

DEVELOPMENT OF STRAIN HARDENING CEMENT BASED COMPOSITE FOR CONCRETE RETROFITTING PURPOSES

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in partial fulfillment of the requirements
for the award of degree of**

**MASTERS OF ENGINEERING
IN
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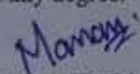


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DECLARATION

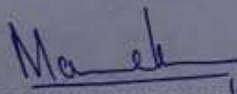
I, Manan Hashim, hereby declare that this thesis entitled "**Development of strain hardening cement based composite for concrete retrofitting purposes**" is an authentic record of my study carried out as requirements for the award of degree of **Master of Engineering in Structural Engineering** in the Civil Engineering Department, Thapar University, Patiala under the supervision of **Dr. Maneek Kumar, Professor** Department of Civil Engineering, Thapar University, Patiala during July 2014 to July 2016. 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.

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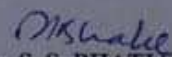
CERTIFICATE

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


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ABSTRACT

With the ever increasing population in the earthquake prone areas it has become imperative to retrofit not only the damaged structures but also the existing buildings. Thus, there is tremendous pressure on Civil Engineers to develop new materials to fulfill the growing demand for efficient and economic retrofitting materials. Strain hardening cement based composites is a relatively new construction material having combination of fine particles and fibers. The material has the ability to seep into the creep of the damaged structure without any vibration. The mechanical and durability properties of the strain hardening cement based composite has shown beneficial result to restore back the virgin strength of the structure. SHCC has also been used in the bridge deck slab due to its abrasion resistance capability developed by the addition of fibers.

Experimental investigations have been carried out to study the effect of the GGBS content with Polyvinyl Alcohol (PVA) fibers on the properties of Strain hardening cement based composite. Flyash in the mix has been replaced with 10, 20 and 30 per cent of GGBS content. Two percentages of PVA fibers (2.0 and 3.0 per cent) of length 12 mm have been used in the investigation. Tests have been performed for Compressive strength, tensile strength and durability properties of different specimens

Test results indicate with the increase in percentage of GGBS content, the tensile strength and durability properties of strain hardening cement based composite increased but no significant change was observed in the compressive strength. Addition of higher percentage PVA fibers have been found to give better results. With regards to both, the mechanical strength and durability properties of the various mixes.

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Contents

CERTIFICATE	i		
ACKNOWLEDGEMENT	ii		
ABSTRACT	iii		
CONTENTS	iv		
LIST OF TABLES	vi		
LIST OF FIGURES	vii		
CHAPTER-1 INTRODUCTION			
1.1	General	1	
1.2	Retrofitting	2	
	1.2.1	Need for retrofitting	2
	1.2.2	Type of retrofitting	3
1.3	Different jacketing techniques	3	
1.4	Reason for consideration of SHCC	5	
1.5	Categories of engineered cementitious composites	5	
	1.5.1	High performance fiber reinforced cement	5
	1.5.2	Strain-hardening cement-based composites	5
1.6	Historical development of SHCC	6	
1.7	Advantages of SHCC	7	
	1.7.1	Self healing behavior of SHCC	7
	1.7.2	Strain hardening mechanism of SHCC	7
	1.7.3	Flowability of SHCC	7
1.8	Application of SHCC	8	
	1.8.1	SHCC dampers	8
	1.8.2	Tensile resistance for deck slabs	8
	1.8.3	Joint and overlay applications	9
	1.8.4	Ductility shear walls	9

1.8.5	Tensile performance for tunnel linings	10
1.9	Materials used for making SHCC	10
1.9.1	Fiber	10
1.9.2	Ground granulated blast furnace slag	11
1.9.3	Flyash	11
1.1	Aim of the study	12
1.9	Outline of thesis	12
CHAPTER-2 LITERATURE REVIEW		
2.1	General	13
2.2	Literature review on development of SHCC	13
2.3	Literature review on retrofitting	20
2.4	Summary of literature review	23
CHAPTER-3 MATERIALS AND METHODS		
3.1	General	24
3.2	Materials	24
3.2.1	Cement	25
3.2.2	Flyash	27
3.2.3	Ground granulated blast-furnace slag	28
3.2.4	Fine aggregates	30
3.2.5	Superplasticizers	31
3.2.6	Polyvinyl alcohol fibers	32
3.3	Mix proportions for the development of SHCC	34
3.3.1	Base mixes	34
3.3.2	Replacement mixes	35
3.4	Experimental methods used for developing SHCC	36
3.4.1	Compressive strength	36
3.4.2	Flow table test	37
3.4.3	Tensile strength	39
3.4.4	Abrasion test	42
CHAPTER-4 RESULTS AND DISCUSSION		
4.1	General	44
4.2	Compression test results	44
4.3	Flow table test results	46
4.4	Tensile test results	49
4.5	Abrasion test results	51
4.6	Closing remarks	53
CHAPTER-5 CONCLUSIONS		
5.1	General	54
5.2	Scope for future work	55
REFERENCES		56

LIST OF TABLES

TABLE NO.	DESCRIPTION	PAGE NO.
2.1	Mix design of SHCC	15
2.2	Compressive strength of SHCC	15
2.3	Compressive strength of SHCC	16
3.1	Physical properties of Cement used in the study	26
3.2	Chemical composition of cement observed present study	26
3.3	Physical properties of fly ash used	27
3.4	Chemical composition of fly ash used	27
3.5	Chemical composition of GGBS	28
3.6	Physical properties of GGBS	29
3.7	Properties of sand tested	30
3.8	Properties of superplasticizer	30
3.9	Properties of PVA fibers	32
3.10.	Mix proportion for the base mixes of SHCC	34
3.11	Replacement ratio of mixes of SHCC	35
3.12	Mix proportions of SHCC	35
3.13	Physical property of abrasive powder	43
4.1	Compressive strength variation in 28 days	45
4.2	Flow table test on SHCC mixes after 28 days	47
4.3	Tensile strength variation in 28 days	49

4.4	Abrasion test on SHCC mixes after 28 days	51
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LIST OF FIGURES

Figure No.	DESCRIPTION	Page No.
1.1	Beam-column joint shear failure due to earthquake	1
1.2	Damper made up of SHCC	8
1.3	The Mihara bridge Japan uses a steel/SHCC deck	9
2.1	Flexural strength results of mixtures	18
2.2	Stress Strain graph for SHCC containing fine sand	19
2.3	Stress Strain graph of SHCC containing coarse sand	20
2.4	Tensile stress versus strain curves	21
3.1	OPC Cement used in the study	25
3.2	Fly Ash used in the study	28
3.3	GGBS used in the study	29
3.4	Grain Size Distribution of sand	31
3.5	River Sand used in the study	31
3.6	PVA fibers used in the study	33
3.7	Compression testing of sample of SHCC	37
3.8	SHCC tested cube	37
3.9	Cylinder Slump flow apparatus	38
3.10.	Flow table machine used in the study	39
3.11	Design and dimension of specimen for tensile test	40
3.12	Casted sample of SHCC	41
3.13	Failure of sample after testing	41
3.14	UTM used for the tensile test	41
3.15	Abrasion Testing Machine used in the study	43
4.1	28-days Compressive strength for trail SHCC mixes	46

4.2	Slump flow test on fresh mixes of SHCC	48
4.3	28-day Tensile strength for trail SHCC mixes	50
4.4	Abrasion test on C1, C1 GGBS 10%, C1 GGBS 20% and C1 GGBS 30%	52
4.5	Abrasion test on C2, C2 GGBS 10%, C2 GGBS 20% and C2 GGBS 30%	53

CHAPTER 1

INTRODUCTION

1.1 GENERAL

In various parts of the world, Reinforced Concrete (RC) structures, even in seismic zones are still being designed only for gravity loads. Such structures, though performing reasonably well under conventional gravity loads, could lead to a questionable structural performance under seismic or wind loads. In most cases, those structures are highly vulnerable to any moderate or a major earthquake. Along with the seismic prone zones like Himalayan region in India, Iran, Turkey, New Zealand and fault regions in US etc., devastations from earthquake have also been seen at the places believed to be seismically not-so-active (as shown in **Figure 1.1** and hence, the existing structures need immediate assessment to avoid collapse which brings forth huge loss of human lives and economy that the world has now been witness to several times.



Figure 1.1: Beam-column joint failure due to earthquake (Ghobarah, 2002).

Moreover, for new structures, the specifications and detailing provisions, though available to a certain extent, have to be considered in such a way that the structure would be able to efficiently resist seismic actions. Generally, a three phase approach (*Sasmal; 2009*) is followed to describe a structure under seismic loading, as underlined below

- (1) The structure must have adequate lateral stiffness to control the inter-story drifts such that no damage would occur to non- structural elements during minor but frequently occurring earthquakes,
- (2) During moderate earthquakes, some damage to non- structural elements is permitted, but the structural element must have adequate strength to remain elastic so that no damage would occur, and
- (3) During rare and strong earthquakes, the structure must be ductile enough to prevent collapse by aiming for repairable damage which would ascertain economic feasibility.

1.2 RETROFITTING

The strengthening and enhancement of the performance of deficient structural elements in a structure or the structure as a whole is referred to as retrofitting. Retrofitting of a building is not the same as repair or rehabilitation. Repair refers to partial improvement of the degraded strength of a building after an earthquake. In fact, it is only a cosmetic enhancement, and on the other hand, rehabilitation is a functional improvement, wherein the aim is to achieve the original strength of a building after an earthquake. Retrofitting means structural strengthening of a building after or before an earthquake to a predefined performance. Up grading of certain building system (existing structures) to make them more resistant to seismic activity

1.2.1 Need for retrofitting

The seismic performance of a retrofitted building is aimed higher than that of the original building. A survey of existing residential building reveals that many buildings are not adequately designed to resist earthquakes. This is per the revision of the Indian earthquake code (IS1893-2002), wherein, many regions of the country have been placed in higher seismic zones. As a result many buildings designed prior to the revision of the code may fail to perform adequately as per the provisions of the new code. It has, therefore, been recommended that the existing deficient buildings be retrofitted to improve their performance in the event of an earthquake and to avoid large scale damage to life and property (*Dowrick; 2003*). The benefits of retrofitting include the reduction in the loss of lives and damage of the essential facilities, and functional continuity of the life line structures. For an existing structure of good condition, the cost of retrofitting tends to be smaller than the replacement cost. Thus, the retrofitting of structures is an essential component of long term disaster mitigation. Retrofitting proves to be a better economic consideration and immediate shelter to the problem rather than replacement of building.

1.2.2 Type of retrofitting

Some Conventional Approaches of retrofitting techniques which are globally used are as follows

- Adding shear walls
- Infill walls
- Adding bracing
- Adding of wing walls
- Wall thickening
- Mass reduction
- Base isolation
- Mass dampers

These techniques of retrofitting are frequently used for the retrofitting of the non ductile reinforced concrete frame buildings. The addition of elements can either be cast in place or precasted concrete elements. New elements are preferably placed at the exterior of the buildings as to avoid interior deformation of the building and the reduction of the space for which the building is designed.

There are various other techniques which are used locally to strengthen the existing damaged or weak structure using new innovative materials are as follows

- Jacketing of beams
- Jacketing of columns
- Jacketing of beam column joints
- Strengthening individual footing

The jacketing techniques main purpose is to increase the confinement of the concrete, increase the flexural and shear strength of the material to be retrofitted.

1.3 DIFFERENT JACKETING TECHNIQUES

In case of damaged structures, materials in some parts of members are to be replaced by a new material. For strengthening existing members in deficient buildings, additional material including reinforcement is to be provided. The material used for replacement should have good bond with existing material and it should be non-shrinking (*Dowrick; 2003*). A variety of strengthening and replacement material is available and some of the prominent ones are discussed as below:

(i) Steel plate bonding

Steel plate can be bonded to concrete members as external reinforcement to increase their strength. The plates are glued to the member surface by epoxies. This requires a careful preparation of the member surface and application of epoxy layer.

(ii) Fiber-reinforced polymer/plastic

Fiber reinforced polymer/plastic is a recently developed material for strengthening of RC and masonry structure. The main advantage of FRP is its high strength to weight ratio and high corrosion resistance. FRP plates are two to ten times stronger than steel plates, while their weight is just 20% of that of steel. FRP composites are formed by embedding continuous fiber matrix in resin matrix. The resin matrix binds the fiber together and also provides bond between concrete and FRP. The commonly used polymers are carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP).

(iii) Ferrocement

Ferrocement is a term commonly used to describe a steel and mortar composite material. Essentially a form of reinforced concrete, it exhibits behavior so different from conventional reinforced concrete in performance, strength, and potential application that it must be classed as a completely separate material. Ferrocement is a versatile construction material and confidence in the material is building up resulting in its wider application especially in developing countries such as for housing, sanitation, agriculture, fisheries, water resources, water transportation freshwater and marine environment, biogas structure, repair and strengthening of older structures, and others. Considered to be an extension of reinforced concrete, ferrocement has relatively better mechanical properties and durability than ordinary reinforced concrete. The uniform distribution and high surface area to volume ratio of its reinforced results in better crack arrest mechanism i.e. the propagation of cracks are arrested resulting in high tensile strength the material.

(iv) Strain hardening cementitious composite (SHCC)

Strain Hardening Cementitious Composites (SHCC) is a new retrofitting material because of its tensile hardening behavior up to several percent strain accompanied by the formation of fine multiple cracks. Their tensile ductility is governed by the spacing and opening of cracks, which depend on the stress transfer between the fibers and the matrix. It is a new class of engineering material which provides high tensile strength to the specimen under consideration. SHCC reinforced by short PVA fibers constitute a relatively new class of

building material which exhibits pseudo strain hardening behavior with multiple cracking formations when tested under tension loads at quasi-static strain rates. They give the material a marked potential for use in application in which high non-elastic deformability is needed. Some examples of promising applications are link slabs for joint-less bridge decks, structural repairs and connecting beams for high rise buildings in earthquake areas.

1.4 REASON FOR CONSIDERATION OF SHCC

Strain-hardening cement-based composites are a recently developed engineering cementitious material which is used for retrofitting. The work done using these engineering cementitious composites is not as much of other material used of retrofitting so this research is based on developing the Strain-hardening cement-based composites which can be further used for retrofitting.

1.5 CATEGORIES OF ENGINEERED CEMENTITIOUS COMPOSITES

Strain-hardening cement-based composites may be classified two classes are as follows

1. High performance fiber-reinforced cement-based composites (HPFRCC)
2. Strain-hardening cement-based composites (SHCC)

1.5.1 High performance fiber-reinforced cement based composites (HPFRCC)

High performance fiber-reinforced cement-based composites are a group of fiber-reinforced cement-based composites which possess the unique ability to flex and self-strengthen before fracturing. The design and composition, HPFRCCs possess the remarkable ability to strain harden under excessive loading. High performance fiber reinforced concretes (HPFRC) may have flexural strength 25–60 MPa, as well as extremely high compressive strength 180–240 MPa. One aspect of HPFRCC design involves preventing crack propagation, or the tendency of a crack to increase in length, ultimately leading to material fracture. This occurrence is hindered by the presence of fiber bridging, a property that most HPFRCCs are specifically designed to possess.

1.5.2 Strain hardening cement based composites (SHCC)

A strain-hardening cement-based composite has tensile strength but significant ductility up to and beyond 3% of tensile strain. Recent developments has made possible to design these composites with low fiber volumes of 1% to 3%. SHCC is designed for a maximum compressive strength of 60 MPa and the tensile strength is in the range of (3 to 6±0.3) MPa.

Strain-hardening cement based composites which are a type of fiber-reinforced cementitious composites. Strain Hardening Cement Composites; demonstrate excellent mechanical behavior showing tensile strain hardening and multiple fine cracks. This strain hardening behavior improves the durability of concrete structures employing SHCC and the multiple fine cracks enhance structural performance. Reliable tensile performance of SHCC enables to design structures explicitly accounting for SHCC's tensile properties. These properties are due largely to the interaction between the fibers and cementing matrix, which can be custom-tailored through micromechanics design. However, compared to conventional concrete mixtures, SHCC mixtures are energy intensive. They require more cement in order to increase interfacial bond strength and to account for the absence of coarse aggregate in the mix design. Such high cement content usually creates negative environmental impacts due to the associated carbon dioxide emissions. A possible solution to this problem is to replace the cement with industrial by-products, such as GGBS and fly ash

1.6 HISTORICAL DEVELOPMENT OF SHCC

Beginning as early as the 1980's, interest in creating a fiber reinforced concrete material with tensile ductility has been gaining ground. Within FRC, the toughness of the material is increased, but no change in ductility is attained. Ductility is a measure of tensile deformation strain capacity typically associated with ductile steel, for example, but not with concrete material. Attempts in achieving tensile ductility in concrete material are exemplified by the early efforts of Aveston et al. (1971), and later Krenchel and Stang(1989) who demonstrated that with continuous aligned fibers, high tensile ductility hundreds of times that of normal concrete can be attained. The modern day version of continuous fiber reinforcement is represented by textile reinforced concrete materials that may be prestressed (Reinhardt et al, 2003; Curbach and Jesse, 1999). Research on continuous fiber reinforced concrete was pioneered by Mobasher et al (2006).Developed in parallel, the use of discontinuous fibers at high dosage (4-20%) such as in cement laminates (Allen, 1971) and in SIFCON (Slurry Infiltrated Fiber Concrete (Lankard, 1986; Naaman, 1992) has resulted in concrete composite materials that attain higher tensile strength than normal concrete and which are not as brittle, but with much less ductility than their continuous fiber and textile reinforced counterparts. These materials may be considered a class of materials separate from FRC in that different degree of tensile ductility is achieved, often accompanied by a strain hardening response distinct from the tension-softening response of FRC. Naaman and Reinhardt (2003) classified such material as High Performance Fiber Reinforced Cementitious Composites (HPRCC). It

should be noted that most members of this class of material have a matrix that does not contain coarse aggregates, and should therefore be regarded as fiber reinforced cement pastes or mortars.

1.7 ADVANTAGES OF SHCC

Some of the advantages of strain-hardening cement based composites which make the materials to be effective in use for retrofitting are as follows.

1.7.1 Self-healing behavior of SHCC

Strain-hardening cement based composites the amount of cementitious materials is very high and some of this cementitious composites remain unreacted during hydration. In the presence of water unreacted cement particles recently exposed due to cracking hydrate and form a number of products Calcium Silicate Hydrate, calcite, etc. that expand and fill in the crack. This self-healing behavior not only seals the crack to prevent transport of fluids, but mechanical properties are regained Ingress retardation may lead to a major enhancement of structural life, or reduced life cycle cost. This micro cracking behavior leads to superior corrosion resistance the cracks are so small and numerous that it is difficult for aggressive particles to penetrate and corrode the reinforcing steel.

1.7.2 Strain hardening mechanism of SHCC

Strain-hardening cement-based composites which are a type of FRCC exhibit unique property. When the strain is applied to the composite the fibers create many micro cracks with a very specific width, rather than a few very large cracks as in conventional concrete. Due to the fiber-bridging action of fine multiple cracks, made possible by the even distribution of the fibers. These mechanical characteristics result in tensile strain hardening after the first cracks appear and result also in a high level of ductility. This allows SHCC to deform without catastrophic failure.

1.7.3 Flowability of SHCC

In strain-hardening cement-based composites the materials used for the development of this composite are fine where as coarse aggregates are not generally used in the development of SHCC. Due to the fineness and the ball bearing action of the fine particles the composite has the ability to flow in small creep without any vibration, filling the cracked and damaged part of the structure and regaining the lost strength of the structural member.

1.8 APPLICATION OF SHCC

SHCC has been applied to the newly constructed structures making use of its excellent mechanical and durability performance. It has also been used for the repair of existing structures making use of its finely distributed cracks nature. The appropriate use of the tensile performance of SHCC in concrete structure can enhance both structural and durability performance. Areas where SHCC can be applied are as follows

1.8.1 SHCC dampers

SHCC dampers used for increasing structural safety by reducing response drift of the first story as well as increasing structural resilience by reducing structural damage. The SHCC damper is a SHCC short column reinforced with steel bars that has very high strength, stiffness and ductility compared with conventional RC columns with the same configuration and bar arrangement. SHCC devices are confirmed to have significant potential as a new structural technology for structural safety and damage mitigation. These SHCC dampers were developed after the 1995 Kobe earthquake in Japan

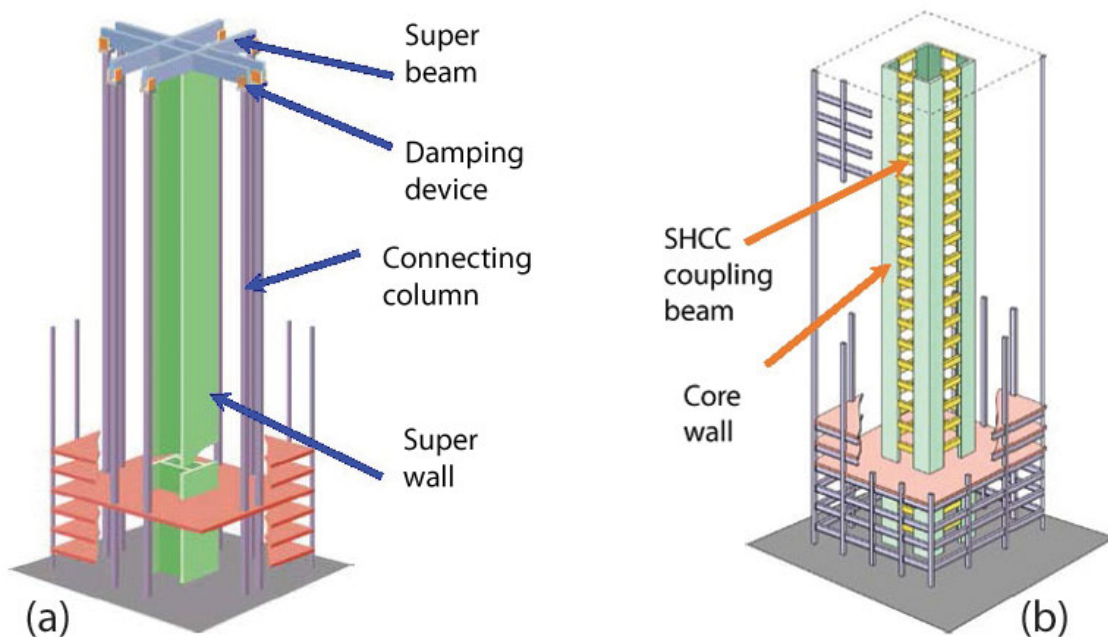


Figure 1.2: Damper made up of SHCC (Toshiyuki 2012)

1.8.2 Tensile resistance for deck slabs

SHCC with excellent crack width control capability and tensile resistance capability works satisfactorily if undergone a large tensile strain. In the hybrid floor, thickness of ECC was

restricted as thin as 40mm to avoid a dead load increase and integration with the steel deck must be done within the limited thickness. This work was realized at the Mihara Bridge Single cable stayed bridge of 972m long, Ebetsu city, Hokkaido prefecture, Japan.



Figure 1.3: The Mihara bridge Japan uses a steel/SHCC composite deck (Victor 2006)

1.8.3 Joints and overlay applications

SHCC was used for coating cracked concrete surface. In coatings on cracked concrete surface, crack opening displacements in the substrate might lead to local stress concentration and cracking within the covering layer. However, repair layers made of SHCC appear to be comparably resistant to such loading conditions. Because of their high deformability these materials are capable of bridging cracks in the substrate. An SHCC with a maximum aggregate size of 0.5mm and a PVA fiber content of 2.2% by volume has been chosen. At first, the crack bridging capacity of this material was investigated in laboratory experiments. The application of the SHCC repair layer, the beam was subjected to bending again and it was found that the repair layer could bridge the distinct cracks being opened in the substrate.

1.8.4 Ductility shear walls

RC Shear wall is an effective element for seismic retrofit to increase only capacity of RC buildings. However, if wall, the seismic retrofit with them will be much more effective to increase structural safety by increasing capacity and ductility. Fukuyama et al introduced one type of ductile shear wall which is consisted with a couple of SHCC dampers and experimentally investigated that this wall exhibited high strength and high ductility.

1.8.5 Tensile performance for tunnel linings

This method was applied to the emergency recovery construction of the Ten-nou tunnel of JR Joetsu line damaged by the Niigata Chuetsu Earthquake. The Ten-nou tunnel suffered considerable damages in lining concrete such as cracks and flaking and the SHCC liner construction was applied to particularly damaged sections of total 37m long. Hence thin inner reinforcing construction method with compressive and tensile resistance, safety and cost effectiveness is needed.

1.9 MATERIALS USED FOR MAKING SHCC

A wide range of fine aggregates i.e. fine sands, waste material and industrial by-products may be used to produce desired Strain-hardening cement-based composites mixes. An aggregate used in SHCC does not require any codes as required in normal concrete but aggregate should be free of reactive or expansive materials. Coarse aggregates are not normally included in SHCC. Where filler is used to improve flowability it should be noted that early strength may be reduced. The cement-based matrix has been composed of Portland cement, fly ash, siliceous sand and a super plasticizer.

1.9.1 Fiber

Special type fiber namely polyvinyl alcohol (PVA) fibers have been used in the study. They are specifically designed for use in concrete products for the purpose of controlling plastic shrinkage, thermal cracking and improving abrasion resistance. When added to concrete or mortar, the fibers develop a molecular and chemical bond with the cement during hydration and curing the result concrete with high tensile strength and amazing ductility. Since fibers are much more expensive than cement, sand or water, it is imperative to minimize the amount of fibers used while maintaining the strain-hardening property. The critical fiber volume fraction can be determined based on knowledge of fiber, matrix and interface properties. Using fiber content below this critical value will lead to normal FRC tension-softening behavior. On the other hand, using fiber content greatly in excess of this critical value leads to not only high cost of material, but also creates difficulties in material processing. Since fibers can be premixed in a conventional manner, the concept of PVA fiber concrete has added an extra dimension to concrete construction.

Tavakoli (1994), performed experiments on concrete specimens reinforced randomly with PVA fibers. The results showed that compressive strength did not change significantly, but tensile strength had an increase of about 80%.

Patel et al., (2012), Strength enhancement in splitting tensile strength due to PVA fibers addition varies from 5% to 23%. Split tensile strength at 28 days is approximately 50% higher than 7 day's strength

1.9.2 Ground granulated blast furnace slag

Ground Granulated Blast Furnace Slag (GGBS) is a by-product of manufacturing of iron in a blast furnace where iron ore, lime stone and coke are heated up to 1500°C. When these materials melt in the blast furnace, two products are produced – molten iron and molten slag. The molten slag is lighter and floats on the top of the molten iron. The molten slag comprises of mostly silicates and alumina from the original iron ore, combined with some oxides from the limestone. The process of granulating the slag involves cooling the molten slag through high pressure water jets. This rapidly quenches the slag and form granular particles generally not larger than 5mm in diameter. The rapid cooling prevents the formation of larger crystals and the resulting granular material comprises some 95% non crystalline calcium aluminosilicates.

1.9.3 Flyash

Fly ash is the residue obtained from combustion of pulverized coal collected by the mechanical or electrostatic separators from the fuel gases of thermal power plants. Its composition varies with the type of fuel burnt, load on boiler and type of separator etc. Fly ash consists mainly of spherical glassy particles ranging from 1 to 150 micro-meters in diameter, out of which the bulk passes through a 45 micro-meter sieve. The fly ash obtained from electrostatic precipitators is finer than Portland cement. The carbon content in fly ash should be as low as possible, whereas the silicon content should be as high as possible. The fly ash may be used in concrete either as an admixture or in part replacement of cement. The pozzolanic activity is due to the presence of finely divided glassy silica and lime, which produce calcium silicate hydrate (CSH) responsible for strength development. Due to the difference in densities of cement and fly ash, a part replacement by equal mass increases the volume of cementitious material; whereas replacement by equal volume reduces the mass in practice the replacement of cement by fly ash is usually on the mass basis.

1.10 AIM OF THE STUDY

The primary object of the work is to develop strain hardening cement-based composite (SHCC) using PVA fibers and by partial replacing of flyash with ground granulated blast furnace slag (GBBS). The compressive strength, tensile strength and durability property of the developed SHCC are tested against the requirements of a material for effective retrofitting.

1.11 OUTLINE OF THESIS

The thesis has been divided into five chapters:

- 1st chapter introduces o the concept and need of retrofitting and strain hardening cement composites.
- 2nd chapter presents the literature review of the research work conducted on use of different retrofitting materials and on strain hardening cement composite.
- 3rd chapter deals with the experimental program wherein the materials used and the respective test procedures are explained in detail.
- 4th chapter deals with the results and discussions where findings of experimental program are discussed.
- 5th chapter provides the conclusion of the research work undertaken.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

This chapter presents a review of literature highlighting the work done by various researchers with regards to the mechanical and durability properties of Strain-hardening cement-based composites SHCC. As emerging construction material Strain-hardening cement-based composites has seen increasing field applications in the recent years. Reliable data on tensile properties, including tensile strength and tensile strain capacity are needed for structural design and for quality control. They named after their ability to resist increased tensile force after crack formation, over a significant tensile deformation range. The increased resistance is achieved through effective crack bridging by fibers, across multiple cracks of widths in the micro-range. Whether these small crack widths are maintained under sustained, cyclic or other load paths, and whether the crack width limitation translates into durability through retardation of moisture, gas and other deleterious matter ingress.

2.3 LITERATURE REVIEW ON DEVELOPMENT OF SHCC

Gideon et al. (2006) investigated the shear behavior of Strain-hardening cement-based composites. The cracks formed in the experiment were restricted to small widths. Strain-hardening cement-based composites make use of fibers to bridge cracks, whereby they are controlled to small widths over a large tensile deformation range. The shear strength of SHCC has been shown to exceed its direct tensile strength by up to 50%. A mechanism of this increased resistance has been argued to be the ability of SHCC to maintain its tensile resistance well beyond its first cracking strain, allowing principal stress rotation and accompanied increased compression upon shear load increase.

Faiz and Hirozo (2006) investigated the various durability properties of strain hardening fiber reinforced cementitious composites. The test data indicated that SHFRCC exhibits excellent durability properties. The SHFRCC specimens showed closely spaced microcracks with crack widths of approximately 0.060 mm, the permeability of these cracked materials was then determined under hydraulic head. The result shows a dramatic rise in permeability with increasing crack width and superior protection of steel against corrosion in reinforced

concrete. The strain hardening and multiple cracking behaviors, together with very small crack width properties, provide very low water and chloride permeability which retards the onset of corrosion of reinforcing steel in reinforced concrete.

Qian et al. (2009) studied the self-healing behavior of a series of pre-cracked fiber reinforced strain hardening cementitious composites incorporating blast furnace slag and limestone powder with relatively high water/binder ratio in this paper, focusing on the recovery of its deflection capacity. Four-point bending tests are used to pre crack the beam at 28 days. For specimens submerged in water, the deflection capacity after self-healing can recover about 65–105% compared with those virgin specimens, while this ratio is about 40–60% for air cured specimens. Furthermore, the stiffness of initial linear stage of self-healed specimen is much larger compared with that of the air cured specimen due to the presence of healing products formed inside the crack and strengthened the bridging fiber. The observations under ESEM and XEDS confirm that the micro cracks submerged in water were healed mainly with calcium carbonate. ESEM also suggests that the healing products grow from both faces of the crack towards the middle of the crack This may be explained by the relatively high concentration of calcium hydroxide near the crack surface via diffusion process from the bulk cementitious material Self-healing behavior in SHCC heavily depends on the availability of unhydrated cement and other supplementary cementitious materials, such as BFS. Low water/cementitious material ratio and high percentage of cementitious material appear to promote self-healing behavior. Micro crack with smaller crack width as in the SHCC mixtures is preferable as far as continuous hydration-based self-healing is concerned, as it requires much less healing products to fill the crack and much easier for the healing products to grow from both faces of the crack to get connected.

Mechtcherine et al. (2009) investigated on the behavior of strain hardening cement-based composites when subjected to cyclic tensile loading. Uniaxial tensile tests on unnotched, dog-bone shaped prisms containing 2.25% by volume of polymeric fiber were performed using both a deformation and load control testing. The composition for the SHCC mix used for the experiments is shown in **Table 2.1** as follows

Table 2.1: Mix design of SHCC (Mechtcherine et al 2009)

Cement [kg/m ³]	Flyash [kg/m ³]	Silica sand [kg/m ³]	Water [kg/m ³]	SP [kg/m ³]	VA [kg/m ³]	PVA Fibers [kg/m ³]
321.0	749.1	535.0	334.5	16.6	3.2	29.3

In the deformation controlled regime, the repeated loading caused a decrease in the tensile the monotonic tests. However, there was no pronounced effect on the strain capacity of the material for the relatively small number of loading cycles applied. There was no effect observed on the strain capacity from repeated loading for the tests on small specimens using a load control regime. The number of cracks, as well as the crack widths, as observed on the specimen's surfaces did not vary much given the different loading conditions. The cracked specimens tested under the load control regime were more prone to failure at lower strain levels. The tensile strength results of the specimen are shown in **Table 2.2** below

Table 2.2: Compressive strength of SHCC (Mechtcherine et al 2009)

Type of loading	Tensile strength f_t [MPa]	Strain capacity ϵ_{tu} [%]
Monotonic, deformation Controlled	3.6	2.5
Cyclic, deformation Controlled	3.9	2.4
Cyclic, load controlled	3.4	2.4

Mechtcherine et al. (2010) studied the behavior of strain hardening cement composite when subjected to low and high strain rates on uniaxial tension test on dumbbell shaped samples. SHCC test for strain capacity 10^{-5} s^{-1} and below showed a moderate increase in tensile and simultaneous decrease in strain capacity with increase in strain rate. Also the number of cracks in the composite failure decreased as the strain rate increased and a predominance of fiber was observed under high strain rate.

Choi et al. (2011) used the recycled materials to develop sustainable strain-hardening cement-based composite exhibits desirable mechanical properties, including strain hardening and ductility. However, SHCC is composed of silica sand and a high volume of cement,

which makes it more energy intensive than conventional concrete. Use of alternative recycled materials – sand, fly ash, and polyethylene terephthalate (PET) fibers are used to partially replace silica sand, cement, and polyvinyl alcohol (PVA) fibers, respectively in SHCC specimens. The effects of the recycled materials on the mechanical behavior of the SHCC specimens are examined by conducting compressive tests, four-point bending (flexural) tests, and uniaxial tensile tests. To determine the mechanical properties, a cylindrical specimen 100×200 mm and flexure beam 100×100×400 mm were used for the compressive strength and flexure beam test and a dumbbell-shaped specimen was prepared for the uniaxial tensile strength test. Test results indicate that fly ash improves both the bending and uniaxial tensile performance of SHCC due to an increase in chemical bond strength at the interface between the PVA fibers and cement matrices. Also, it is noted that recycled sand increases the elastic modulus value of SHCC due to its larger grain size compared to that of silica sand.

Table 2.3: Compressive strength of SHCC (Choi et al 2011)

SHCC	F _{cu} (MPa)
PVA2.0	23.11
PVA2.0 a30	23.53
PVA2.0 a50	24.80
PVA2.0 FA20	18.30

The control specimen, PVA2.0, has a compressive strength of 23.48 MPa. Similarly, the compressive strength values for the specimens replaced with PET fiber and recycled aggregate are 23.11–26.01 MPa, respectively. The test results show that compressive strength is not affected by replacement with PET fiber and recycled aggregate. However, the compressive strength values decreased 21.1% and 23.5% for the specimens replaced with fly ash. This decrease in compressive strength values results in a low strength development for flyash concrete in its early stages. In particular, the high volume of fly ash in SHCC exaggerates the low strength development in the early stages. This result indicates that an adequate curing method and mix design for SHCC with fly ash is needed in order to attain the desired compressive strength. Also the replacement of cement with flyash shows the carbon dioxide emission of specimen PVA2.0 is similar to that of the SHCC that includes recycled aggregate or PET fiber. The replacement fly ash in SHCC reduces carbon emissions by 20%.

Yao et al. (2011) studied the effect of free drying shrinkage of Strain Hardening Cement-based Composites. The influence of fly ash, ground granulated blast furnace slag, expansive admixtures, shrinkage reducing admixtures, a combination of coarse sand and stone powder, and a superabsorbent polymer on drying shrinkage and on mechanical properties of SHCC have been investigated. Experimental results have shown that shrinkage of SHCC decreased by approximately 25 %, if Portland cement is replaced by 80 % instead of 50 % of fly ash. On the contrary shrinkage slightly increases with increasing content of GGBS. Shrinkage of SHCC containing GGBS is larger than shrinkage of SHCC containing fly ash. Shrinkage evolution can be substantially delayed by the addition of superabsorbent polymer. Superabsorbent polymer added to SHCC may act as artificial flaws in the cement-based matrix, which may trigger initiation of cracks. In this way ductility of SHCC can be improved significantly. Expansive admixtures, shrinkage reducing admixtures and a combination of coarse sand and stone powder can reduce free drying shrinkage of SHCC significantly. Addition of inert particles seems to be the most promising alternative to reduce shrinkage strain. But the partial replacement of cement with ground granulated blast furnace slag showed increase in the mechanical properties of the compound when compared with the partial replacement of fly ash hence effective replacement of both fly ash and ground granulated blast furnace slag can help in increasing the mechanical properties as well as help in reducing the shrinkage.

Hakan et al. (2013) preformed the effects of fiber volume fraction and matrix properties on the mechanical performance of 15 mm thick short cut PVA fiber-reinforced cementitious composites. Fiber volume ratios of mixtures varied between 0.5 and 2.0% by volume and two different water to cement ratios have been used 0.25 and 0.35 for production of matrix. Test results providing good compaction and dispersion of fibers, increasing PVA volume fraction has a positive effect on the compressive strength of composites also the fiber content and matrix strength should be optimized in accordance with the desired performance. Under flexural loads, higher peak loads are reached for lower water to cement ratio mixtures. On the other hand, higher mid span deflections can be reached for higher water to cement ratio mixtures. The Figure below shows the flexural strength of the various mixes

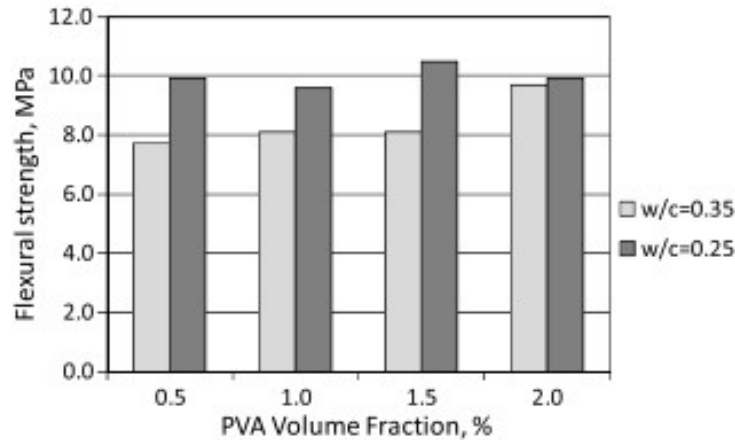


Figure 2.1: Flexural strength results of mixtures (Hakan et al 2013)

Magalhaes et al. (2015) investigated on the influence of pre-heating on the mechanical behavior of PVA strain hardening cement-based composites (PVA-SHCC) by using uniaxial tensile, bending and compression tests. Tests were conducted on specimens that were previously heated to temperatures ranging from 90°C to 250°C and unheated specimens. The temperatures were selected based on the results of thermal analyses tests carried out to investigate the thermal degradation of the PVA fiber. The study showed that temperature affects the mechanical properties of SHCC after exposure to temperatures up to 250°C. The deterioration of the composite was observed in terms of reduced stiffness, tensile strength, ductility and several changes in the cracking pattern. At 90°C the residual tensile properties are slightly altered. However, the toughness and crack density were reduced as compared to unheated specimens due to changes in fiber microstructure. Heating to 110°C showed similar tendencies as specimens heated to 145°C. However, the specimens exhibited only one single crack and the maximum post-cracking tensile stress, strain capacity and toughness were strongly reduced, while the first-cracking strength was slightly increased. At temperatures of 250°C the composite loses load-bearing capacity in the post-cracking stage, due to the melting and decomposition of PVA fiber. In this case, the composite is therefore considered to be a quasi-brittle material with strain softening behavior with reduced strain capacity (about 92%), toughness and post-cracking tensile stress. Regarding the bending performance, the tendency was similar as reported in tensile tests. The results also indicated that there are relatively good correlations between the results of bending and uniaxial tension tests. Compressive strength of the composite has indicated an increase up to 190°C due to a refinement of the matrix pore structure as indicated by the micro structural studies.

Huang et al. (2015) created strain hardening cement composite modal of fiber bridging to account for fiber tensile rupture at the pullout stage and two-way fiber pullout induced by both the slip-hardening interface behavior and the chemical bond and fiber tensile rupture at the debonding stage. The corresponding crack opening tends to be more easily affected by the fiber-pullout rupture. It was also found that a higher tendency of fiber-debonding rupture tends to raise this critical value.

Slowik et al. (2015) preformed comparative mechanical tests on Strain hardening cement based composite in laboratories. The purpose was to investigate and compare the crack patterns in terms of crack widths and spacing. The procedure was to use a base SHCC mix with 2 % by volume polyvinyl alcohol (PVA) short fiber for prepare the specimens. Finally, two types of SHCC were tested. One containing sand aggregate with maximum particle size less than 0.3 mm, and other prepared with coarse sand SHCC. Uniaxial tension tests on the specimens in setups developed by the laboratory. Suggested strain levels were 0.2, 0.5, 1 %, and subsequent 0.5 % intervals up to ultimate tensile strain. Stress strain results for tensile test are shown

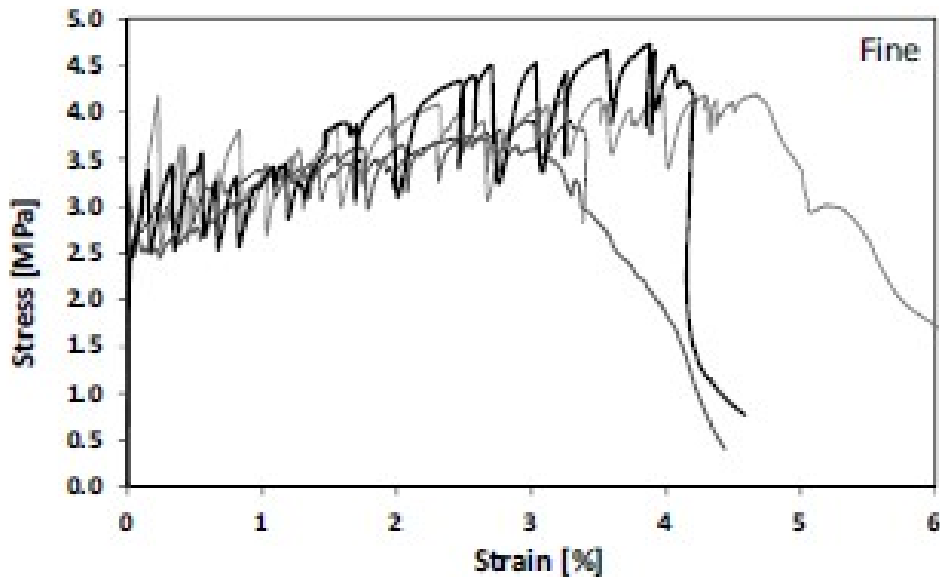


FIG 2.21: Stress Strain graph for SHCC containing fine sand (Slowik et al 2015)

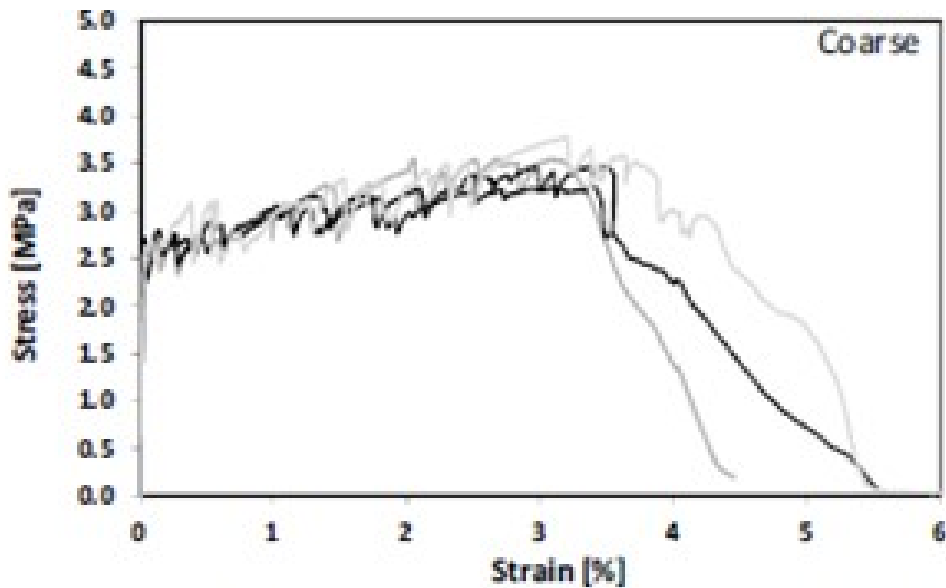


FIG 2.3: Stress Strain graph for SHCC containing coarse sand (Slowik et al 2015)

SHCC can be prepared from natural sand containing particles of size up to 1–1.2 mm, although a lower ductility and lower ultimate tensile strength than for specimens containing only fine sand with maximum particle size 0.2–0.3 mm have been found and the average crack width is stabilized in the range of 40–80 μm for a large range in tensile deformation, the maximum crack width may exceed 100 μm at a strain of 0.5 %, and reach beyond 200 and 250 μm at strains of 2 and 3 %, respectively. Crack spacing appears to stabilize at roughly 3 % average tensile strain for the SHCC tested here.

Zhiming et al. (2015) performed the study to evaluate the effect of applied loads on water and chloride penetrations of SHCC. The capillary absorption test was carried out under loading and after unloading, and then the water and chloride penetrations were evaluated. Under uniaxial tensile loading, more passageways are provided for the water and chloride penetrations of SHCC after cracking. The results drawn show that the absorbed water amount and chloride content increase with the increase in tensile strain.

Ahmed and Khalil (2015) investigated the use of cementitious repair materials for the compression side of over-reinforced concrete beams to change their failure mode to ductile failure strengthening material was an ultra-high-performance strain-hardening cementitious composite. The specimens with a UHP-SHCC strengthening layer at the compression zone experienced ductile failure with increased flexural crack depths up to 95% of the beam depth.

Repairing beams that fail in the compression side using a UHP-SHCC layer after removing the crushed concrete enhances the beam's carrying capacity by increasing its failure load and deformation and a considerable increase in ductility was achieved by providing over-reinforced concrete beams with a UHP-SHCC layer in the compression zone this increase ranges from 16.5 to 135% depending on the configuration of the UHP-SHCC layer.

Mo and Victor (2012) investigated the correlation between the rheological parameters of ECC mortar before adding PVA fibers, dispersion of PVA fibers, and ECC composite tensile properties. The correlation between Marsh cone flow rate and plastic viscosity was established for ECC mortar. The experimental program consists of three sets of investigations. First, the fresh viscosity and flowability and tensile strength of six ECC mortar mixes with the same mix design except for the different fiber ratio. The results on tensile strength and flowability are shown below

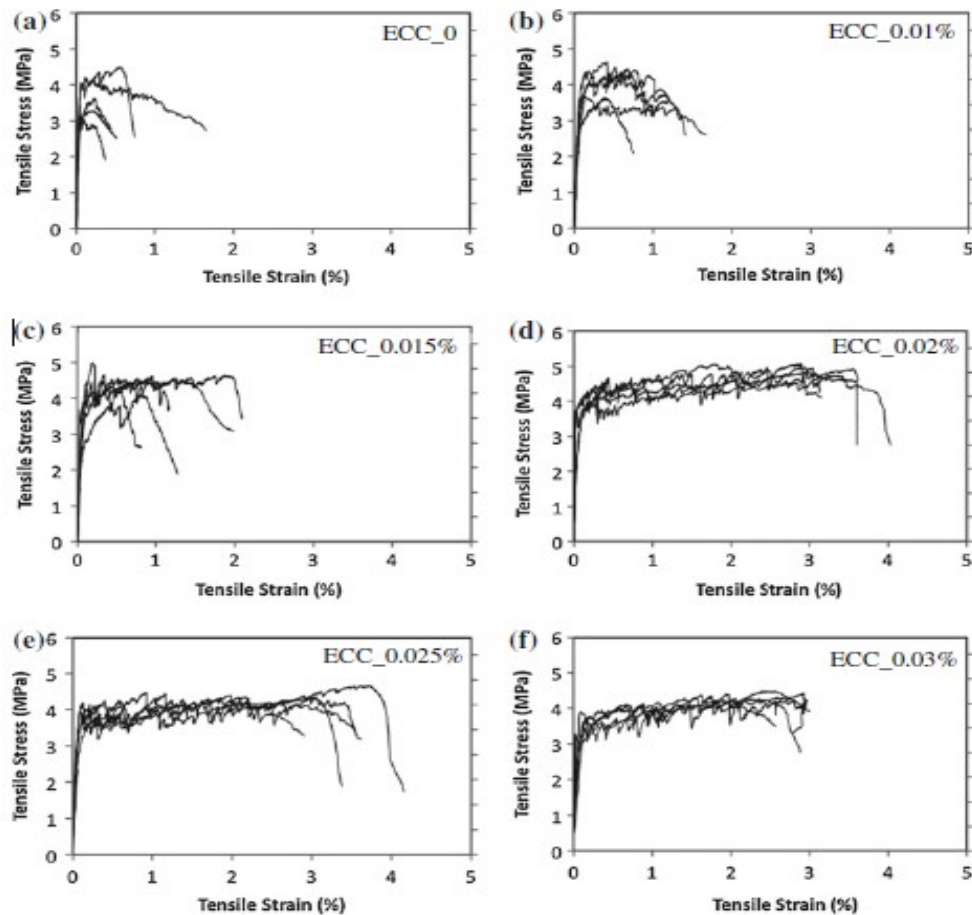


Figure 2.4: Tensile stress versus strain curves of ECC with different fiber content (Mo and Victor 2012)

And also the plastic viscosity of general ECC mortar before adding fibers so that maximized the fact that the optimal amount of fiber varies for different ECC mix compositions.

2.3 LITERATURE REVIEW ON RETROFITTING

Kondraivendhan and Pradhan (2009) studied effect of ferrocement confinement on behavior of concrete. The effect of different grades of concrete confined with ferrocement was studied by keeping all other parameters constant. In this investigation, concrete mixes had been chosen over a wide range of grades of concrete, namely M25, M30, M35, M40, M45, M50 and M55. The M25, M30, M35, M40, M45, M50 and M55 have a characteristic compressive strength of 25N/mm^2 , 30 N/mm^2 , 35 N/mm^2 , 40 N/mm^2 , 45 N/mm^2 , 50 N/mm^2 and 55 N/mm^2 , respectively. A total of 42 cylindrical specimens (21 each for controlled and confined specimens) with a diameter of 150 mm and a height of 900 mm, three replicates for each grade of concrete, were cast. Column specimens of size 150mm x 900mm with different grade of plain cement concrete were casted and then confined with ferrocement. It was found that with the increase in compressive strength of the concrete significantly improved in lower grades of concrete such as M25 which showed 78% increase as compared to higher grade of concrete M55 which resulted in an increase of 45.3%.

Lee et al. (2009) proposed an effective rehabilitation strategy to enhance the strength and stiffness of the beam–column joint in this study. An analytical model is proposed to predict the column shear of the joints strengthened with carbon fiber reinforced polymer (CFRP). Three full scale interior beam–column joints, including two specimens strengthened with CFRP and one prototype specimen, are tested in this study. The specimens are designed to represent the pre-seismic code design construction in which there is no transverse reinforcement. A new optical non-contact technique, digital image correlation (DIC), which can measure the full strain field of specimen, is used to measure and observe the full strain field of the joint. The experimental results show that the beam–column joints strengthened with CFRP can increase their structural stiffness, strength, and energy dissipation capacity. The rehabilitation strategy is effective to increase the ductility of the joint and transform the failure mode to beam or delay the shear failure mode. By observing the measured results, it is found that the mechanical anchorages can prevent the debonding of CFRP. Comparing the analytical and experimental results, the proposed model can accurately predict the column shear and shear strength of the joints strengthened with CFRP.

Esmaeli et al. (2014) assessed the effectiveness of a repair strategy, for damaged RC beam–column joints, that combines strain hardening cementitious composite (SHCC) and laminates of carbon fiber reinforced polymers (CFRP laminates). According to this technique, the existing concrete cover in the joint zone of the frame is replaced by a self-compacting SHCC. This thin layer of SHCC is reinforced with CFRP laminates that are bonded into the saw cut grooves. Two full-scale severely damaged interior RC beam–column joints were retrofitted using two different configurations of this technique: (i) applying the strengthening system to only the front and rear faces of the specimen; (ii) jacketing all sides of the elements of the specimen with the strengthening system. The effectiveness of these retrofitting configurations is assessed and compared by evaluating experimentally the hysteretic response, the dissipated energy, the degradation of secant stiffness, the displacement ductility and the failure modes of each repaired specimen, and also using the values of these indicators obtained in the virgin state of the specimens. This comparison revealed that the adopted retrofitting strategies can restore and even enhance the performance of this type of structural elements, mainly when the solution based on four-sided jacketing is used.

2.4 SUMMARY OF LITERATURE REVIEW

The studies discussed so far describe such retrofitting techniques, to improve and strengthen the beam, column and beam column joints which makes use of different materials such as ferrocement, steel jacketing, FRP etc. These materials improve the durability and stiffness of beam-column joints and help them to restore to their virgin state. In addition to all these materials, which have successfully been used for retrofitting purposes, experiments are being conducted to develop new class of material composites. As can be seen from the review very less work has been done to check the effectiveness of use of Strain Hardening Cementitious Composites (SHCC) as a retrofit material. SHCC, as can be observed from the review, exhibits high tensile strength and improves the strength of structure and can help restore the structural system to its pre-defined state.

CHAPTER 3

MATERIALS AND METHODS

3.1 GENERAL

The aim of this work is to optimize the mixture proportions of SHCC using various industrial by-products as fillers and cementitious materials. An effort has been made to generate a mix of SHCC by replacing building materials with industrial by-products. The objective is to obtain a SHCC that satisfies the desired strength and durability properties.

In its fresh state SHCC must possess flowability, consistency and density while avoiding heavy bleeding as well as any significant segregation. Flowability is particularly an important aspect of SHCC as it allows the materials to be self-compacted, so that it can readily flow into and fill the voids. The consistency of the mix is equally important. This aspect will heavily depend on the quantity of fines present in the mix. The finer a material is the greater is the surface area to volume ratio, which means there is more surface area available to hold and absorb water in the mix. Fineness is measured in terms of surface area per unit mass.

The objective is to develop a mix with sufficient compressive and tensile strength which would meet the requirements of a strain hardening cement based composite.

3.2 MATERIALS

The basic materials for a SHCC mix are cement, fine aggregate, flyash, fibers, superplasticizer and water. The coarse aggregates are generally not used in SHCC mixes due to the requirement of flowability in small voids. In this study, Ground Granulated Blast-Furnace Slag (GGBS) were used as partial substitute of Fly Ash (FA). The basic properties of all the materials are discussed here under.

3.2.1 Cement

Cement is a binding material that sets and hardens when water is added to it causing initiation of hydration reaction, which further results into formation of CSH gel around other particles which acts as link between them and can bind them together. Other supplementary cementing materials can also be used with cement but cement is considered necessary component for the initiation of the hydration reaction without which other pozzolonas cannot show any binding property.



Figure 3.1: OPC Cement used in the study.

In the present study, 43-grade Ordinary Portland Cement (OPC) manufactured by JK Lakshmi Cement Company was used. **Figure 3.1** shows the cement used for developing different mixes.

Various physical properties of cement are shown in **Table 3.1**. It can be observed from the table that the physical properties of the cement complies with the specifications of IS 8112: 1989. The ordinary cement contains two basic ingredients namely argillaceous and calcareous. In argillaceous materials clay predominates and in calcareous materials calcium carbonate predominates. The chemical composition of cement used is presented in **Table 3.2**

Table 3.1: Physical properties of cement used in the study.

Property	Value	IS 8112:1989 Specifications
Grade	OPC-43	OPC-43
Specific Gravity	3.14	3.10-3.25
Initial Setting time	52 minutes	30 minutes, minimum
Final Setting time	174 minutes	600 minutes, maximum
Blaine Fineness	3250 cm ² /g	2250 cm ² /g
28-Day Compressive Strength	47.3 MPa	43-58 MPa

Table 3.2: Chemical composition of cement observed present study.

Constituent	Cement Used	IS 8112:1989 Specifications
CaO	63.49 %	-
SiO ₂	21.25 %	-
Al ₂ O ₃	4.74 %	-
Fe ₂ O ₃	4.30 %	-
SO ₃	2.92 %	Max. 3.5%
MgO	1.02 %	Max. 6%
K ₂ O	0.78 %	-
TiO ₂	0.36 %	-
BaO	0.32 %	-
Na ₂ O	0.30 %	-
P ₂ O ₅	0.21 %	-
Cl	0.09 %	Max. 0.1%
MnO	0.08 %	-
SrO	0.04 %	-
Ratio of alumina to iron oxide	1.12	Min. 0.66%

3.2.2 Flyash

Fly ash is a finely divided residue that results from the combustion of ground or powdered coal and that is transported by flue gases in the thermal power plant. Coal burning power plants annually produce millions of tons of FA as a waste product world-wide. According to ACI 229R (1999), Fly ash used in production of SHCC mixes do not need to conform to either class F or C as described in ASTM C 618 (2003). In the present study fly ash obtained from Guru Nanak Thermal Power Plant, Bathinda, Punjab was used as a partial replacement of cement. It is acidic in nature and its main constituents are silica, aluminium oxide and ferrous oxide. Fly Ash used in this study is shown in Figure 3.2 The fly ash was having specific gravity of 2.36 and a fineness value of 3527 cm²/g. The fly ash particle size 50µm used in the study. Various physical properties and constituents found in the fly ash are given in **Table 3.3** and **Table 3.4**

Table 3.3: Physical properties of fly ash used.

Physical properties	Value
Colour	Whitish grey to grey with slight black
Bulk density	1120 kg / m ³
Specific gravity	2.36
Fineness	3527 cm ² /gm

Table 3.4: Chemical composition of fly ash used.

Constituent	Class F Fly ash (%)	ASTM C 618 (2003):Requirements
SiO ₂	68.95	-
Al ₂ O ₃	17.41	-
Fe ₂ O ₃	1.28	-
SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃	87.64	70 minimum
CaO	9.04	-
MgO	3.17	5 maximum
Na ₂ O	0.15	1.5 maximum



Figure 3.2: Fly Ash used in the study

3.2.3 Grand Granulated Blast furnace Slag

GGBS is a by-product obtained from the blast furnace in the production of iron, copper and steel. When molten slag is quickly quenched from a high temperature with water in pond or powerful water jets, most of the lime, magnesia, silica and alumina are held in non-crystalline or glassy state. This GGBS should be finely grounded into particle size of less than $45\mu\text{m}$ to be used for replacing cement. GGBS is commonly used as a cementitious material and may be used as substitute of Portland cement from 10% to 90% (Buokini et al. 2009) to enhance the workability and durability properties. GGBS was used in the design mix as replacement material for fly ash to study its effectiveness for development of SHCC. As shown in **Table 3.5**, GGBS was having a high SiO_2 content of 73.47% and a reasonable content of lime (CaO) as 12.40%.

Table 3.5: Chemical composition of GGBS

Constituent	Composition (%)
CaO	12.40
SiO_2	73.47
Al_2O_3	4.35
SiO_2	5.48
MgO	2.14

Table 3.6 shows the physical properties of the GGBS used in the study which are as follows

Table 3.6: Physical properties of GGBS

Physical properties	Value
Initial setting time	> 1 Hour
Final Setting Time	< 6 Hours
Fineness	4490 cm ² /gm
Specific Gravity	2.9
Bulk Density	650 – 700 kg/m ³
Particle Size Distribution	
< 2.5 microns	10%
< 6 microns	50%
< 12 microns	90%

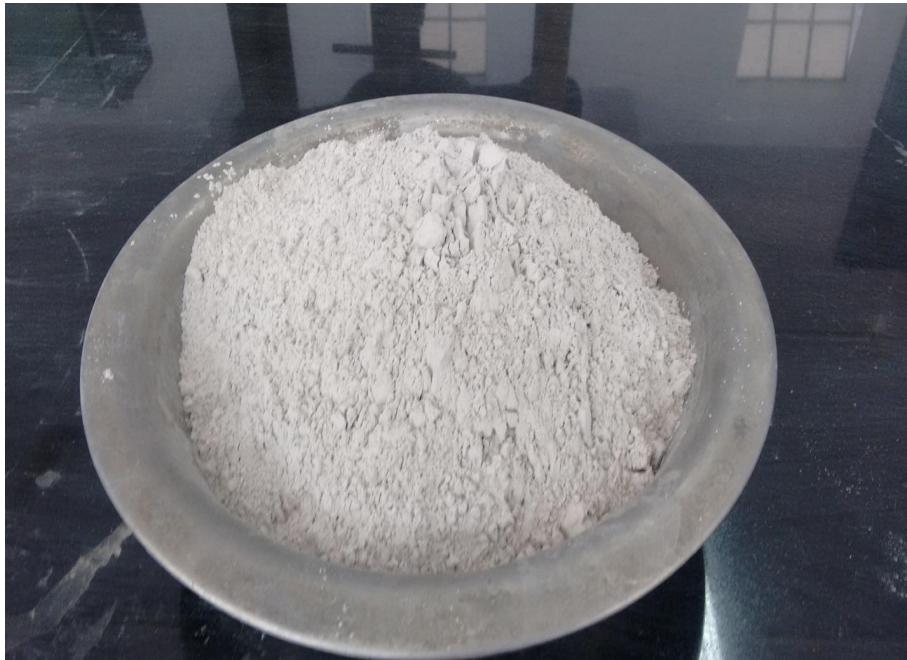


Figure 3.3: GGBS used in the study

In the present study, a product GGBS of Counto Microfine Products Pvt. Ltd. has been used as is shown in **Figure 3.3**. The GGBS was having a specific gravity of 2.9 and Blaines fineness value of 4490 cm²/g. GGBS is always to be used with suitable water reducing agent,

as we know that, the use of blended cement in construction is widely agreed to provide an important benefit of environmental protection.

3.2.4 Fine Aggregates

An important factor considered to control the behavior of SHCC is the type and size of fine aggregates used in the mix. River sand from Pathankot as shown in Figure 3.5 was used as one of the fine aggregates in this study. Sand was classified as fine sand. The sand used in the study was having grain size less than 300 μm , which is conforming to the ASTM C33 (2003). The river sand had a specific gravity of 2.59 and a fineness modulus of 2.45. Fine aggregates were used after oven drying to check the change in moisture content of sand due to various environmental factors. **Table 3.7** shows the properties of the sand used in the present work.

Table 3.7: Properties of sand tested.

S.No.	Tests	Properties	Description	Relevant IS Codes
1.	Grain Size Analysis	Fines, < 75 μ (%)	0	IS 2720 Part IV
		Sand (%)	100	IS 2720 Part IV
		Effective size (D_{10}) (mm)	0.14	IS 2720 Part IV
		D_{30} (mm)	0.17	IS 2720 Part IV
		D_{60} (mm)	0.22	IS 2720 Part IV
		Uniformity coefficient, C_u	1.5	IS 2720 Part IV
		Coefficient of curvature, C_c	0.93	IS 2720 Part IV
2.		Classification	Sand	IS 1498-2007

The grain size distribution of sand is shown in the **Figure 3.4**. It is done to determine the percentage of various grain sizes. The grain size distribution helps in determining the textural classification of sand as well. This is then useful in evaluating the engineering characteristics. IS: 2720- Part IV (2006) is used. The sieves for soil tests used are 4.75 mm to 75 microns for evaluating the and grain size distribution of sand. **Figure 3.5** shows the sand used in the study.

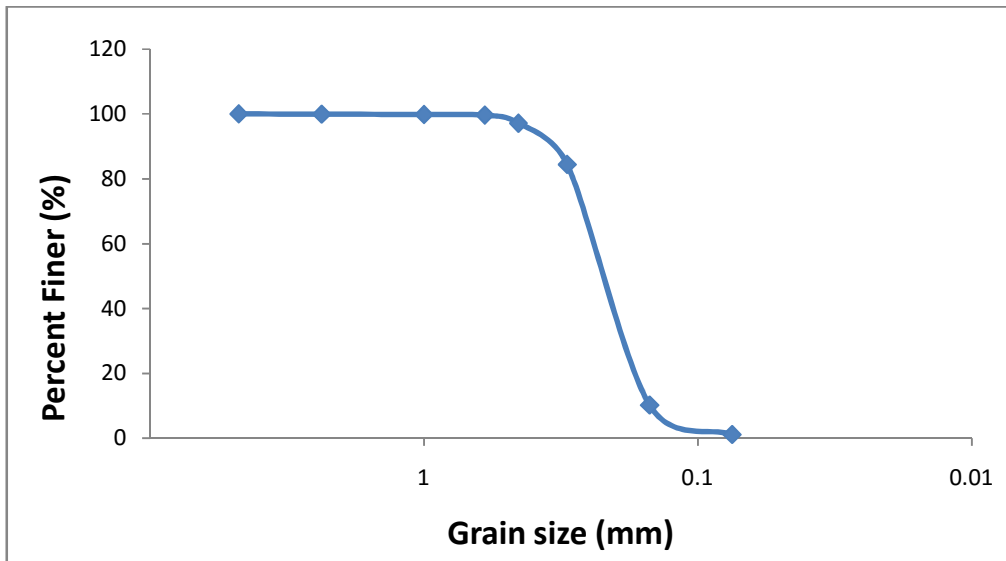


Figure 3.4: Grain Size Distribution of sand.



Figure 3.5: River Sand used in the study

3.2.5 Superplasticizers

Different types of superplasticizers were examined for their effects on mix workability in order to develop SHCC mixes. AURAMIX 300 procured from FOSROC Constructive Solutions was then tested and used in the present study. It is a unique combination of the latest generation superplasticizers and based on a polycarboxylic ether polymer with long lateral chains which greatly improves cement dispersion. It is a high performance retarding

superplasticizers intended for applications where retardation and long workability retention are required. Table 3.8 shows the characteristics of AURAMIX 300.

The optimum dosage of AURAMIX 300 to meet the specific requirement was determined by trials using the constituent materials. The normal dosage ranges between 0.5 to 1.0 ltrs/ 100 kg of cementitious material. In this study, to attain medium workability of the control mix, generally super plasticizers of the amount of 1% of cement content by weight is used. The properties of super plasticizer are provided in **Table 3.8**

Table 3.8: Properties of superplasticizers used in the study

S.No	Characteristics	Values
1	Type	Polycarboxylic Ether
2	Physical state	Liquid
3	Colour	Light Yellow
4	Specific gravity	1.22
5	pH	6
6	Chloride content	Nil

3.2.6 Polyvinyl alcohol fibers

The fibers used in this study were Polyvinyl Alcohol (PVA) fibers. They are specifically designed for use in concrete products for the purpose of controlling plastic shrinkage, thermal cracking and improving abrasion resistance. PVA fibers are unique in their ability to create a fully-engaged molecular bond with mortar and concrete that is 300% greater than other fibers. If the composition of a PVA-fiber reinforced cement-based composite is optimized, strain hardening can be observed instead of the usual strain softening and a strain capacity of up to 6 % can be reached. The specification of the fibers used is given in the table below **Table 3.9**.

Table 3.9: Properties of PVA fibers

Properties	Value
Filament Diameter	8 Denier (38 Microns)
Fiber Length	12mm
Specific Gravity	1.3
Tensile Strength	1600 MPa
Flexural Strength	40 GPa
Melting	225° C
Color	White
Water Absorption	Less than 1 % by weight
Alkali resistance	excellent
Concrete surface	Not fuzzy
Corrosion resistance	excellent

The role of fibers is to reduce the formation of plastic shrinkage cracking, provides multi-dimensional reinforcement, improves impact, toughness and provides better abrasion resistance of concrete. **Figure 3.6** represent the PVA Fibers used in the development of SHCC.



Figure 3.6: PVA fibers used in the study

3.3 MIX PROPORTIONS FOR THE DEVELOPMENT OF SHCC

The performance of the SHCC was to be optimized by varying the quantities of each constituent. Numerous pours had to be carried out for each mix in which the performances and observations were to be recorded. As the pouring program proceeded, subsequent mix designs were then varied depending on the results of the previous pour. This method of optimization is known as “Trial Mixing”. The various base mixes for the development of SHCC were made from the previous research papers and trial and mixing of the materials locally available by determining their properties.

For the development of the SHCC two base mixes were used. The variation in the two mixes was in the amount of PVA fibers which was 2% and 3% of the volume of the cement. In addition to the base mixture three replacements were made in the mixture, flyash was replaced by GGBS in percentages of 10%, 20%, and 30% and the variation in the compressive, tensile strength of SHCC was studied. The cubes, dumbbells were casted for each mix and for each percentage of fibers to determine the compressive and tensile strength after 28 days, respectively.

3.3.1 Base mixes

The base mixes used of two proportions one set of mixes contained 2% of PVA fiber and the other set of mix contained 3% of PVA fiber with the rest of the materials remaining same in both the mixes. The percentage ingredients used in developing the base mix of SHCC is shown in **Table 3.10**.

Table 3.10: Mix proportion for the base mixes of SHCC

TRAIL	C1	C2
CEMENT	1	1
SAND	1	1
FLYASH	1.1	1.1
PVA FIBER	0.02	0.03
SUPERPLASTICIZER	0.01	0.01
WATER	0.78	0.78

3.3.2 Replacement mixes

It included mixes with varying percentage of the replacement of the flyash used in the base mix, by Ground granulated blast-furnace slag. The replacement is done in three variations of 10%, 20% and 30% of the amount of flyash by weight. The percentage variation of ingredients used in developing the SHCC is shown in **Table 3.11**.

Table 3.11: Replacement ratio of mixes of SHCC

Cement	PVA fibers	Sand	Superplasticizer	Water	Flyash	GGBS
1	0.02	1	0.01	0.78	1.1	0
1	0.02	1	0.01	0.78	0.99	0.11
1	0.02	1	0.01	0.78	0.88	0.22
1	0.02	1	0.01	0.78	0.77	0.33
1	0.03	1	0.01	0.78	1.1	0
1	0.03	1	0.01	0.78	0.99	0.11
1	0.03	1	0.01	0.78	0.88	0.22
1	0.03	1	0.01	0.78	0.77	0.33

A uniform workability slump was maintained for all the mixes. The mix proportions for each mix are also shown in **Table 3.12**.

Table 3.12: Mix proportions of SHCC

Cement (kg/m ³)	PVA fiber (kg/m ³)	Sand (kg/m ³)	Superplasticizer (kg/m ³)	Water (kg/m ³)	Flyash (kg/m ³)	GGBS (kg/m ³)
500	10	500	5	390	550	0
500	10	500	5	390	495	55
500	10	500	5	390	440	110
500	10	500	5	390	385	165
500	15	500	5	390	550	0
500	15	500	5	390	495	55
500	15	500	5	390	440	110
500	15	500	5	390	385	165

The mixes were tested in the Structural Laboratory of Thapar University, Patiala. The idea was to get the replacement of conventional construction materials with the industrial by-products and finding the best combination of these materials to make the mix more economical, and environmentally friendly.

Trial mixtures were evaluated to determine how well they meet the requirements for strength, flowability and durability. Adjustments are then made to achieve the desired properties.

3.4 EXPERIMENTAL METHODS USED FOR DEVELOPING SHCC

The primary purpose of this study is to design a set of SHCC mixes using the materials above with a compressive strength of not less than 21 Mpa and not more than 30 MPa at 28-days. The mixes must also have sufficient flowability for a successful concreting operation as well as having moderate effects of bleeding while eliminating the occurrence of segregation. This objective was achieved using trial mixes.

The desired properties of SHCC evaluated as a part of the program include, cylinder flow test, abrasion test, compressive strength and tensile strength in hardened state. Table slump flow test are performed to evaluate the fluidity of the SHCC for its use as a structural fill. Compressive strength test was carried out to check if the mix lies in the strength range of SHCC considered in this project i.e. the 28-day compressive strength values lying between 20 MPa to 30 MPa. All these tests were performed for all mixes defined in the previous section. The details of the tests are described here under.

3.4.1 Compressive strength

Fresh SHCC mixtures were introduced into $75 \times 75 \times 75$ mm cubic moulds without compaction. The hardened SHCC samples were demoulded after 2 days and stored into plastic bags at room temperature. The hardened SHCC samples were removed from the plastic bags after 28-day of casting and subsequent curing.

The unconfined compressive strengths of the SHCC samples having size $75 \times 75 \times 75$ mm were determined at 28 day of casting. Compression testing machine as shown in **Figure 3.7** was used for this purpose. Cubes were subjected to compression at a constant loading rate of 0.1kN/sec. The unconfined compressive strengths of three identical SHCC samples were measured and the measurements are reported in terms of the mean \pm standard deviation.



Figure 3.7 Compression testing of sample of SHCC.



Figure 3.8: SHCC cube tested for compression

3.4.2 Flow table test

Flowability is the ease with which a material could be transported and placed. It can be used to evaluate the consistency of the SHCC mix. If the consistence is not correct, the concrete

will not have the desired qualities. Following test was performed to evaluate the flowability of various SHCC mixes.

The flowability of SHCC can be evaluated using the slump flow test (ASTM C 230:1997). For the test 60 mm diameter and 40 mm height cylinder **Figure 3.9** was placed on a level surface. Then, the mix was poured into the cylinder the sample tamped twice in two layers. The tamping was done 20 times for each layer in a rotating motion. Then the cylinder is lifted and flow table was allowed to drop 25 times in 15 sec. The SHCC subsided resulting in formation of a spread. Diameter of this spread was measured in two perpendicular directions and mean of these values was considered as cylinder slump flow.

This test was used to find the initial amount of water to be added to the mix by trail. Also the spreads of different mixes at the fixed water content were also found out. Since the amount of material required for carrying out this test was very less this test is considered to be most suitable for initial iterations. The **Figure 3.10** shows the flow table machine used in the study.

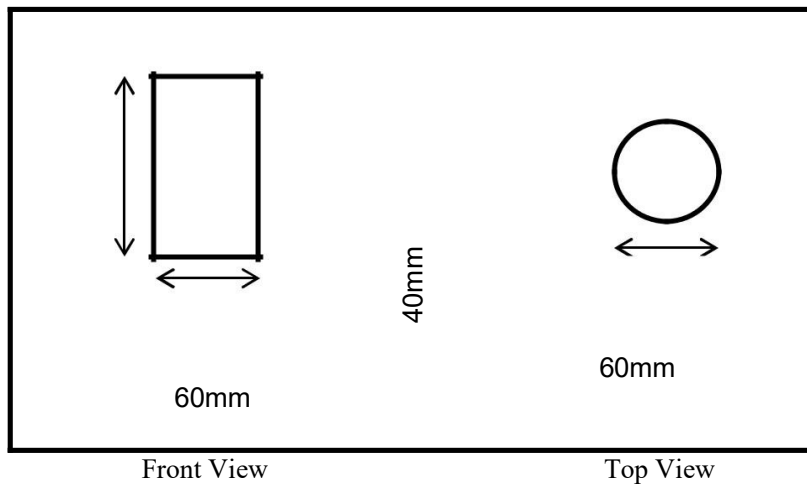


Figure 3.9 Cylinder Slump flow apparatus (ASTM C 230:1997)



Figure 3.10: Flow table machine used in the study

Trials were done to achieve a required spread without segregation. The amount of water was kept constant and the flowability of the different mixes was recorded. The quantity of spread for different mixes observed from cylinder slump test is stated in the succeeding chapters.

3.4.3 Tensile strength

Fresh concrete mix was injected in a dumbbell shaped mould without any compaction. The hardened SHCC samples were demoulded after 2 days and stored into plastic bags at room temperature. The hardened SHCC samples were removed from the plastic bags after 28-days of casting.

The tensile strengths of the SHCC samples were determined after 28 days of curing. Universal Testing machine as shown in **Figure 3.14** was used for this purpose. Specimens were placed in the grips of a Universal Test Machine at a specified grip separation and pulled until failure. A typical test speed for standard test specimens was kept at 2 mm/min as per ASTM D 3039. The machine had a stroke rate of 10 KN and a maximum capacity of 1000

KN. The tensile strengths of three identical SHCC samples were measured and the experimental. The measurements are reported in terms of the mean \pm standard deviation.

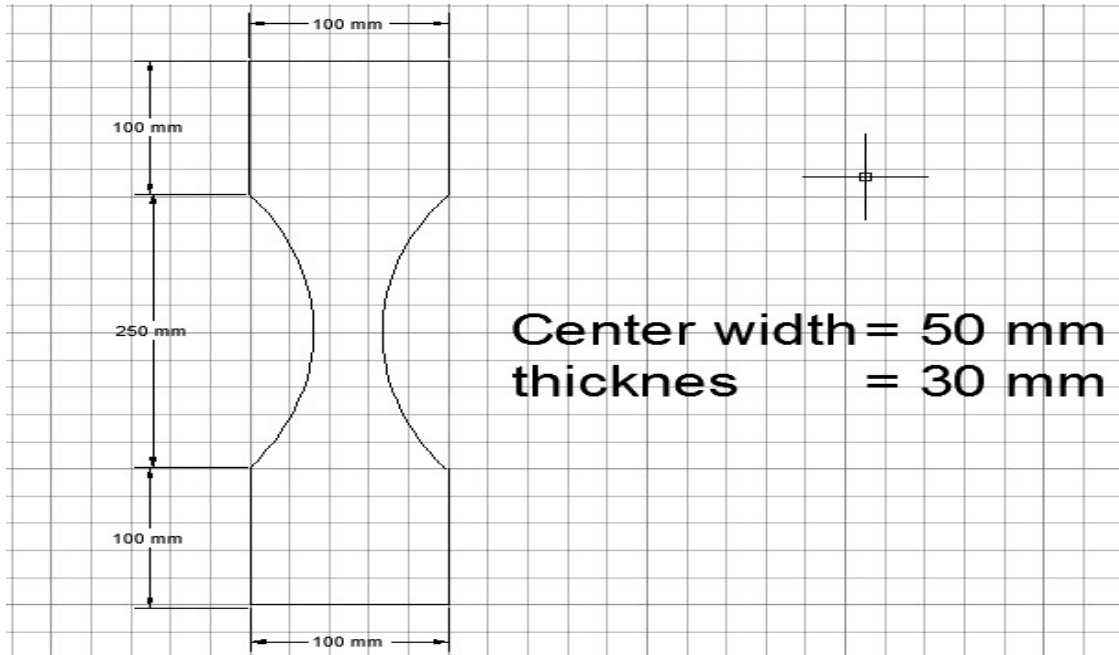


Figure 3.11: Design and dimension of specimen for tensile test

The **Figure 3.11** above represents the dimensions of the mould made for testing the tensile strength property of the strain hardening cementitious composite. The **Figure 3.12** shows the SHCC sample made and cured for testing after 28 days and **Figure 3.13** represent the tested sample and the failure at the predetermined failure cross sectional area. The area was small compared to the other parts of the dumbbell that is material placed will be less compared to the other areas, hence the strength at that cross section will be less. So the failure area was predetermined.



Figure 3.12: Casted sample of SHCC



Figure 3.13: Failure of sample after testing



Fig 3.14: UTM used for the tensile test

3.4.4 Abrasion test

The abrasion test was done according to the standard code of practise IS 1237:1980. Abrasion results are recorded mainly in term of the localized loss of material from the surface and loosening between the aggregate and paste. The abrasion resistance of cement-based composites is influenced by a number of factors, including compressive strength, properties of the aggregate, water/cementitious ratio. The abrasion resistance is a surface property that is mainly dependent on the quality of the surface layer characteristics. The top 3-5 mm is the most important part which is susceptible to abrasion.

Fresh mortar was filled in a mould of size 70×70×25 mm without any compaction, and the sample was demoulded after 2 days and stored in plastic bags at room temperature. The hardened sample was removed from plastic bags after 28 days. Sample having 70 x 70 mm surface and properly dries in oven at temperature of 1100 °C were placed one at a time on a disc rotating at 30 rpm under a constant load of 300N. About 20 gram abrasive powder was uniformly spread over the disc at the end of predefined constant revolution 22. The test cycle shall be repeated 16 times, the specimen being turned 90° in the clockwise direction and spreading 20 g of abrasive powder on the testing track after each cycle. The wear was determined from the difference in readings obtained by the measuring instrument before and after the abrasion of the specimen. The average loss in thickness of the specimen obtained by the following formula

CALCULATION

$$T = ((W_1 - W_2) \times V_1) / (W_1 \times A)$$

Where,

T = Average loss in thickness in mm,

W₁ = Initial mass of the specimen in gm.

W₂ = Final mass of the abraded specimen in gm.

V₁ = Initial volume of the specimen in mm³

A = Surface area of the specimen in mm²

In the study, the abrasive powder used during the testing was Aluminum Oxide neutral (Al_2O_3) manufactured by Qualikems Fine Chem Pvt.Ltd. The properties of the powder as specified in **Table 3.13**.

Table 3.13: Physical property of abrasive powder

S.NO	Properties	Values
1	pH value	6.5-7.5
2	Weight Per mol	0.9 gm
3	Particles size	0.230

The **Figure 3.15** shows is the abrasion testing machine on which the tests were conducted on $70 \times 70 \times 25$ mm moulds.



Figure 3.15: Abrasion testing machine used in the study

CHAPTER 4

RESULTS AND DISCUSSION

4.1 GENERAL

This chapter presents the test results of SHCC control mix (C1 with 2% PVA) and (C2 with 3% PVA) and also for the mixes proposed for varying replacement of flyash level with GBBS in increment of 10%, 20% and 30%. The chapter, herein, deals with the presentation of the results obtained for the mechanical (i.e. compressive strength and tensile strength) and durability property (i.e. abrasion test) was conducted on the strain hardening cement composite. In addition to above to above mentioned test above fresh mortar test for flowability of the various mixes was also conducted. In order to achieve the objective of study, for the development of SHCC, an experimental program making use of various industrial by-products was devised. The purpose was to determine the best proportion of materials that can provide the desired properties of SHCC. The mixes were cast using the proportions as laid down in Tables in the previous chapter. The experimental program included the following:

1. Obtaining and testing of properties of materials used for making SHCC.
2. Making trial design mixes for SHCC.
3. Checking the flowability of various SHCC mixes.
4. Casting and curing of specimens.
5. Cubical specimens of size 75mm x 75mm x 75mm were tested for the compressive strength of SHCC.
6. Dumbbell shaped specimens were tested for the tensile strength of SHCC.
7. Cubical specimens of size 70mm x 70mm x 25 mm were tested for the abrasion property of the SHCC mixes.

4.1 COMPRESSION TEST RESULTS

The compressive strength test was conducted on C1 and C2 control mix of SHCC and also on mixes prepared with replacements of flyash with GBBS in increment of 10%, 20% and 30%. The compressive strength of the different samples, measured using the compression

testing machine are shown in the **Table 4.1**. The table presents the average of the values these specimens which were casted and tested, after 28 days of curing for each of the SHCC mixes.

Table 4.1: Compressive strength variation in 28 days

MIX	Compressive strength (MPa)
C1	21.72
C1 GGBS 10%	22.59
C1 GGBS 20%	22.76
C1 GGBS 30%	24.66
C2	27.74
C2GGBS 10%	28.12
C2 GGBS 20%	28.93
C2 GGBS 30%	29.2

From the above table it is observed that the control mixes C1 and C2 having compressive strength of 21.72 MPa and 27.74 MPa respectively. The replacement of fly ash with GGBS in control mix C1 with replacements of 10, 20 and 30 percent shows marginal increase in compressive strength, with values of 22.59 MPa, 22.76 MPa and 24.66 MPa respectively. Similarly in replacement mixes of control mix C2 the results, compressive strength values are 28.12 MPa, 28.93 MPa and 29.2 MPa respectively. On observing the values of mixes C1 and C2 it can be said that with the increase in percentage of PVA fibers the compressive strength increases. Now as percent replacement level of flyash with GGBS is increased, the sample shows slight increase in strength. If the percentage of GGBS is raised from 10 to 20 percent there is a very marginal increase in the compressive strength of about 0.17 and 0.81 MPa, respectively for C1 and C2 mixes. A similar trend has been recorded as the percentage of replacement is increased from 20 to 30 percent a slight increase of about 1.9 MPa and 0.27 MPa respectively. **Figure 4.1** shows the trend of strength for both the mixes C1 and C2 also the mixes with the replacement of flyash with GGBS at varying percentages.

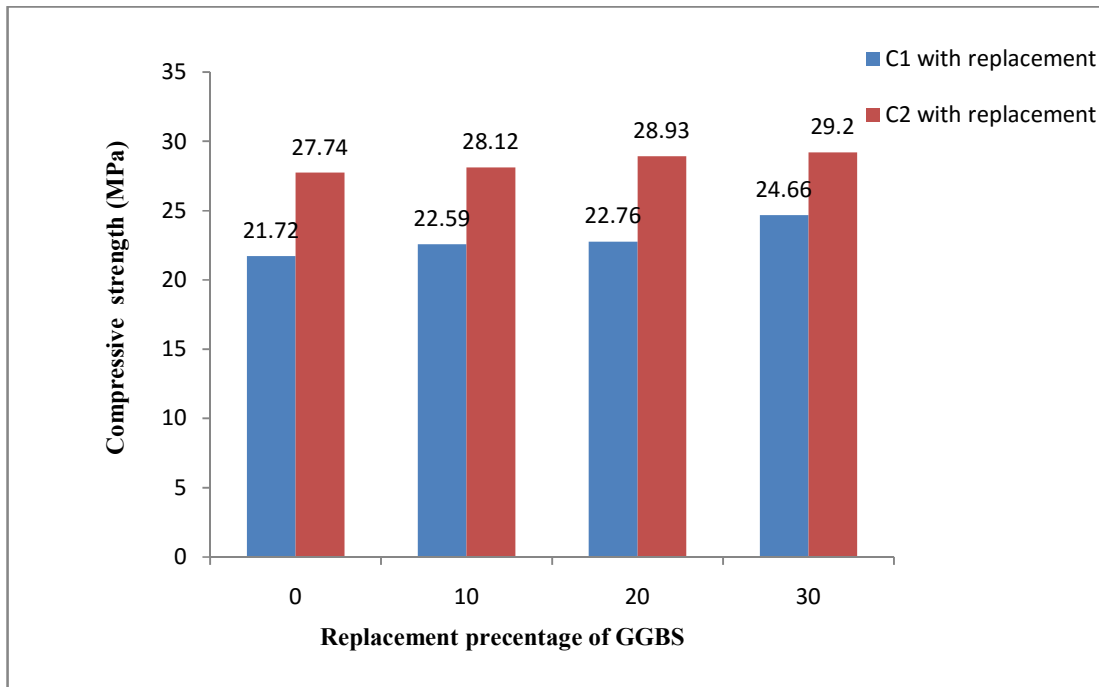


Figure 4.1: 28-days Compressive strength for trail SHCC mixes.

The mix containing higher quantity of GGBS has shown greater compressive strength as compared to the mix containing replacements less percentage of GGBS. This boost in the compressive strength may be due to the fact that mix containing GGBS shows better formation of CSH gel as compared to the mix containing flyash as seen in the previous research findings (Achtemichuk et al., 2009). (Choi et al 2011), had a similar range of compression results between 20 MPa to 30 MPa. However, not much variation in the compressive strength has been shown as the percentage of replacement is variedly increased. This indicates that for the development of SHCC along with minimum percentage of PVA fibers, it is necessary to optimize the percentage of flyash and GGBS at the w/b ratio of 0.78. Thus it can be concluded from the above results that all the mixes prepared as a part of the trail process, satisfy the minimum compressive strength requirement to qualify as SHCC mixes. It also signifies that any further replacement of flyash by GGBS (beyond 30% in C2 mix) would increase the strength beyond 30 MPa which is not desirable.

4.2 SLUMP FLOW TEST RESULTS

The test was conducted on C1 and C2 control mix of SHCC and also on mixes having different percentages replacement of flyash with GGBS (10%, 20% and 30%) for measuring

the flowability. The water/cement ratio was kept constant for all the mixes i.e. 0.78 and the workability of the different samples were measured as shown in the **Table 4.2**

Table 4.2: Slump flow test on fresh mixes of SHCC

MIX	SLUMP FLOW (mm)
C1	115
C1 GGBS 10%	119
C1 GGBS 20%	124
C1 GGBS 30%	131
C2	112
C2GGBS 10%	118
C2 GGBS 20%	125
C2 GGBS 30%	129

From **Table 4.2**, it can be seen that mix C1 and C2 have moderate flowability of 115 mm and 112 mm, respectively a decrease in flowability of the composite is observed as the percentage of the PVA fibers in increased from 2% to 3%. The presence of fiber in the mix increase friction between particles and fibers increase which hinders the flowability of the composite. However, as the percentage of GGBS is increased (as replacement for flyash) in both the mixes a higher slump value is observed. This increases marginal for a 10% replacement level but it is significant when 20% of flyash is replaced by GGBS in both the mixes. Again a significant increase in flowability is observed for mixes having 30% GGBS. **Figure 4.2** shows the trend of increase in flowability for both the mixes C1 and C2 with replacement of flyash with GGBS with varying percentages.

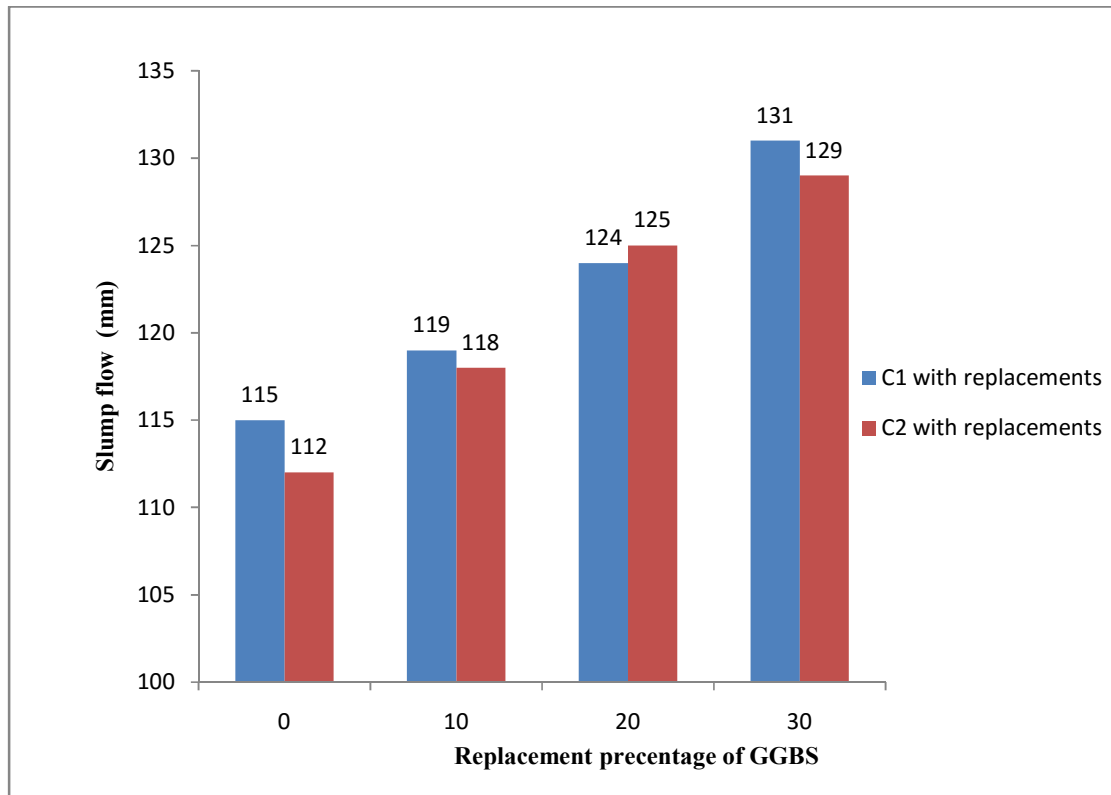


Figure 4.2: Slump flow test on fresh mixes of SHCC

It indicates that the GGBS replacement in the SHCC increase the workability, which may be because of very fine sized particles of GGBS. Increase of GGBS in the mix provides better mobility characteristics, arising from the consistent fineness and particle shape of the GGBS and from its slightly lower relative density. The smoother surface texture and glassy surface of GGBS particles also helps to improve workability of the matrix. The result show that mix containing higher quantity of GGBS has shown better flow. Similar observations were made by Soni et al. (2013). Similar pattern of rheology of engineered cementitious composites, as the percentage of fiber was increased a decline in the flowability of composite was recorded by Mo et al. (2012). To qualify as an SHCC mix, a minimum flowability of at least 115mm slump values is required. Thus from the results it can be considered that except C2 all mixes have the desired workability to qualify as an SHCC mix.

4.4 TENSILE TEST RESULTS

The tensile strength test was conducted on C1 and C2 control mix of SHCC and also on mixes prepared with replacement of flyash with GBBS in increment (10%, 20% and 30%).

The tensile strength of the different sample, measured using universal testing machine shown in the **Table 4.3**. The table presents the average of the values these specimens which were casted and tested, after 28 days of curing for each of the SHCC mixes.

Table 4.3: Tensile strength variation in 28 days

MIX	Tensile strength (MPa)
C1	2.6
C1 GGBS 10%	2.7
C1 GGBS 20%	3.12
C1 GGBS 30%	3.38
C2	3.34
C2GGBS 10%	3.78
C2 GGBS 20%	3.91
C2 GGBS 30%	4.04

From the above, table it is observed that the control mixes C1 and C2 having tensile strength values of 2.6 MPa and 3.34 MPa respectively. The replacement of flyash with GGBS in control mix C1 with replacements of tensile strength was when the percentage of GGBS was (10%, 20% and 30%) shows a increase in the tensile strength with a values of 2.7 MPa, 3.12 MPa, and 3.38 MPa respectively. Similarly in replacement mixes of control mix C2 the results, tensile strength values are 3.78 MPa, 3.91 MPa and 4.04 MPa respectively. **Figure 4.3** shows the trend of increase in strength for both the mixes C1 and C2 with replacement of flyash with GGBS with varying percentages.

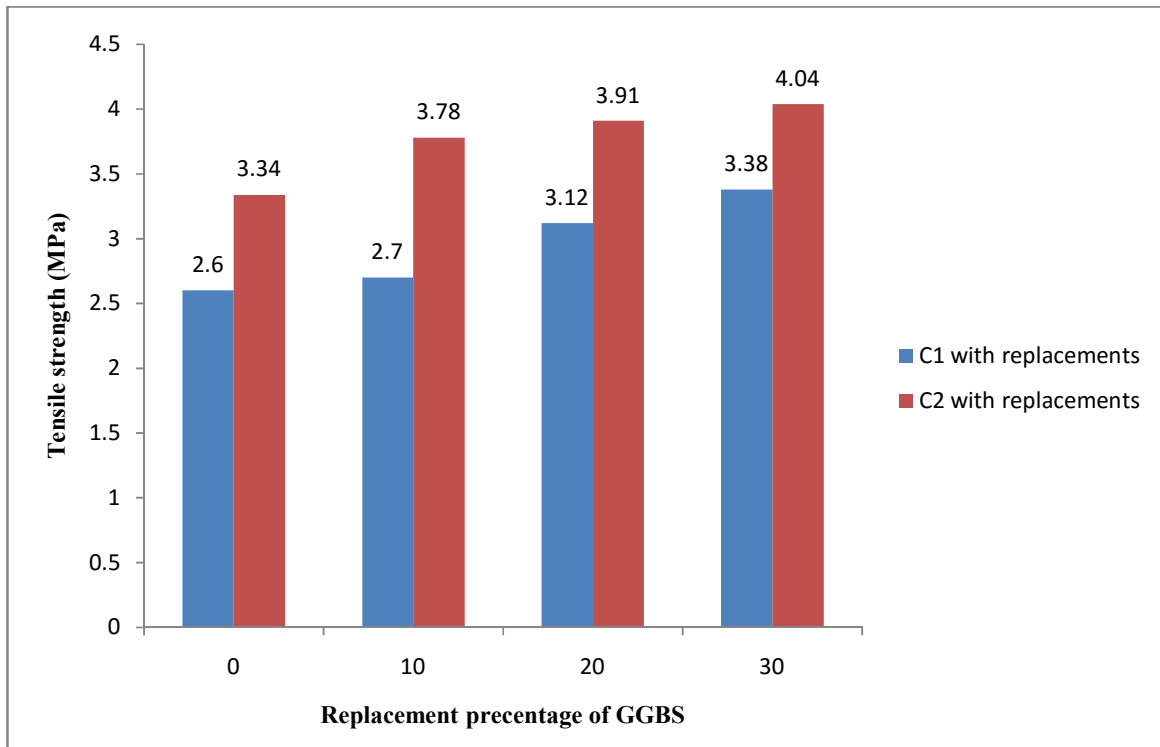


Figure 4.3: 28-day Tensile strength for trail SHCC mixes

From the above recorded values it can be seen that for Mix C1 and C2 with $w/b = 0.78$, the mix was able to achieve strength merely at 2.6 MPa and 3.34 MPa after 28 days of dry curing. Thus, it can be said that with the increase in percentage of PVA fibers the tensile strength also increased indicating that the micro cracks developed in the mix were prevented. It can also be observed with the replacement of flyash with GGBS from the trend of values that a marginal increase in the percentage of GGBS does not lead to a significant increase in strength at 28 days. However as the replacement percentage increase a higher tensile strength is recorded. Thus, it can be concluded with optimized use of GGBS in the development of SHCC the tensile strength can be increased. Since the requirement for SHCC need the tensile strength to be in the range of 3 MPa to 6 MPa, (Gideon et al 2015) except 2 mixes rest all achieved that range after 28 days of curing. This indicates that, the development of SHCC, along with minimum percentage of PVA fibers it is necessary to optimize percentage of flyash and GGBS at the w/b ratio of 0.78.

Thus it can be concluded from the above results that all the mixes except C1 and C1 with 10% GGBS, prepared as a part of trail process, satisfy the minimum tensile strength requirements to qualify as SHCC mixes.

4.5 ABRASION TEST RESULTS

After testing and identifying the mixes which qualify as SHCC mixes they were also tested for abrasion resistance. The test was conducted on C1 and C2 control mix of SHCC and also for mixes with varying percentage replacement of flyash with GGBS (increment of 10%, 20% and 30%). The abrasion results of the different samples were measured as shown in the **Table 4.4**. It has already been established that only five mixes i.e. C1 (20), C1 (30), C2 (10), C2 (20) and C2 (30) qualify to be SHCC mixes on the basis of replacements of both flowability and tensile strength. The mix C2 although does not have the desired tensile strength but it does not fulfill the flowability criteria.

Table 4.4: Abrasion test on SHCC mixes after 28 days

MIX	Weight before test (grams)	Weight after test (grams)	Weight loss (grams)	Volume loss (mm ³)	Thickness loss (mm)
C1	180.27	175.5	4.77	3241.38	0.60
C1 GGBS 10%	177.88	175.01	2.87	1976.47	0.40
C1 GGBS 20%	173.29	170.69	2.6	1837.95	0.37
C1 GGBS 30%	174.93	172.43	2.5	1750.70	0.35
C2	181.02	176.96	4.06	2747.48	0.56
C2GGBS 10%	197.74	194.97	2.77	1672.65	0.34
C2 GGBS 20%	180.76	178.31	2.45	1660.35	0.33
C2 GGBS 30%	178.20	175.99	2.21	1519.21	0.31

From the above table it can be observed that the addition of fibers in the mix help in increasing the abrasion resistance of the sample, indicating that addition of higher percentage of PVA fibers creates better bond in the matrix.

The control mix C1 with the replacements of fly ash with GBBS in the increments of 10%, 20% and 30% observed the results of 0.40 mm, 0.37 mm and 0.35 mm, respectively. A continuous decline in the thickness loss has been noted as the percentage of replacement of GGBS increased. The **Figure 4.2** shows the thickness loss for the mixes C1 and replacement of flyash with GGBS with varying percentages.

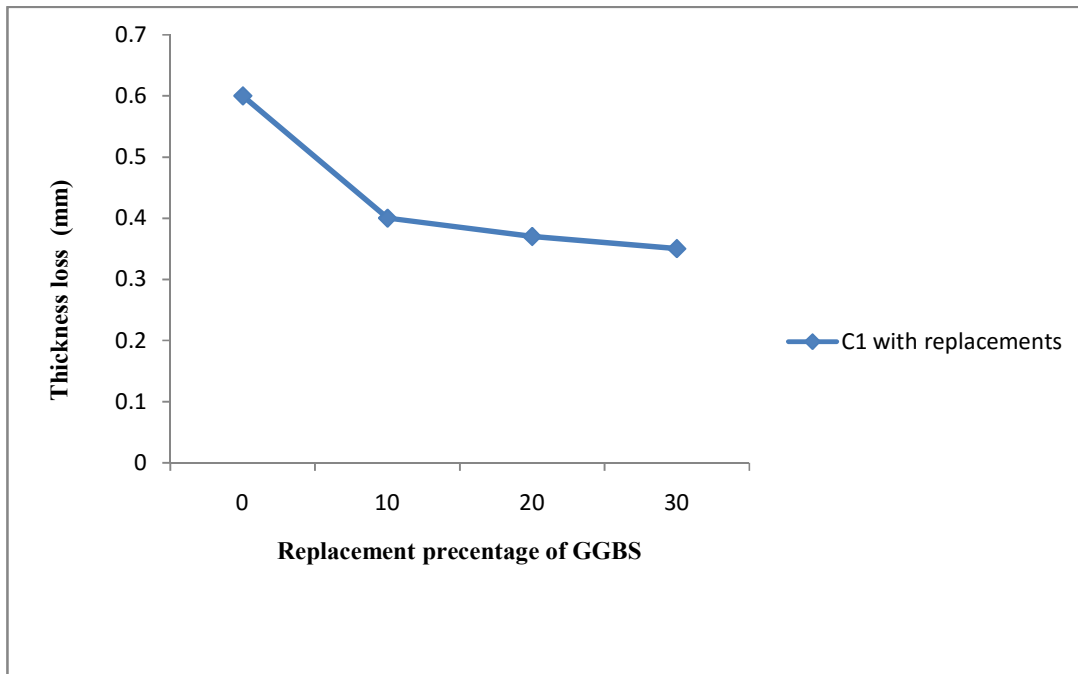


Figure 4.4: Abrasion test on C1, C1 GGBS 10%, C1 GGBS 20% and C1 GGBS 30%

Similarly the control mix C2 with the replacements of fly ash with GBBS in the increments of 10%, 20% and 30% observed the results of 0.34 mm, 0.33 mm and 0.31 mm, respectively, following similar trend as recorded in case of C1 **Figure 4.5** shows the thickness loss for the mixes C2 and replacement of flyash with GGBS with varying percentages.

Comparing the two graphs of the various mixes of C2 and the replacement mixes shows better results than C1 fiber and its various mixes. The increase in the fiber content of strain hardening cement composite results in improving durability properties of the composite.

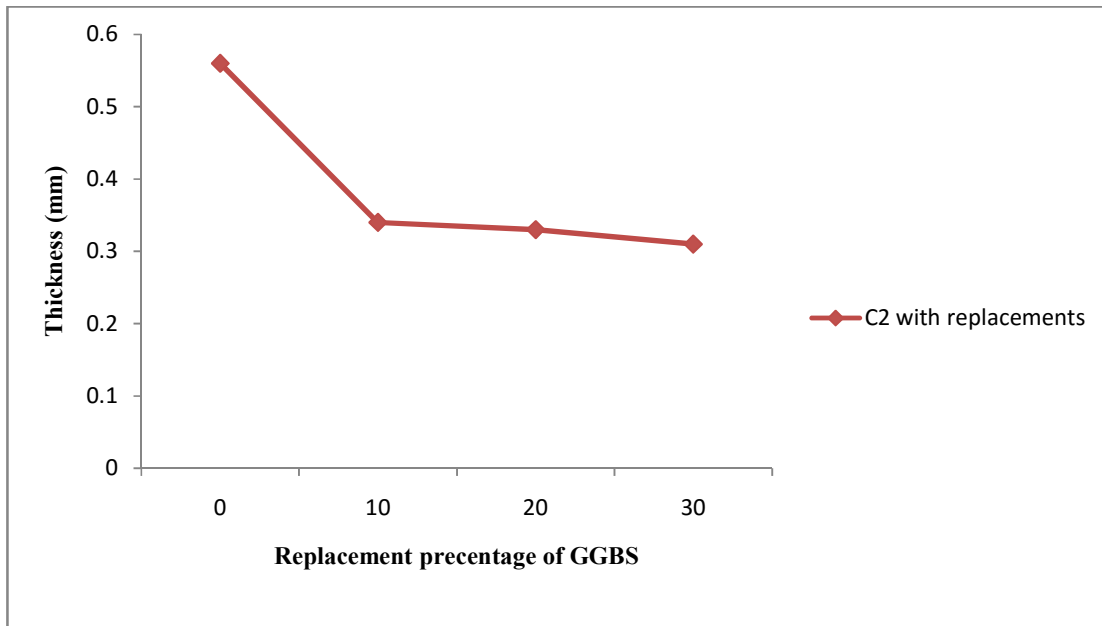


Figure 4.5: Abrasion test on C2, C2 GGBS 10%, C2 GGBS 20% and C2 GGBS 30%

Thus, it can be concluded that all the five SHCC mixes showed better abrasion resistance property as compared to the mixes which failed to qualify as SHCC

4.6 CLOSING REMARKS

This chapter shows the results obtained by compressive strength test, flowability of various fresh mixes, tensile strength test. In addition to this abrasion test has also been performed to check the durability for all the proposed SHCC mixes.

CHAPTER 5

CONCLUSIONS

5.1 GENERAL

The aim of this project was to develop Strain hardening cement based composite (SHCC) by optimizing the mix proportions using various cementitious materials. The mechanical and durability properties were investigated for SHCC specimens with the addition of different percentages of PVA fibers and by replacing flyash partially with GGBS. Based upon the experimental study conducted the following conclusions are obtained from the study

- All the mixes developed qualify the minimum compressive strength requirement to be a SHCC and a marginal difference in the compressive strength of the various mixes.
- The supplementary cementitious materials like flyash and GGBS play a significant role in increasing the flowability of the SHCC mixes.
- Except the mix C2 (control mix with 3 percent of PVA fiber), rest all qualify the flowability criteria of SHCC of the mixes taken for the study.
- The tensile strength of all the mixes except C1 (control mix with 2 percent PVA fiber) and C1 with 10% of replacement of flyash with GGBS satisfy the minimum strength required to be an SHCC
- The addition of the PVA fibers and the replacement of flyash by GGBS in percentage (10, 20 and 30 percent) improve the abrasion resistance of all the mixes used in the study.
- A set of five mixes have been obtained which satisfy the strength and flowability requirement of an SHCC mix. These mixes include C1 with 20% GGBS, C1 with 30% GGBS, C2 with 10% GBBS, C2 with 20% GBBS and C2 with 30% GGBS.
- It can also be concluded that industrial by-products can be successfully used as a replacement to the conventional building material in SHCC and they also can provide better fresh and hardened properties.

5.2 SCOPE FOR FUTURE WORK

From the above study, it is suggested that further work could be done on SHCC as stated below:

- Only the effect of 2% and 3% PVA fibers were investigated in the study. The percentage replacements can be further varied to study their effect on properties of SHCC.
- Effect of replacement of conventional building material by industrial waste product in higher percentage can be investigated.
- Work can be extended to study different properties like flexural strength and various other durability of SHCC.

REFERENCE

- Aveston J., Cooper G. A., Kelly A., (1971). “The properties of fiber composites. In Conference proceedings”. IPC Science and Technology Press Hellertown, 15: 15-24.
- Ahmed A., Khalil A., (2015). “Improving the Failure Mode of Over-Reinforced Concrete Beams Using Strain-Hardening Cementitious Composites” J. Perform. Constr. Facil., 04016003
- Achtemichuk, S., Hubbard, J., Sluce, R. and Shehata, M.H. (2009), “The utilization of recycled concrete aggregate to produce controlled low-strength materials without using portland cement” Cement and Concrete Composites, 31, 564-569.
- Cement and Concrete Composites, 31, 564-569.
- ASTM C. (2003). 618. Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete.
- ASTM, C. (1994). 33, Standard specification for concrete aggregates. Annual Book of Standards.
- Barros J. A. O., Esmaceli E., Fasan L., Prizzi F. R. L., Sena-Cruz J., (2015). “Retrofitting of interior RC beam–column joints using CFRP strengthened SHCC: Cast-in-place solution”. Composite Structures. 122: 456-467.
- B. Kondraivendhan and B. Pradhan, (2009). “Effect of ferrocement confinement on behavior of concrete”, Construction Build Material, vol. 23(3): pp 1218–22, 2009.
- Baghi H., Barros J. A. O., (2016). “Shear Properties of the Strain Hardening Cementitious Composite Material”. Journal of Materials in Civil Engineering.10: 1943-5533
- Boukini, A. Swamy, R.N. and Bali, A. (2009), “Durability properties of concrete containing 50% and 65% slag.” Construction and building materials, 8, 2836-45.
- Choi W. C., Yun H. D., Kang J. W., Kim S. W., (2012). Development of recycled strain-hardening cement-based composite for sustainable infra structures. Composites Part B: Engineering, 43: 627-635.
- Dowrick, D.J.;(2003), “Earthquake risk reduction”, John Wiley & Sons Ltd., England
- Da Silva Magalhães M., Toledo Filho R. D., Fairbairn E. D. M. R., (2015). “Thermal stability of PVA fiber strain hardening cement-based composites”. Construction and Building Materials, 94: 437-447.

- Faiz A and Hirozo M.,(2006). “A review on durability properties of strain hardening fiber reinforced cementitious composites” *Cement & Concrete Composites* 29 (2007) 365–376
- Hakan N., Bekir Y., Erman T., (2013). “Behavior of PVA Fiber-Reinforced Cementitious Composites under Static and Impact Flexural Effects” *Journal of Materials in Civil Engineering*, Vol. 25, No. 10
- IS: 2386 (Part I, III), 1963: Methods of Test for aggregates for Concrete, Bureau of Indian Standard, New Delhi
- IS 1237-1980 specification for cement flooring tiles Bureau of Indian Standard, New Delhi.
- IS 383 – 1970: Specification for coarse and fine aggregates from natural sources for concrete, Bureau of Indian Standard, New Delhi.
- IS 1999 – 1959 (Reaffirmed 1999): Methods of sampling and analysis of concrete, Bureau of Indian Standard, New Delhi.
- IS 5816(1999): Method of test splitting Tensile strength of Concrete, Bureau of Indian Standard, New Delhi
- Ghobarah, A. and El-Amoury, T; (2002). “Seismic rehabilitation of beam–column joint using GFRP sheets”. *Engineering Structures* 24 1397–1407.
- Krenchel H., Stang H., (1989). “Stable microcracking in cementitious materials”. *Brittle Matrix Composites*. 2:20-33.
- Kashiyani B. K., Pitroda J., Shah B. K., (2013). “Effect of Polypropylene Fibers on Abrasion Resistance and Flexural Strength for Interlocking Paver Block”. *International Journal of Engineering Trends and Technology*. 4: 1837-1843.
- Mechtcherine V., Andrade S., marko B., (2010). “Behavior of strain hardening cement composite under high and low strain rates” *Journal of advanced concrete technology* vol 9 no1 51-62
- Naaman A. E., Reinhardt H. W., (2003). “Setting the stage: toward performance-based classification of FRC composites”. In *High Performance Fiber Reinforced Cement Composites*. 4: 1-4.
- Patel et al. (2012). “An investigation on properties of various fibre reinforced concrete”, *International Journal on Advanced Engineering Research and Studies*, Vol.2(12): 36-38.

- Qian S., Zhou J., De Rooij M. R., Schlangen E., Ye, G., Van Breugel K., (2009). “Self-healing behavior of strain hardening cementitious composites incorporating local waste materials”. *Cement and Concrete Composites*,31: 613-621
- Sasmal, S; (2009), “Performance Evaluation and Strengthening of Deficient Beam-Column Sub assemblages under Cyclic Loading”, University of Stuttgart.
- Shah S. P., Skarendahl A. L., Lankard D. R., (1986). “Preparation, properties and applications of cement based composites containing 5-20 percent steel fiber reinforcement”. *Steel Fiber Concrete*. 1-78.
- Slowik V., Toledo-Filho R. D., Wittmann F. H., Mihashi H., (2016).”Comparative testing of crack formation in strain-hardening cement-based composites (SHCC)”. *Materials and Structures*, 49: 1175-1189
- Toshiyuki K., Kabele., Fukuyama H . Uchida Y., Suwada H (2012) “Strain Hardening Cement Composites: Structural Design and Performance Strain Hardening Cement Composites” *Structural Design and Performance Volume 6 of the series RILEM State-of-the-Art Reports* pp 59-78
- Tavakoli M.(1994), “ Tensile and Compressive Strengths of fiber reinforced concrete”, *International Concrete Journal*, Vol. 142: 61-72.
- Ting H., Zhang X., Cheng S., Lo S., (2015). “Effect of Slip-Hardening Interface Behavior on Fiber Rupture and Crack Bridging in Fiber-Reinforced Cementitious Composites” *Journal of Engineering Mechanics J. Eng. Mech.*, 2015, 141(10): 04015035
- Van-Zijl G. P., (2007). “Improved mechanical performance: Shear behavior of strain-hardening cement-based composites (SHCC)”. *Cement and Concrete Research*, 37: 1241-1247.
- Van-Zijl G. P., Slowik V., Toledo-Filho R. D., Wittmann F. H., Mihashi H., (2016).”Comparative testing of crack formation in strain-hardening cement-based composites (SHCC)”. *Materials and Structures*, 49: 1175-1189.
- Victor C. Li (2006) “Engineered cementitious composites” *The University of Michigan, Ann Arbor, USA Monterrey, Mexico, 2006 1st 230 International Conference on Advanced Construction Material*
- Yao Y., Yang Y., Zhu Y., Yu P., (2011).”Reduction of Drying Shrinkage of SHCC”. *Restoration of Buildings and Monuments*. 17: 79-90.

- Zhiming M., Tiejun Z., Jianzhuang X., Penggang W., (2015) “Effect of Applied Loads on Water and Chloride Penetrations of Strain Hardening Cement-Based Composites” J. Mater. Civ. Eng., 04016069