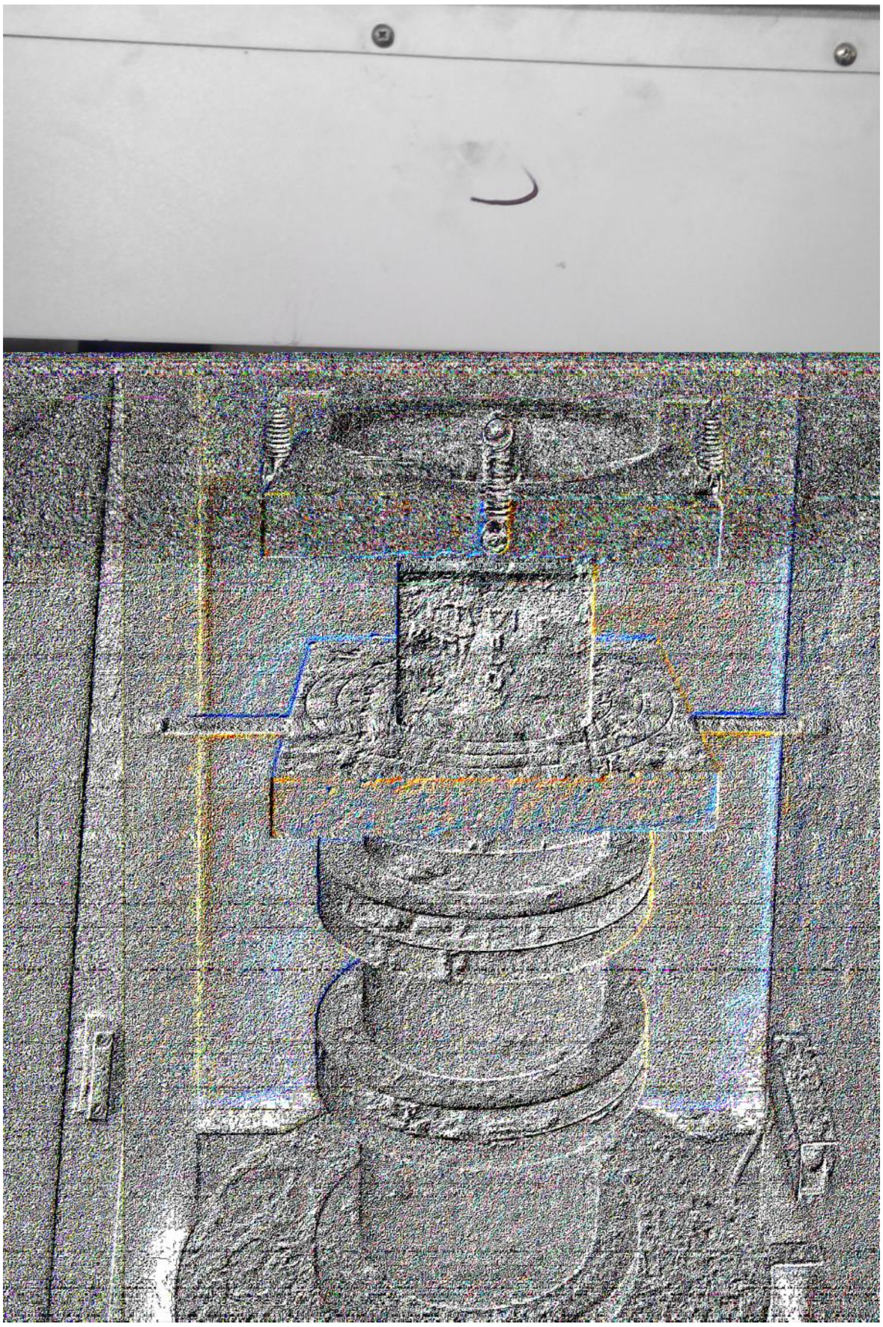

Plate 3.3: Testing for compressive strength

3.5.2 Setup for splitting tensile strength test

The cylinders were tested by placing them uniformly in the compression testing machine of capacity 5000 kN. Specimen were taken out from curing tank at the age of 7 and 28 days of standard curing and tested after surface water dipped down from specimens. This test was performed on Compression Testing Machine (CTM) as shown in figure 3.4. 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

$$f_{ct} = \frac{2P}{\Pi l d}$$

Where,

f_{ct} = Split tensile strength in N/mm^2

P = maximum applied load to specimen in Newton

l= length of the specimen (in mm)

d = cross sectional dimension of the specimen (in mm)

Plate 3.4: Testing for splitting tensile strength

3.5.3 Setup for flexural strength test

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 3.5. 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

$$f_b = \frac{p \times l}{b \times d^2}$$

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

Plate 3.5: Testing for flexural strength

3.5.4 Setup for Rapid chloride permeability test

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 3.11 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 3.6 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.

Table 3.10: Chloride Ion Penetrability Based on Charge Passed (ASTM 1202-97)

Charge Passed (Coulombs)	Chloride ion permeability
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very low
<100	Negligible

Plate 3.6: Vacuum desiccator's bowl

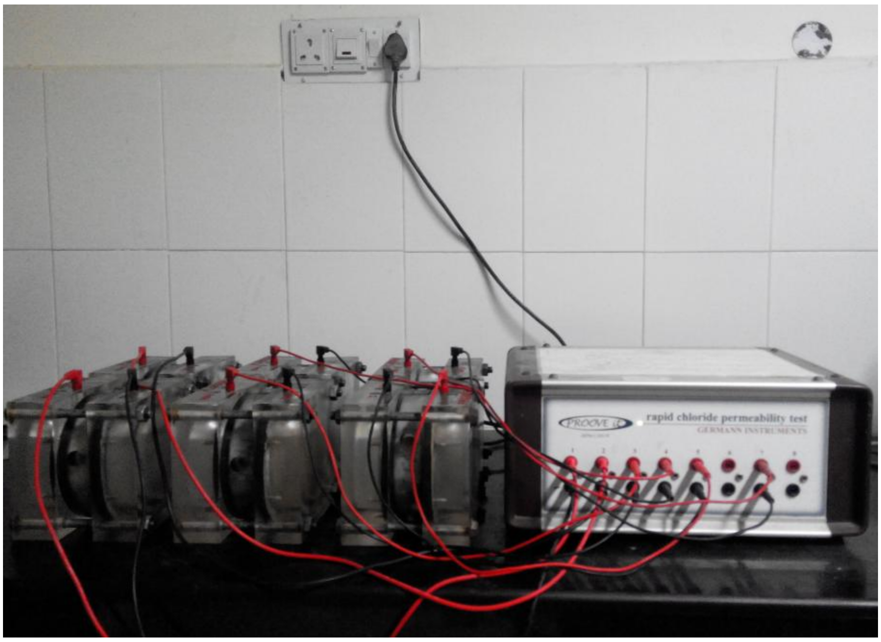

Plate 3.7: Rapid chloride permeability test

3.6 Closing Remarks

The experimental programme described in this chapter includes the significant material properties and specifications of the ingredients of concrete and the testing procedure. The specimen details and the test set-up have been discussed.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 General

In this chapter, results of compressive strength, split tensile strength, flexural strength and chloride penetration resistance of various concrete mixes incorporating 0%, 50% and 100% recycled aggregates, 10% of silica fume and steel fibre at 1.5% volume fraction are discussed. All the tests conducted were in accordance with the methods described in Chapter 3.

4.2. Compressive Strength Test

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 4.1 shows the average compressive strength of different mix combinations tested at 7 and 28 days. The data is further represented in the form of bar graphs in Figure 4.1 - 4.9.

Table 4.1: Compressive strength of specimen at 7 and 28 days

Mix Type	**Average static compressive strength (MPa)**	
	7 days	**28 days**
CC	29.4	44.2
NASF10	33.8	50.2
NASTF1.5	33.2	53.3
NASF10+STF1.5	35.4	56.0
RA50	23.8	38.3
RA100	22.3	36.7
RA50SF10	26.1	43.7
RA100SF10	24.0	40.6
RA50STF1.5	30.0	46.3
RA100STF1.5	29.3	44.8
RA50SF10+STF1.5	31.3	50.1
RA100SF10+STF1.5	29.8	48.7

- The compressive strength decreases when recycled aggregate are used without any mineral admixture or other supplementary materials. After replacing 50% of aggregates there is decrease of 19% at 7 days and 13.3% at 28 days, whereas, replacing 100% aggregates caused greater strength loss of 24.14% at 7 days and 16.9% at 28 days.
- Use of silica fume contributed to recover some strength losses of recycled aggregate concrete. 10% silica fume was used to replace cement. At 0% replacement of recycled aggregate the amount of increase in compressive strength is 15.5% at 7 days and 13.8% at 28 days. By adding 50% recycled aggregate a decrease of 11.2% at 7 days and 1.13% at 28 days is observed. Concrete having 100% recycled showed a decrease of 18.36% at 7 days and 8.14% at 28 days.
- Use of steel fibre enhanced the compressive strength of recycled aggregate concrete. 1.5% of steel fibre as volume fraction was used. At 0% substitution of aggregates an increase of 14.96% at 7 days and 20.58% at 28 days. After replacing 50% recycled aggregates an increase of 2.0% at 7 days and 4.75% at 28 days, whereas, replacing 100% aggregates an increase of 0% at 7 days and 1.35% at 28 days is observed.
- Use of steel fibre and silica fume enhanced the compressive strength of recycled aggregate concrete. 1.5% of steel fibre as volume fraction was used. 10% silica fume was used to replace cement. At 0% substitution of aggregates an increase of 20% at 7 days and 26.6% at 28 days. After replacing 50% recycled aggregates an increase of 6.4% at 7 days and 13.33% at 28 days, whereas, replacing 100% aggregates an increase of 1.36% at 7 days and 10.18% at 28 days is observed.

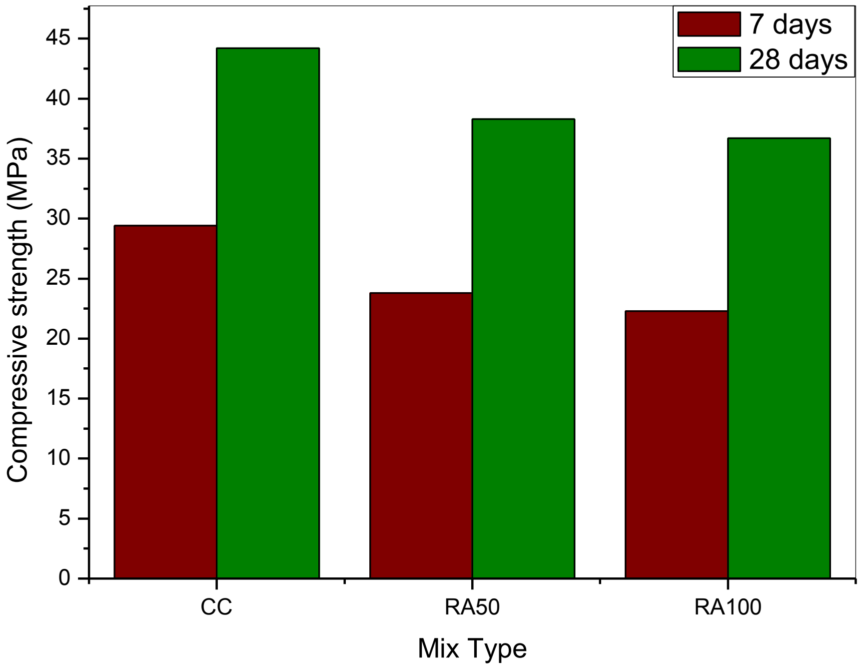

Fig 4.1: Compressive strength value of control mixture and recycled aggregate concrete

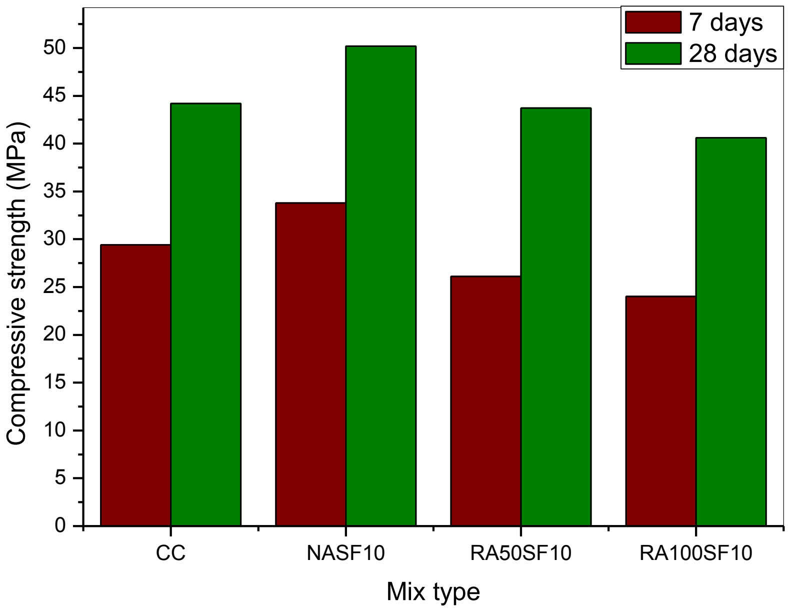

Fig 4.2: Compressive strength value of control mixture and recycled aggregate concrete containing silica fume

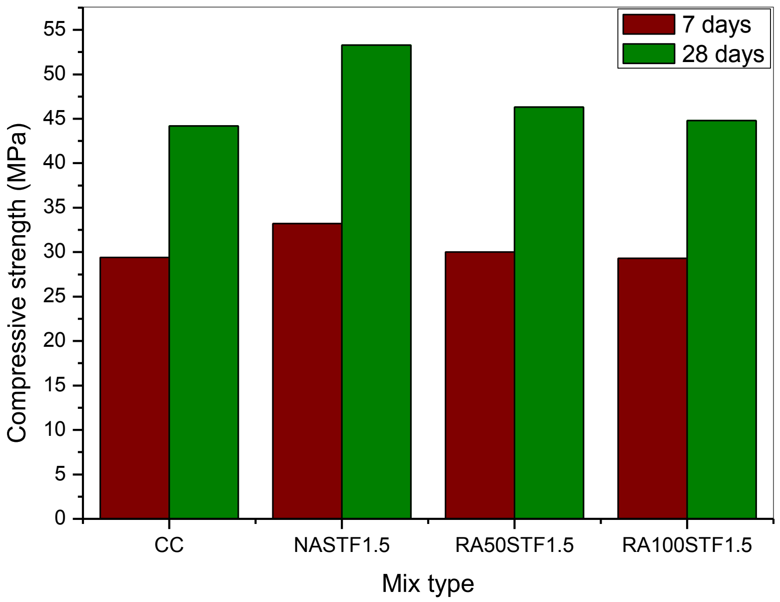

Fig 4.3: Compressive strength value of control mixture and recycled aggregate concrete containing steel fibre

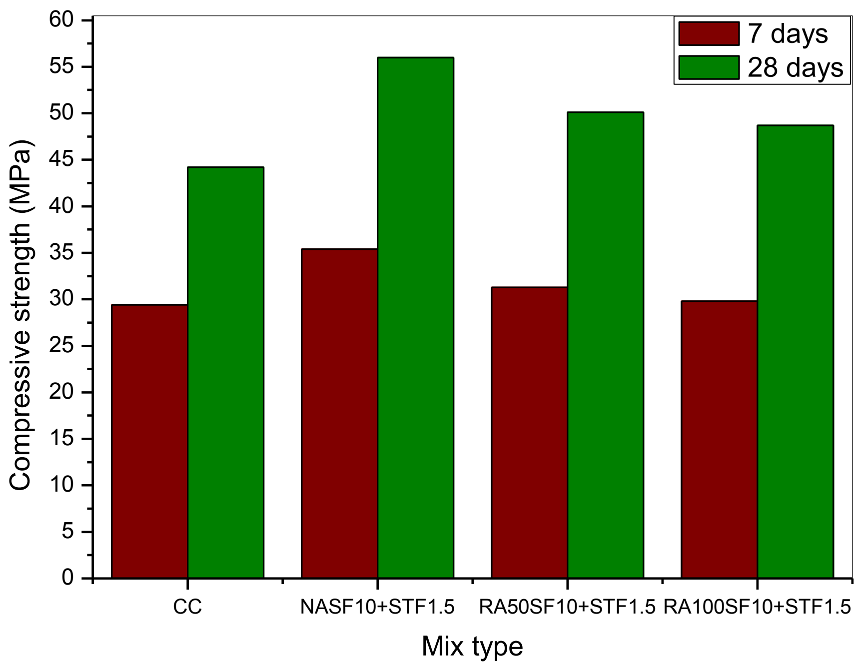

Fig 4.4: Compressive strength value of control mixture and recycled aggregate concrete containing silica fume and steel fibre

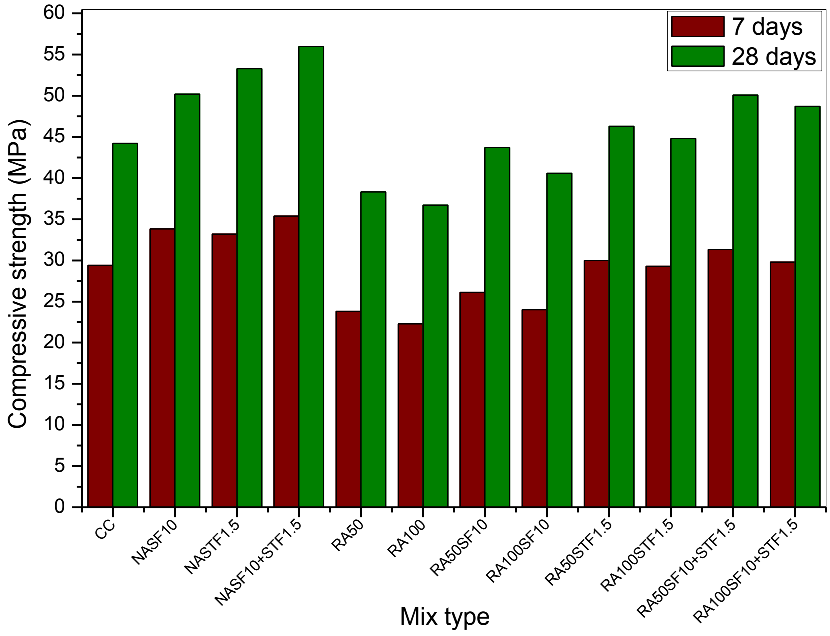

Fig 4.5: Compressive strength value of control mixture and recycled aggregate concrete with and without silica fume and steel fibre

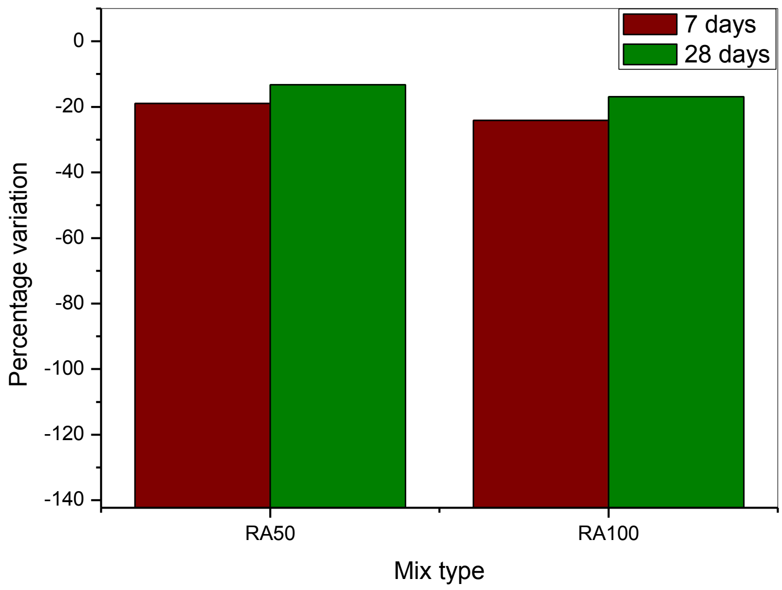

Fig 4.6: Percentage variation of compressive strength of recycled aggregate concrete with respect to control mixture

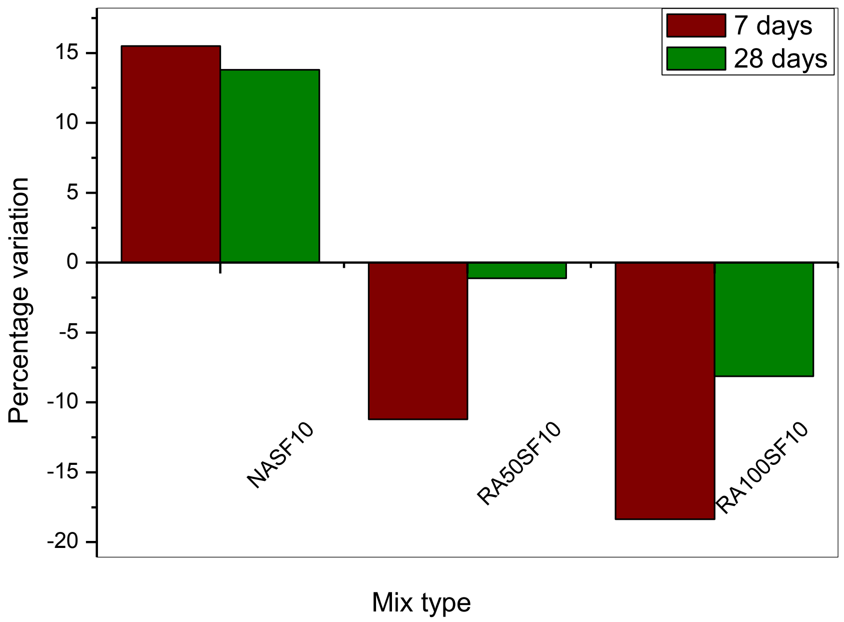

Fig 4.7: Percentage variation of compressive strength of recycled aggregate concrete containing silica fume with respect to control mixture

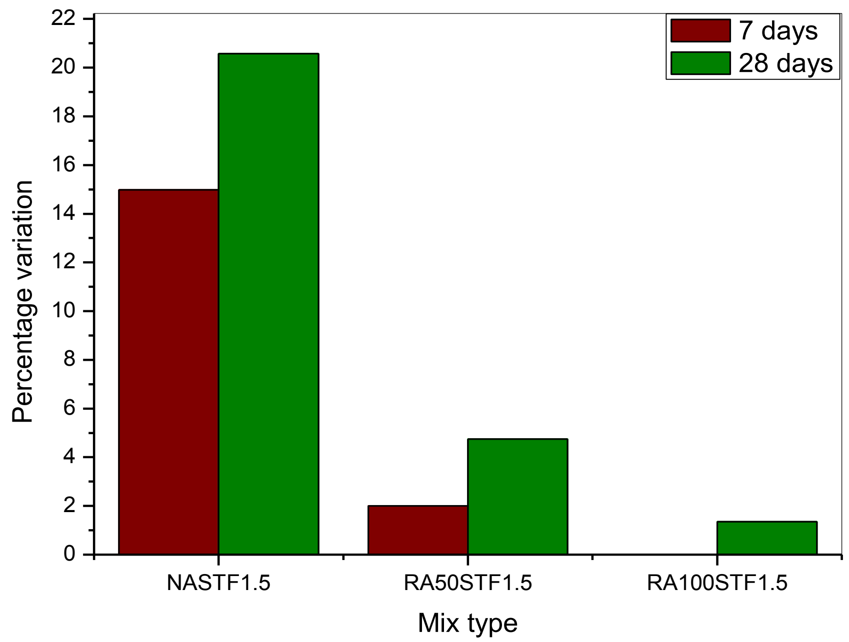

Fig 4.8: Percentage variation of compressive strength of recycled aggregate concrete containing steel fibre with respect to control mixture

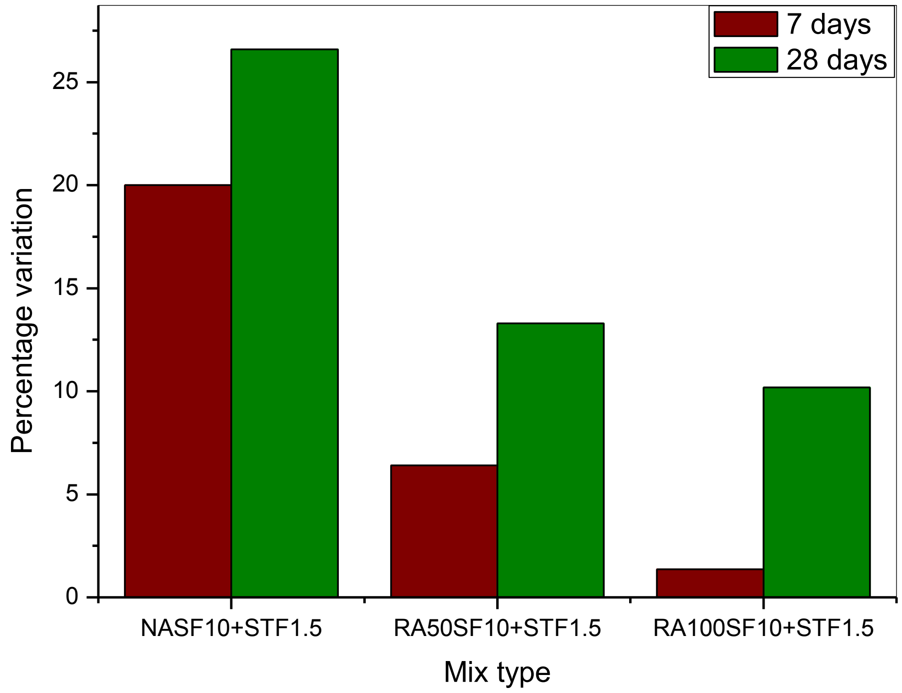

Fig 4.9: Percentage variation of compressive strength of recycled aggregate concrete containing silica fume and steel fibre with respect to control mixture

4.3 Split Tensile Strength Test

Split tensile strength studies were carried out at the age of 7 and 28 days. Test results are given below in Table 4.2. The data is further represented in the form of bar graphs in Figure 4.9 - 4.18.

Table 4.2: Splitting tensile strength of concrete mixes at 7 and 28 days

Mix Type	Average splitting tensile strength (MPa)	
	7 days	**28 days**
CC	2.59	3.02
NASF10	2.99	3.77
NASTF1.5	4.50	5.90
NASF10+STF1.5	4.83	6.11
RA50	2.33	2.89
RA100	2.28	2.76
RA50SF10	2.92	3.63
RA100SF10	2.85	3.53
RA50STF1.5	4.34	5.55
RA100STF1.5	3.89	5.04
RA50SF10+STF1.5	4.50	5.74
RA100SF10+STF1.5	4.37	5.28

- The splitting tensile strength decreases when recycled aggregate are used without any mineral admixture or other supplementary materials. After replacing 50% of aggregates there is decrease of 10% at 7 days and 4.3% at 28 days, whereas, replacing 100% aggregates caused greater strength loss of 11.9% at 7 days and 8.6% at 28 days.
- Use of silica fume contributed in enhancing the splitting tensile strength of recycled aggregate concrete. 10% silica fume was used to replace cement. At 0% replacement of recycled aggregate the amount of increase in strength is 15.4% at 7 days and 24.8% at 28 days. By adding 50% recycled aggregate an increase of 12.7% at 7 days and 20.19% at 28 days is observed. Concrete having 100% recycled showed an increase of 10% at 7 days and 16.8% at 28 days.

- Use of steel fibre enhanced the splitting tensile strength of recycled aggregate concrete. 1.5% of steel fibre as volume fraction was used. At 0% substitution of aggregates increase of 73.7% at 7 days and 95.3% at 28 days is observed. After replacing 50% recycled aggregates an increase of 67.5% at 7 days and 83.7% at 28 days, whereas, replacing 100% aggregates an increase of 50.1% at 7 days and 66.8% at 28 days is observed.
- Use of steel fibre and silica fume enhanced the splitting tensile strength of recycled aggregate concrete. 1.5% of steel fibre as volume fraction was used. 10% silica fume was used to replace cement. At 0% substitution of aggregates increase of 86.4% at 7 days and 102.3% at 28 days is observed. After replacing 50% recycled aggregates an increase of 73.7% at 7 days and 90% at 28 days, whereas, replacing 100% aggregates an increase of 68.7% at 7 days and 74.8% at 28 days is observed.

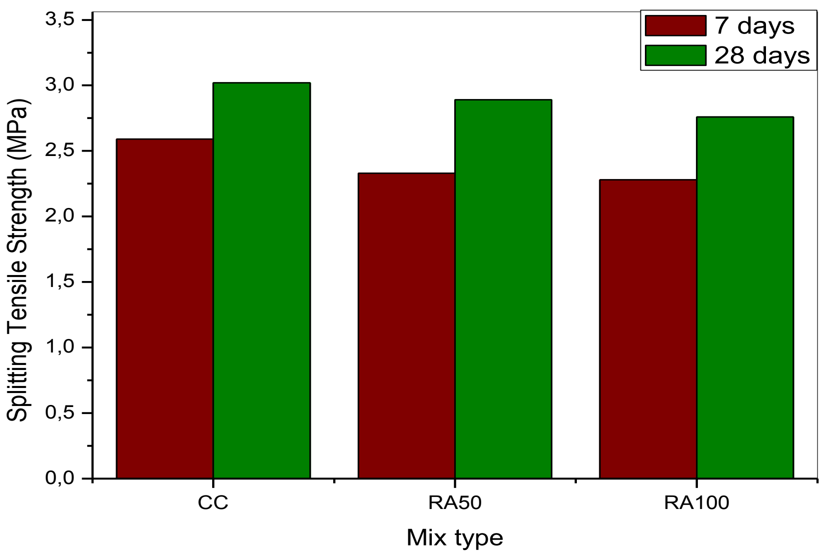

Fig 4.10: Splitting tensile strength value of control mixture and recycled aggregate concrete

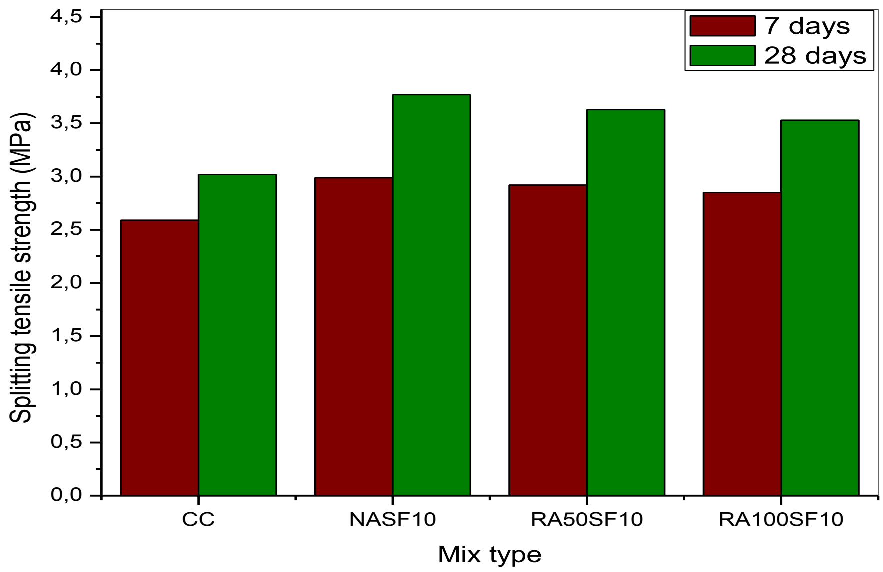

Fig 4.11: Splitting tensile strength value of control mixture and recycled aggregate concrete containing silica fume

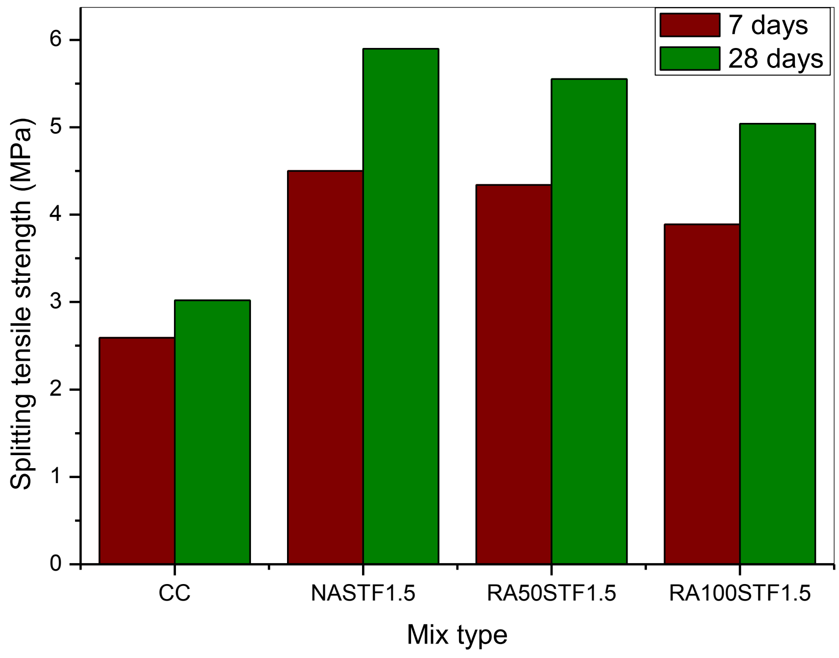

Fig 4.12: Splitting tensile strength value of control mixture and recycled aggregate concrete containing steel fibre

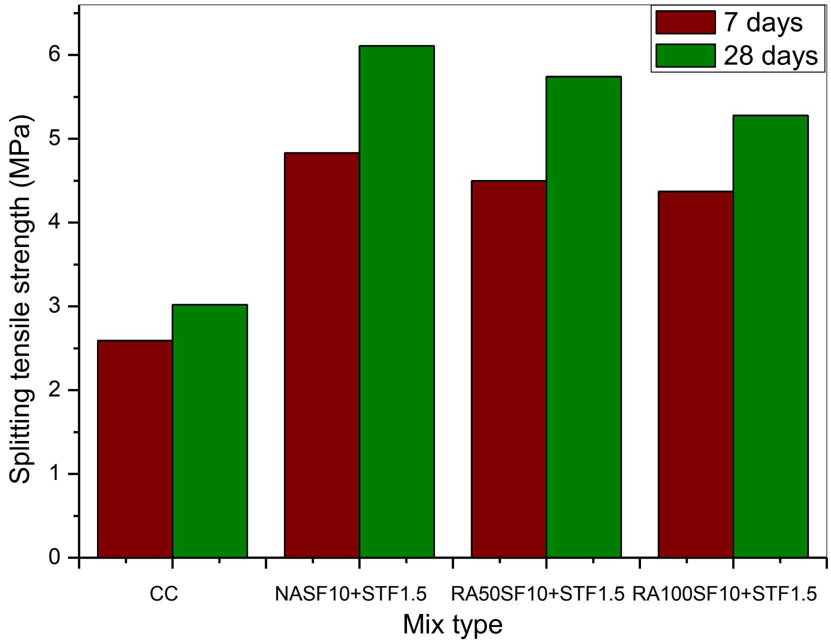

Fig 4.13: Splitting tensile strength value of control mixture and recycled aggregate concrete containing silica fume and steel fibre

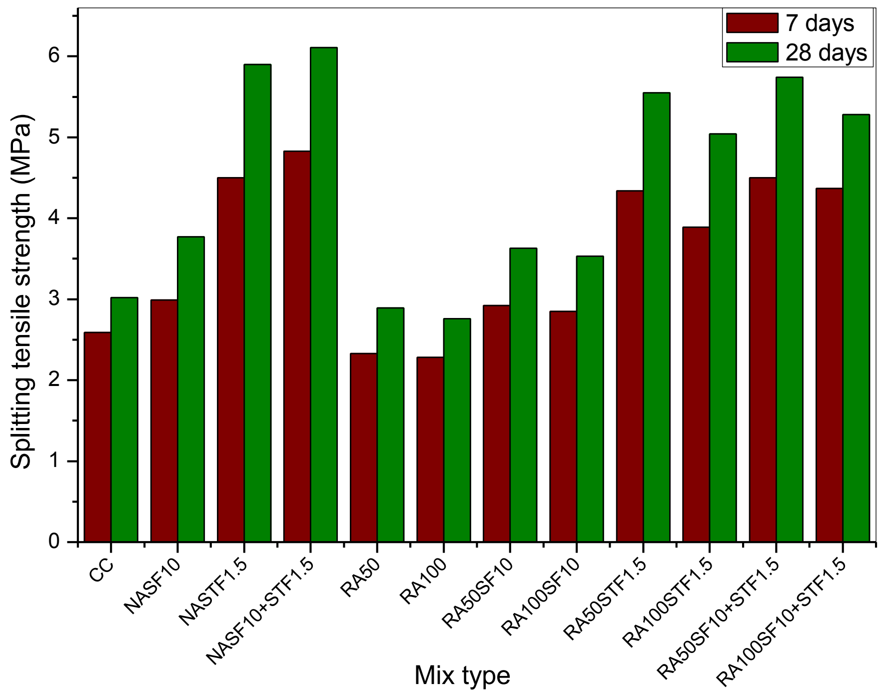

Fig 4.14: Splitting tensile strength value of control mixture and recycled aggregate concrete with and without silica fume and steel fibre

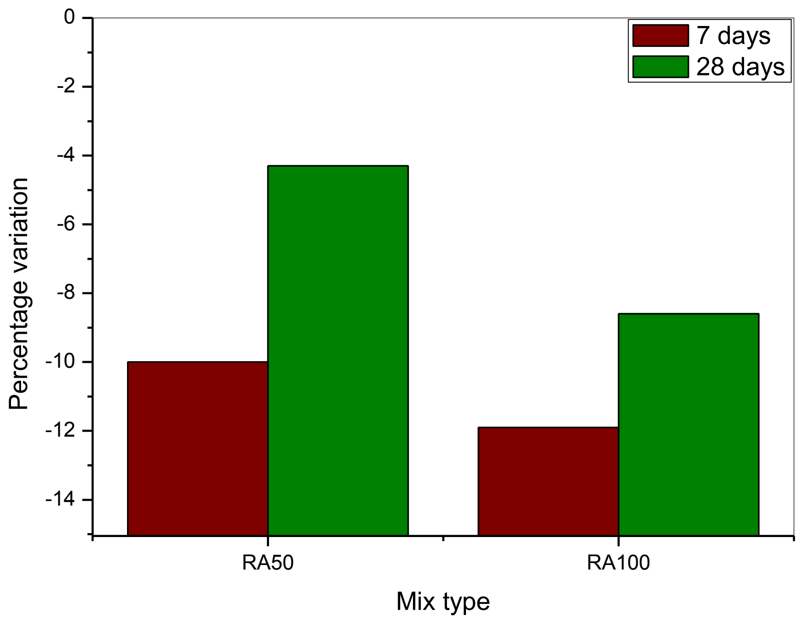

Fig 4.15: Percentage variation of splitting tensile strength of recycled aggregate concrete with respect to control mixture

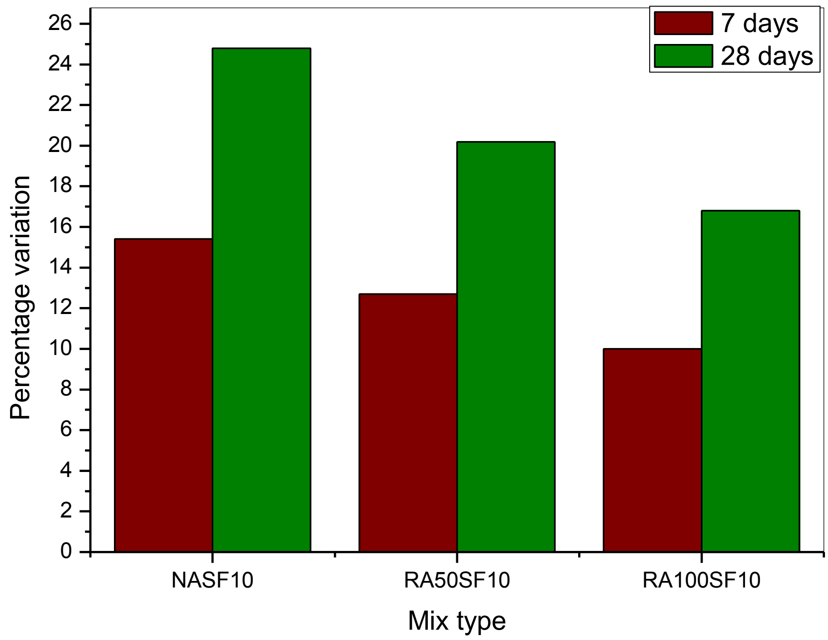

Fig 4.16: Percentage variation of splitting tensile strength of recycled aggregate concrete containing silica fume with respect to control mixture

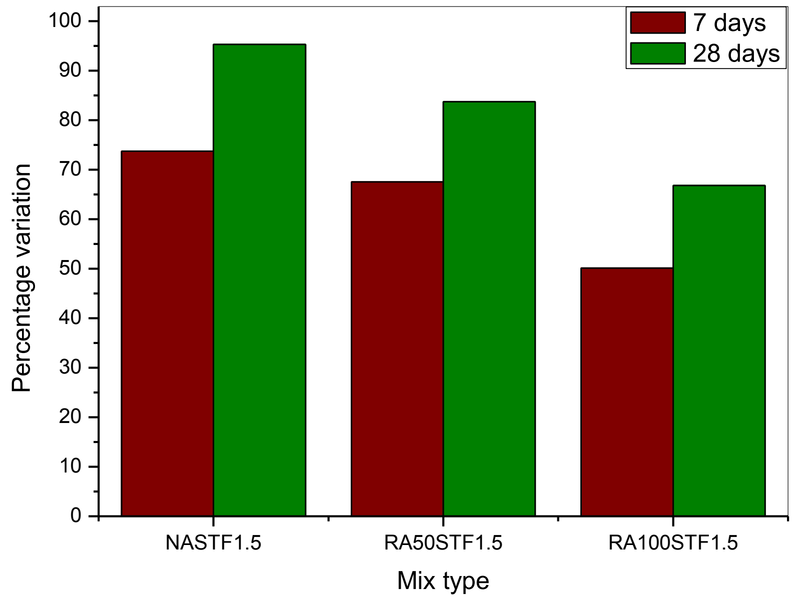

Fig 4.17: Percentage variation of splitting tensile strength of recycled aggregate concrete containing steel fibre with respect to control mixture

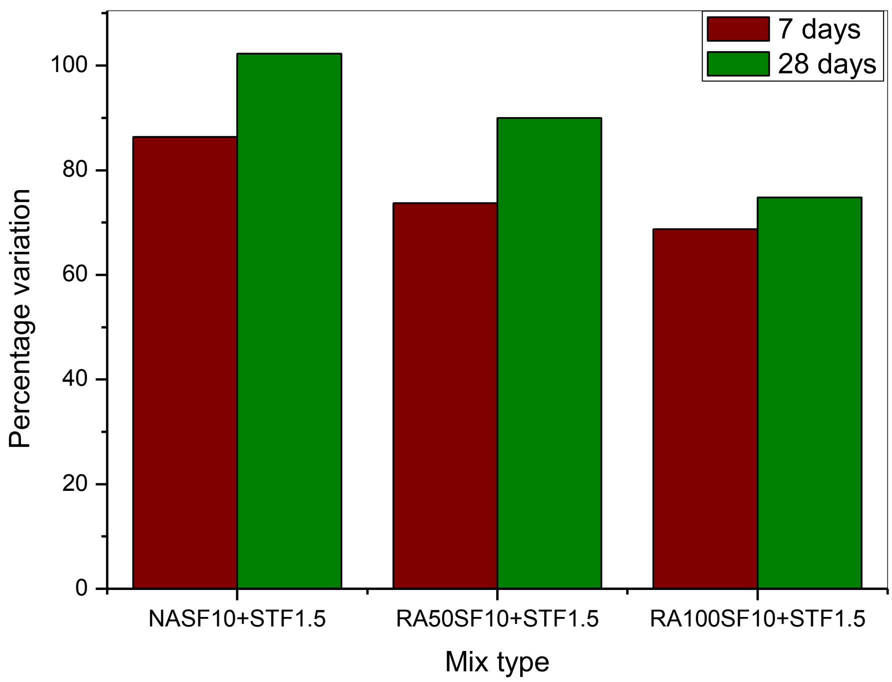

Fig 4.18: Percentage variation of splitting tensile strength of recycled aggregate concrete containing silica fume and steel fibre with respect to control mixture

4.4 Flexural Strength Test

Flexural strength studies were carried out at the age of 28 days. Test results are given below in Table 4.3. The data is further represented in the form of bar graphs in Figure 4.19 - 4.27.

Table 4.3: Flexural strength of concrete mixes at 28 days

Mix Type	**Average flexural strength (MPa)**
	28 days
CC	5.33
NASF10	7.13
RA50	4.51
RA100	4.19
RA50SF10	6.58
RA100SF10	5.69
RA50STF1.5	7.33
RA100STF1.5	5.95
RA50SF10+STF1.5	7.81
RA100SF10+STF1.5	6.6

- The flexural strength decreases when recycled aggregate are used without any mineral admixture or other supplementary materials. After replacing 50% of aggregates there is decrease of 15.38% at 28 days, whereas, replacing 100% aggregates caused greater strength loss of 21.38% at 28 days.
- Use of silica fume contributed in enhancing the flexural strength of recycled aggregate concrete. 10% silica fume was used to replace cement. At 0% replacement of recycled aggregate the amount of increase in strength is 33.7% at 28 days. By adding 50% recycled aggregate an increase of 18.99% at 28 days is observed. Concrete having 100% recycled showed an increase of 6.75% at 28 days.
- Use of steel fibre enhanced the flexural strength of recycled aggregate concrete. 1.5% of steel fibre as volume fraction was used. At 0% substitution of aggregates an increase of 56.6% at 28 days observed. After replacing 50%

recycled aggregates an increase of 37.5% at 28 days, whereas, replacing 100% aggregates an increase of 11.6% at 28 days is observed.

- Use of steel fibre and silica fume enhanced the splitting tensile strength of recycled aggregate concrete. 1.5% of steel fibre as volume fraction was used. 10% silica fume was used to replace cement. At 0% substitution of aggregates an increase of 61.9% at 28 days. After replacing 50% recycled aggregates an increase of 46.5%at 28 days, whereas, replacing 100% aggregates an increase of 23.8% at 28 days is observed.

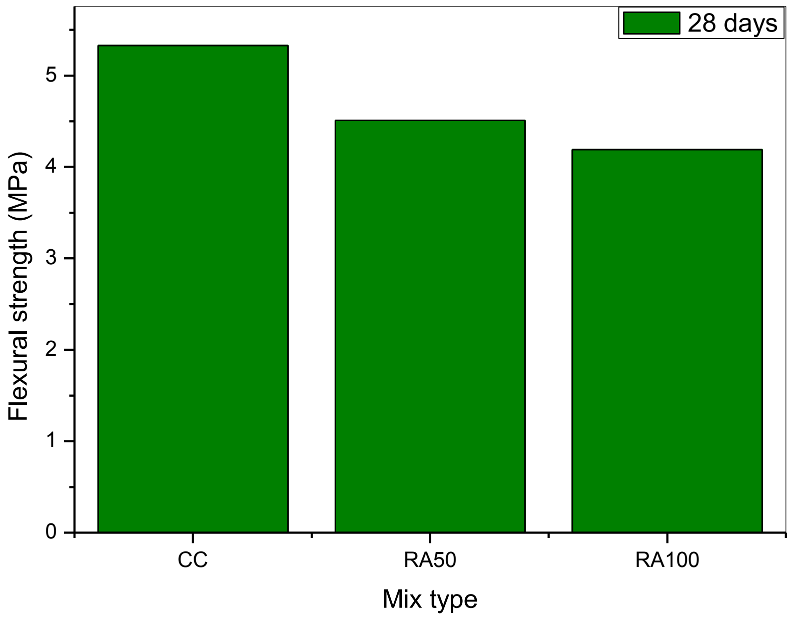

Fig 4.19: Flexural strength value of control mixture and recycled aggregate concrete

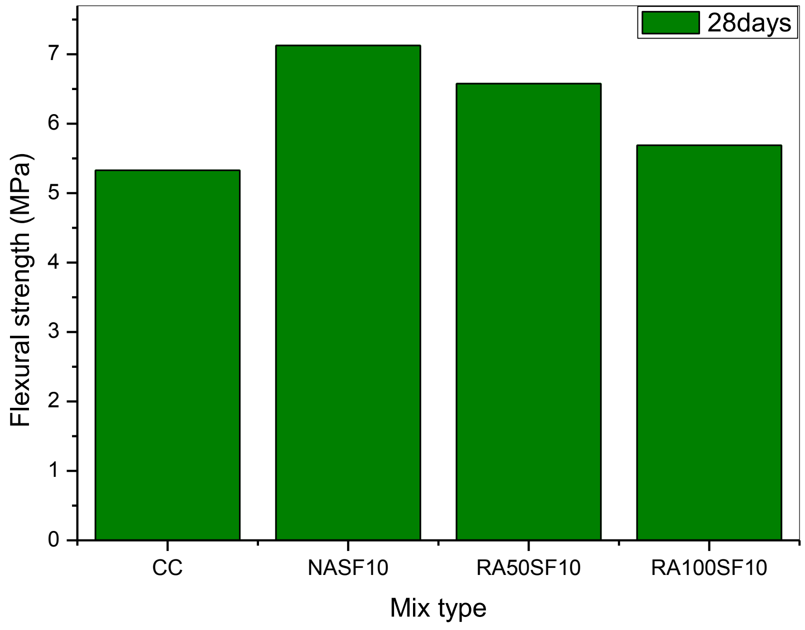

Fig 4.20: Flexural strength value of control mixture and recycled aggregate concrete containing silica fume

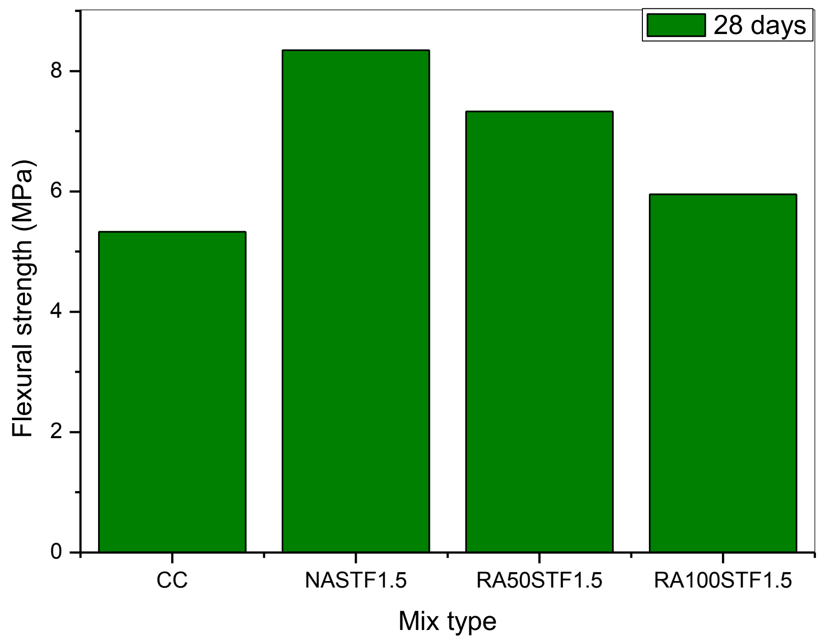

Fig 4.21: Flexural strength value of control mixture and recycled aggregate concrete containing steel fibre

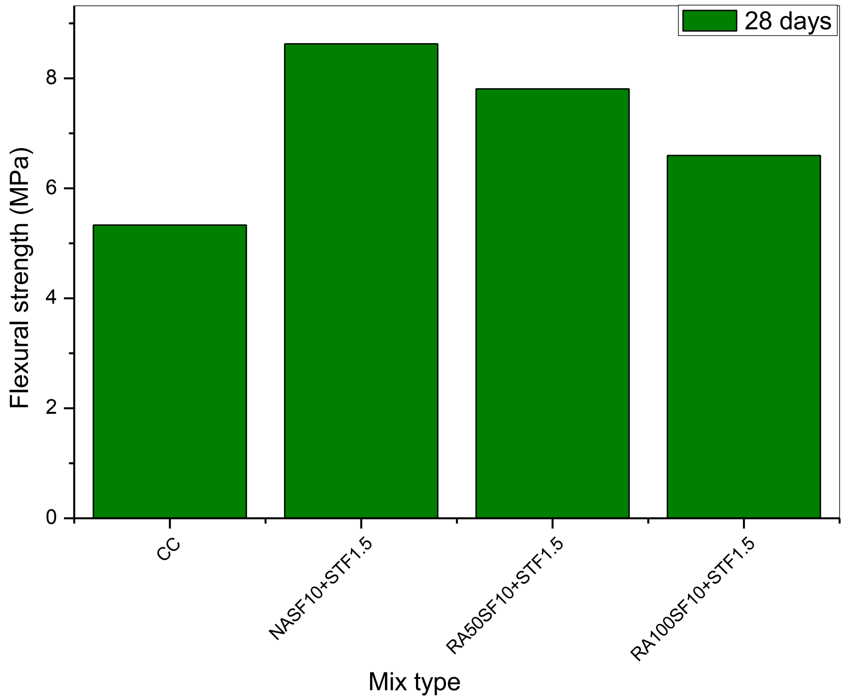

Fig 4.22: Flexural strength value of control mixture and recycled aggregate concrete containing silica fume and steel fibre

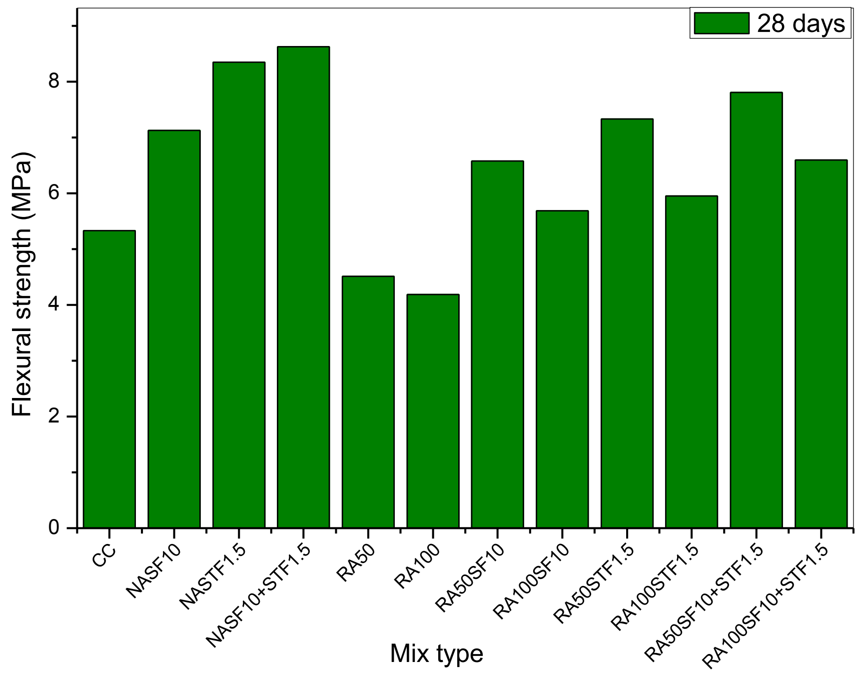

Fig 4.23: Flexural strength value of control mixture and recycled aggregate concrete with and without silica fume and steel fibre

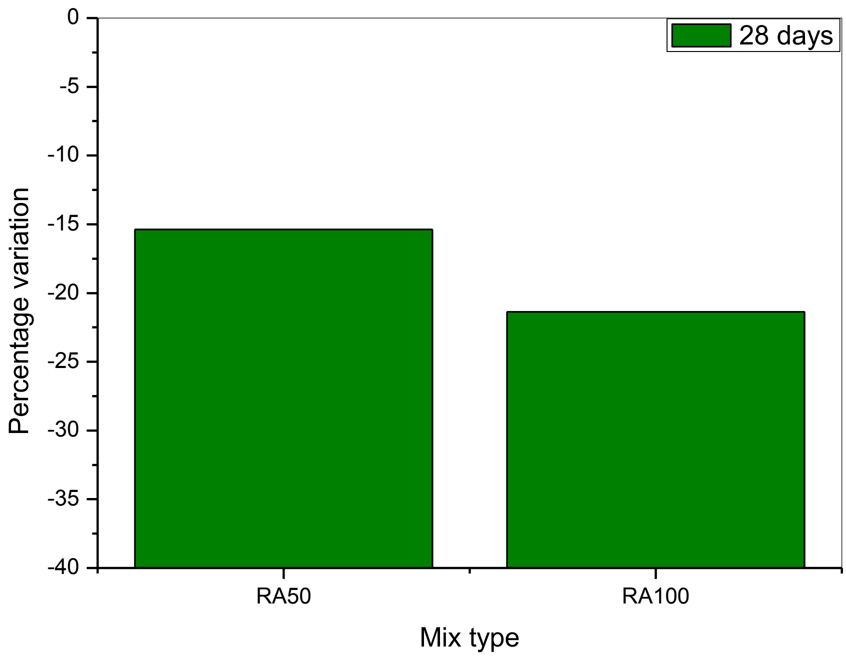

Fig 4.24: Percentage variation of flexural strength of recycled aggregate concrete with respect to control mixture

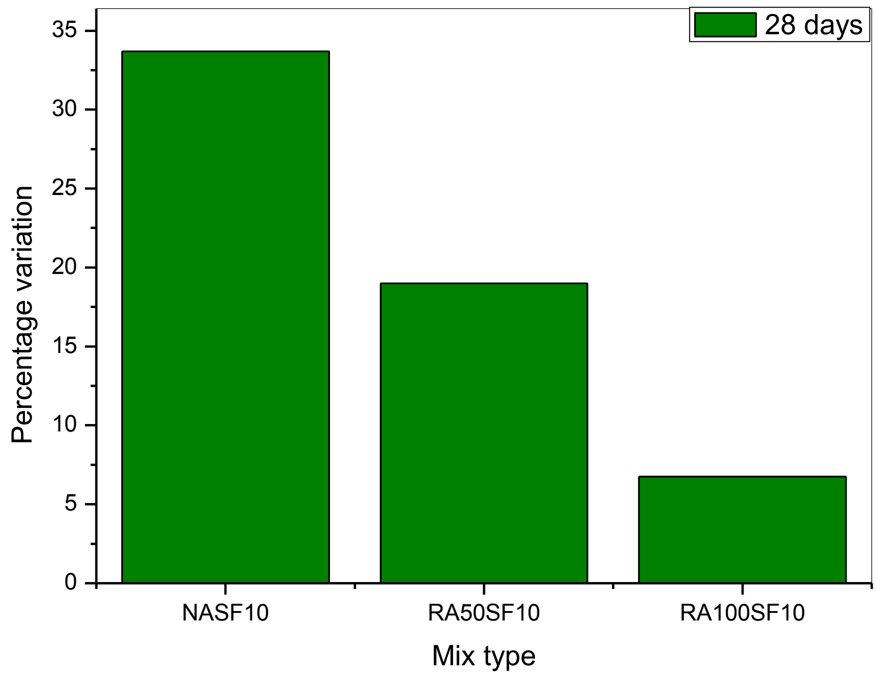

Fig 4.25: Percentage variation of flexural strength of recycled aggregate concrete containing silica fume with respect to control mixture

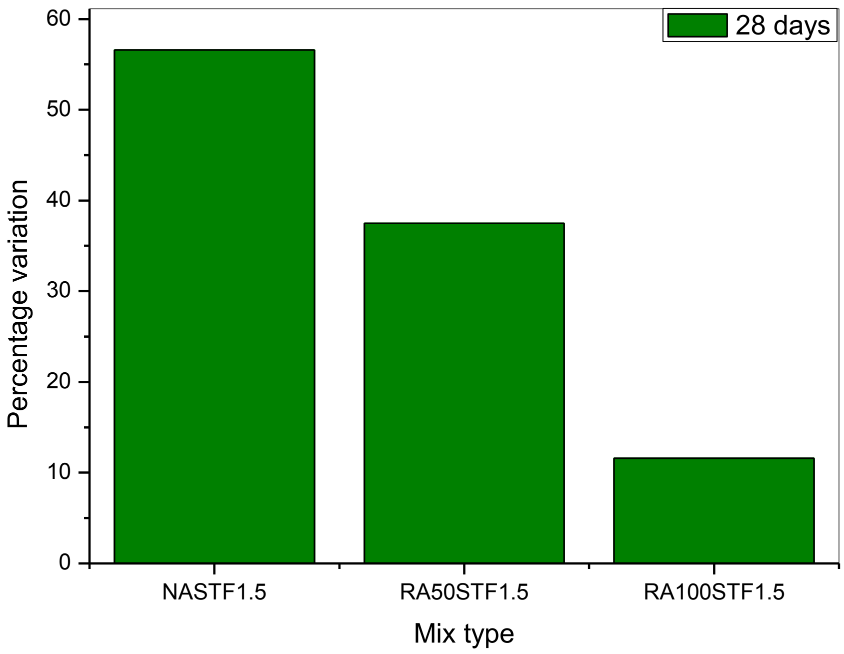

Fig 4.26: Percentage variation of flexural strength of recycled aggregate concrete containing steel fibre with respect to control mixture

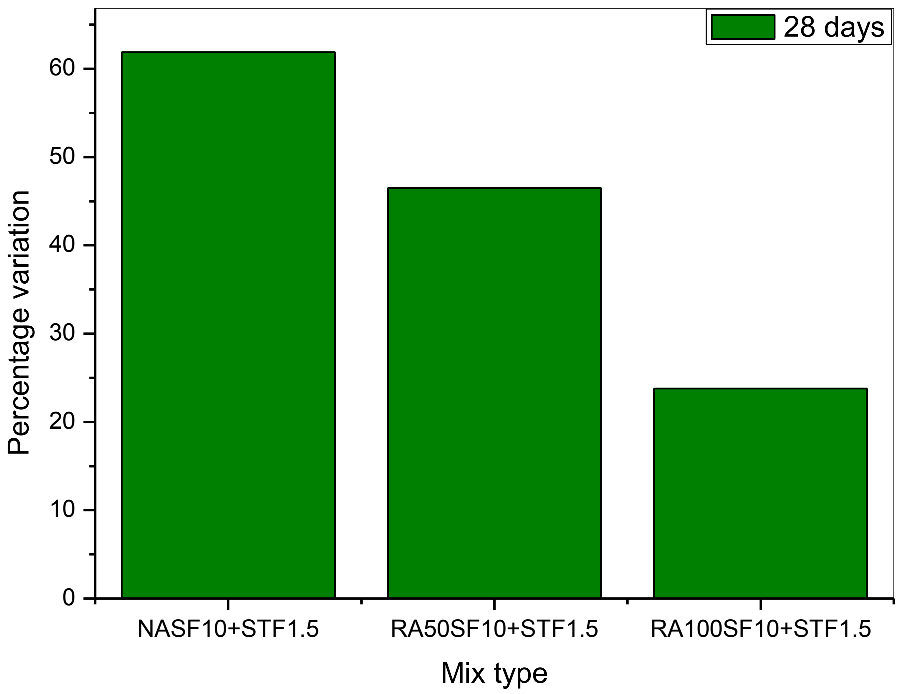

Fig 4.27: Percentage variation of flexural strength of recycled aggregate concrete with and without steel fibre with respect to control mixture

4.5 Rapid Chloride Permeability Test (RCPT)

Rapid chloride permeability test were carried out at the age of 28 days. The results are presented in Table 4.4 and further in form of graphs Fig.4.28 to 4.32

Table 4.4: Rapid chloride permeability of samples at 28 days

Mix Type	Total charge passed (Coulombs)	Permeability
	28 days	
CC	2804	Moderate
NASF10	1076	Very Low
RA50	3321	Moderate
RA100	3921	Moderate
RA50SF10	1141	Very Low
RA100SF10	1868	Low

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

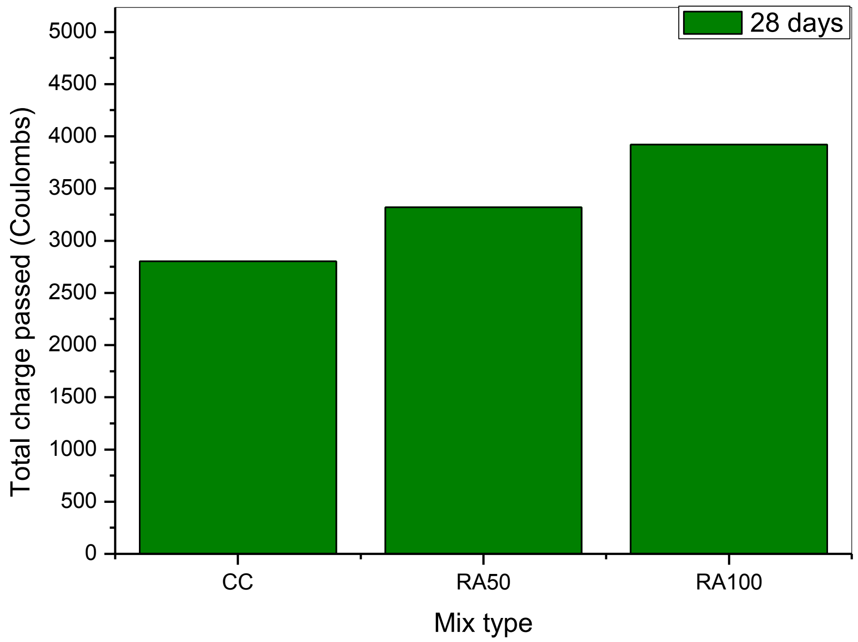

Fig 4.28: Total charge passed in coulombs of control mixture and recycled aggregate concrete

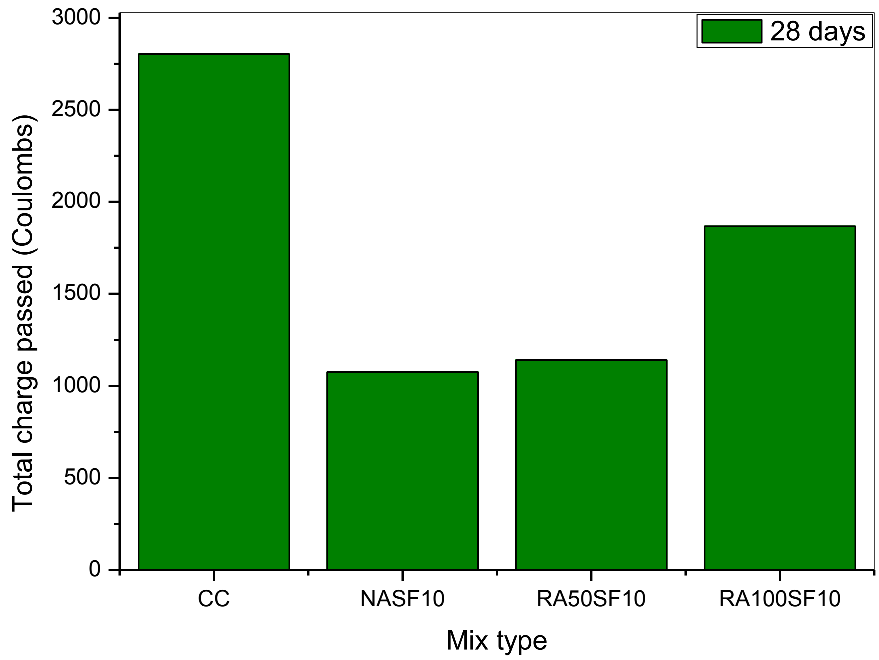

Fig 4.29: Total charge passed in coulombs of control mixture and recycled aggregate concrete containing silica fume

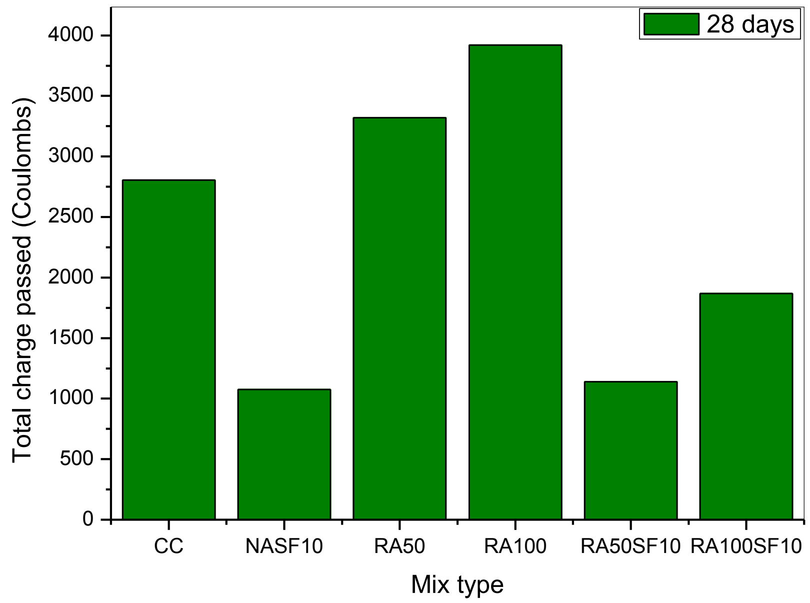

Fig 4.30: Total charge passed in coulombs of control mixture and recycled aggregate concrete with and without silica fume

4.6 Effect of Recycled Aggregate, Silica Fume and Steel Fibre on Properties of Concrete

- When recycled aggregates are used without mineral admixture the low mechanical strength can be explained by some mechanisms: (a) The interfacial transition zone (ITZ) is not properly bonded due to adhered mortar content i.e. the new cement paste and old paste have no proper bonding; (b) Heterogeneity of recycled aggregates procured from various quality of concrete. (c) High porosity and absorption capacity of recycled aggregates tend to lower the effective water content for hydration process which causes a weak interfacial transition zone. The similar trend is observed by *Poon et al. (2004), Thomas et al. (2011)* and *Kou et al. (2012).*
- Silica fume has very high pozzolanic activity and recycled aggregate concrete prepared with silica fume showed mechanical strength nearly equal to that of control mixture. When concrete containing recycled aggregate are prepared with the use of silica fume, two possible mechanisms may enhance the

properties of the concrete produced: (a) part of silica fume would penetrate into the pores of recycled aggregates, which would subsequently improve the interfacial transition zone bonding between paste and aggregates; (b) cracks present in aggregates would be filled by hydration products. As observed by *Kou et al. (2011), Randonjanin et al. (2013)* and *Dilbas et al. (2014).*

- Steel fibre addition in recycled aggregate concrete enhanced its mechanical strength. This may be credited to crack resisting property of fibres and offering greater resistance to sliding of pre-existing micro-cracks. As presented by *Carneiro et al. (2014).*
- Steel fibre in combination with silica fume is used in recycle aggregate improved the mechanical properties. This may be attributed that silica fume enhances the strength of the transition zone in concrete while the steel fibres act as crack resistors.
- Since recycled aggregates are highly porous and causes weak interfacial transition zone, it causes high amount of charge to pass causing low resistance. Similar observations were made by *Kou et al. (2011), Kou et al. (2012),* and *Andreu and Miren (2014).*
- The addition of silica fume increased the resistance to chloride ion penetration of both natural and recycled aggregate. This is due to reduction in average pore size of the paste and the improvement of interfacial transition zone. Similar trend was reported by *Kou et al. (2011)* and *Kou et al. (2012)*
- The addition steel fibre decreased the resistance to chloride ion penetration of both recycled and natural aggregate concrete. This can be attributed to the fact that steel fibre have high electrical conductivity.

CHAPTER 5

CONCLUSIONS

5.1 General

The strength and durability characteristics of recycled aggregate concrete mixtures have been computed in the present work by replacing 0%, 50% and 100% recycled aggregate with the natural aggregates. Silica fume and steel fibre were used as supplementary materials. While silica fume was added as 10% replacement of cement, steel fibre were added as 1.5% of volume fraction. On the basis of present study, following conclusions are drawn.

5.2 Compressive Strength

- After adding 50% and 100% recycled aggregate there is a decrease of 19% and 24.14% at 7 days, and at 28 days decrease of 13.3% and 16.9% as compared to control mixture.
- Addition of 10% silica fume as cement replacement causes some strength gain in recycle aggregate concrete though the value is still less than control mixture. By adding 50% recycled aggregate a decrease of 11.2% at 7 days and 1.13% at 28 days is observed. Concrete having 100% recycled showed a decrease of 18.36% at 7 days and 8.14% at 28 days.
- Steel fibre addition was at 1.5% of volume fraction. After replacing 50% recycled aggregates an increase of 2.0% at 7 days and 4.75% at 28 days, whereas, replacing 100% aggregates an increase of 0% at 7 days and 1.35% at 28 days is observed.
- Combined effect of silica fume and steel fibre was incremental. After replacing 50% recycled aggregates an increase of 6.4% at 7 days and 13.33% at 28 days, whereas, replacing 100% aggregates an increase of 1.36% at 7 days and 10.18% at 28 days.
- Higher percentage of recycled aggregates causes decrease in the compressive strength.
- The compressive strength gain tends to increase marginally with supplementary material addition.

5.3 Splitting Tensile Strength

- After replacing 50% of aggregates there is decrease of 10% at 7 days and 4.3% at 28 days, whereas, replacing 100% aggregates caused greater strength loss of 11.9% at 7 days and 8.6% at 28 days.
- Addition of 10% silica fume as cement replacement causes strength gain in recycle aggregate concrete. By adding 50% recycled aggregate an increase of 12.7% at 7 days and 20.19% at 28 days is observed. Concrete having 100% recycled showed an increase of 10% at 7 days and 16.8% at 28 days.
- Steel fibre addition was at 1.5% of volume fraction. After replacing 50% recycled aggregates an increase of 67.5% at 7 days and 83.7% at 28 days, whereas, replacing 100% aggregates an increase of 50.1% at 7 days and 66.8% at 28 days is observed.
- Combined effect of silica fume and steel fibre was incremental. After replacing 50% recycled aggregates an increase of 73.7% at 7 days and 90% at 28 days, whereas, replacing 100% aggregates an increase of 68.7% at 7 days and 74.8% at 28 days is observed.
- Higher percentage of recycled aggregate does not seem to have significant effect on split tensile strength.
- There is a sufficient increase in strength gain when supplementary materials are used.

5.4 Flexural Strength

- After replacing 50% of aggregates there is decrease of 15.38% at 28 days, whereas, replacing 100% aggregates caused greater strength loss of 21.38% at 28 days.
- Addition of 10% silica fume as cement replacement adds to the strength gain in recycle aggregate concrete. By adding 50% recycled aggregate an increase of 18.99% and at 100% recycled an increase of 6.75% at 28 days is observed.
- Steel fibre addition was at 1.5% of volume fraction. After replacing 50% and 100% recycled aggregates an increase of 37.5% and 11.6% at 28 days is observed.

- Combined effect of silica fume and steel fibre was beneficial. After replacing 50% recycled aggregates an increase of 46.5%at 28 days, whereas, replacing 100% aggregates an increase of 23.8% at 28 days is observed.
- Higher percentage of recycled aggregate does not seem to have significant effect on flexural strength.
- There is a sufficient increase in strength gain when supplementary materials are used.

5.5 Rapid Chloride Permeability

- The resistance to chloride decreases as the percentage of recycled aggregate in concrete increases.
- Use of silica fume appreciably enhances the resistance to chloride attack at all replacement levels.
- Use of steel fibre causes increase in the total charge passed in both natural and recycled aggregate concrete.
- Combination of silica fume and steel fibre though improved the resistance to chloride attack, the values were still high.

Replacing natural aggregate with equal amount of recycled concrete aggregate in concrete and yet achieving comparative mechanical properties in combination with supplementary materials like silica fume and steel fibre, favours the use of recycled aggregate in concrete while contributing towards the sustainable construction and economic challenges at different levels.

5.6 Future Scope of the Study

While studies have shown that recycled concrete aggregate can be used as aggregate for new concrete, there is a need to obtain long-term in-service performance for concrete made with recycled aggregate concrete to assess its durability and performance. If additional research supports the use of concrete buildings then existing specification should be revised to permit and encourage the use of recycled concrete as aggregate. Further testing and studies on the recycled aggregate concrete is highly recommended to indicate the strength characteristics of recycled aggregates for application in high strength concrete. Below are some of the recommendations for further studies:

- More trials with different particle sizes of recycled aggregate and percentage of replacement of recycled aggregate are recommended to get higher strength characteristics in the recycled aggregate concrete
- More investigations and laboratory tests should be done on the durability of recycled aggregate concrete in new concrete, and its creep and shrinkage characteristics.
- The influence of contaminants in the demolished concrete from buildings should be carefully studied and investigated to extend life time of concrete made with recycled aggregate concrete.
- Study of other supplementary materials along with recycled aggregates to enhance the properties of concrete.

REFERENCES

Andreu G., Miren E. (2014). “Experimental analysis of properties of high performance recycled aggregate concrete.” Construction and Building Materials Vol. 52 pp 227-235.

Butler L., West J.S., Tighe S.L. (2013). “Effect of recycled concrete coarse aggregate from multiple sources on the hardened properties of concrete with equivalent compressive strength.” Construction and Building Materials Vol. 47 pp 1292-1301.

Corinaldesi V., Moriconi G. (2009). “Influence of mineral additions on the performance of 100% recycled aggregate concrete.” Construction and Building Materials Vol. 23 pp 2869-2876.

Carneiro J.A., Lima P.R.L., Monica B.L., Filho R.D.T. (2014). “Compressive stress-strain behavior of steel fiber reinforced-recycled aggregate concrete.” Cement and Concrete Composites Vol. 46 pp 65-72.

Dilbas H., Simsek M., Cakir O. (2014). “An investigation on mechanical and physical properties of recycled aggregate concrete (RAC) with and without silica fume.” Construction and Building Materials Vol. 61 pp 50-59.

Duan Z.H., Poon C.S. (2014). “Properties of recycled aggregate concrete made with recycled aggregates with different amounts of old adhered mortars.” Materials and Design Vol. 58 pp 19-29.

Hemlatha B.R., Prasad N., Subramanya B.V.V. (2008). “Construction and demolition waste recycling for sustainable growth and development.” Journal of Environmental Research and Development Vol. 2

Gayarre F.L., Perez C.L.C., Lopez M.A.S., Cabo A.D. (2014). “The effect of curing conditions on the compressive strength of recycled aggregate concrete.” Construction and Building Materials Vol. 53 pp 260-266.

IS: 10262-1982 (Reaffirmed 2004): Recommended guidelines for concrete mix design, Bureau of Indian Standard, New Delhi-2004.

IS: 15388-2003: Silica fume specification, Bureau of Indian Standard, New Delhi-2003.

IS: 2386 (Part I, III)-1963: Methods of Test for Aggregates for Concrete, Bureau of Indian Standard, New Delhi-1963.

IS: 383-1970: Specification for Coarse and Fine Aggregates from Natural Sources for Concrete, Bureau of Indian Standard, New Delhi-1970.

IS: 516-1959 (Reaffirmed 2004): Methods of tests for strength of concrete, Bureau of Indian Standard, New Delhi-2004.

IS: 5816-1999: Methods of test for Splitting Tensile Strength of Concrete, Bureau of Indian Standard, New Delhi-1999.

IS: 8112-1989 (Reaffirmed 2005): Specification for 43 Grade Ordinary Portland Cement, Bureau of Indian Standard, New Delhi-2005.

Ismail S., Ramli M. (2013). "Engineering properties of treated recycled concrete aggregate (RCA) for structural applications." Construction and Building Materials Vol. 44 pp 464-476.

Kanellopoulos A., Nicolaides D., Petrou M.F. (2014). "Mechanical and durability properties of concretes containing recycled lime powder and recycled aggregates." Construction and Building Materials Vol. 53 pp 253-259.

Koenders E.A.B., Pepe M., Martinelli E. (2014). "Compressive strength and hydration processes of concrete with recycled aggregates." Cement and Concrete Research Vol. 56 pp 203-212.

Kou S.C., Poon C.S., Agrela F. (2011). "Comparisons of natural and recycled aggregates concretes prepared with the addition of different mineral admixtures." Cement and Concrete Composites Vol. 33 pp 788-795.

Kou S.C., Poon C.S. (2013). "Long-term mechanical and durability properties of recycled aggregate concrete prepared with the incorporation of fly ash." Cement and Concrete Composites Vol. 37 pp 12-19.

Kou S.C., Poon C.S., Wan H.W. (2012). "Properties of concrete prepared with low-grade recycled aggregates." Construction and Building Materials Vol. 36 pp 881-889.

Lage I.M., Abella F.M., Herrero C.V., Ordonez J.L.P. (2012) "Properties of plain concrete made with mixed recycled coarse aggregate." Construction and Building Materials Vol. 37 pp 171-176.

Li J., Xiao H., Zhou Y. (2009). "Influence of coating recycled aggregate surface with pozzolanic powder on properties of recycled aggregate concrete." Construction and Building Materials Vol. 23 pp 1287-1291.

Lima C., Caggiano A., Faella C., Martinelli E., Pepe M., Realfonzo R. (2013). "Physical properties and mechanical behaviour of concrete made with recycled aggregate and fly ash." Construction and Building Materials Vol. 47 pp 547-559.

Mas B., Cladera A., Bestard J., Muntaner D., Lopez C.E., Pina S., Prades J. (2012). "Concrete with mixed recycled aggregates: influence of the type of cement." Construction and Building Materials Vol. 34 pp 430-441.

Matias D., De Brito J., Rosa A., Pedro D. (2013). "Mechanical properties of concrete produced with recycled coarse aggregates – Influence of the use of superplasticizers." Construction and Building Materials Vol. 44 pp 101-109.

Mukharjee B.B., Barai S.V. (2014). "Influence of Nano-Silica on the properties of recycled aggregate concrete." Construction and Building Materials Vol. 55 pp 29-37.

Poon C.S., Shui Z.H., Lam L., Fok H., Kou S.C. (2004). "Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete." Cement and Concrete Research Vol. 34 pp 31-36.

Radonjanin V., Malesev M., Marinkovic S., Al Malty A.E.S. (2013). "Green recycled aggregate concrete." Construction and Building Materials Vol. 47 pp 1503-1511.

RILEM. (1994) "Specifications for concrete with recycled aggregates." Materials and Structures Vol. 27 pp 557–559.

Shah R.A., Pitroda J.R. (2011). "Recycling of construction materials for sustainability." National conference on recent trends in engineering and technology.

Sheen Y.N., Wang H.Y., Juang Y.P., Le D.H. (2013). "Assessment on the engineering properties of ready-mixed concrete using recycled aggregates." Construction and Building Materials Vol. 45 pp 298-305.

Surya M., Kanta Rao V.V.L., Lakshmy P. (2013). "Recycled aggregate concrete for Transportation Infrastructure." Procedia - Social and Behavioral Sciences Vol. 104 pp 1158 – 1167.

Tam V.W.Y., Tam C.M., Le K.N. (2007). "Removal of cement mortar remains from recycled aggregate using pre-soaking approaches." Resources, Conservation and Recycling Vol. 50 pp 82–101

Tangchirapat W., Buranasing R., Jaturapitakkul C., Chindaprasirt P., (2008). "Influence of rice husk-bark ash on mechanical properties of concrete containing high amount of recycled aggregates." Construction and Building Materials Vol. 22 pp 1812-1819.

Thomas C., Setien J., Polanco J.A., Alaejos P., Juan M.S.D. (2013). "Durability of recycled aggregate concrete." Construction and Building Materials Vol. 40 pp 1054-1065.

Thomas J., Wilson P.M. (2013). "Construction waste management in India." American Journal of Engineering Research Vol. 2 pp 06-09.

www.b-i-m.de/projekte/projframe.htm

www.concreterecycling.org

www.projects.bre.co.uk