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MASTER OF SCIENCE (MSc) THESIS

EFFECTIVENESS OF HYBRID FIBER REINFORCEMENT ON ENHANCEMENT OF THE MECHANICAL PROPERTIES OF CEMENT BASED HIGH STRENGTH COMPOSITES EXPOSED TO ACID ATTACK

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The study entitled **"Effectiveness of Hybrid Fiber Reinforcement on Enhancement of the Mechanical Properties of Cement Based High Strength Composites Exposed to Acid Attack"** prepared by Ahmed Motasem ANWER under supervision of Assoc. Prof. Dr. Kasım MERMERDAŞ was unanimously accepted as a MASTER of SCIENCE thesis on 23/12/2020 by the following committee in Graduate School of Natural and Applied Science, Department of Civil Engineering, at Harran University.

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Yüksek Lisans Tezi

HİBRİT ELYAF TAKVİYESİNİN ASİT SALDIRISINA MARUZ KALAN ÇİMENTO BAZLI YÜKSEK MUKAVEMETLİ KOMPOZİTLERİN MEKANİK ÖZELLİKLERİNİN İYİLEŞTİRİLMESİNE ETKİSİ

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İyileştirilmiş bir basınç dayanımı değerine sahip olan yüksek mukavemetli beton, çekme dayanımı eksikliğinden kaynaklanan gevrek kırılmanın sebep olduğu doğal zayıflığı ortadan kaldıran lif takviyesiyle üretilebilir. Bu tez, farklı hacimsel oranlara sahip tek tip (çelik veya cam) fiber veya hibrit çelik-cam fiberler kullanılarak yüksek performanslı çimento esaslı kompozitlerin (YPÇEK) mekanik özelliklerinin iyileştirilmesi üzerine deneysel bir çalışma sunmaktadır. Ayrıca normal çimentonun silis dumanı (SD) ile kısmi yer değiştirmesinin YPÇEK'in taze ve sertleşmiş özelliklerine etkisi de araştırılmıştır. Deneysel programın bir diğer aşaması, agresif sülfürik asit (H_2SO_4) maruziyetinin YPÇEK üzerindeki etkisinin değerlendirilmesidir. Bu nedenle, SD ve çelik-cam elyaf takviyesinin asidik ortamlarda YPÇEK'in performansı üzerindeki rolünü araştırmak tezin en önemli amacıdır. Deney programında iki seri halinde on dört karışım hazırlanmıştır. İlk seri, bağlayıcı olarak sadece çimentoya dayanıyordu, ikinci seri ise% 85 OPC ve% 15 SF'den oluşmuştur. Takviyesiz yalın karışım kontrol grubu olarak kabul alınmıştır. Karışım hacmine göre lif yüzdeleri% 0.5 ve% 1.0 olarak belirlenmiştir. YPÇEK üretimi için su/bağlayıcı oranı 0.25 olarak sabitlenmiştir. 28, 56 ve 90 günlük ıslak kürleme yaşlarında bir dizi tahribatlı ve tahribatsız deney yapılmıştır. Asit saldırısı için bazı numuneler 28 günlük kürlemeden sonra bir ay ve iki ay boyunca % 7'lik sülfürik asit çözeltilerine maruz bırakılmıştır. Asite maruz kalmayan numuneler üzerinde yapılan testler karşılaştırma için kullanılmıştır. Deneysel sonuçlar, % 15 SD ile % 0.5 çelik -% 0.5 cam elyafı hibrid birleşimine sahip numunelerin daha yüksek bir eğilme dayanımı ve daha düşük kapiler su geçirimliliği sergilediğini göstermiştir. Ayrıca, %1.0 çelik elyaf ve %15 SD içeren numuneler her yaşta daha yüksek basınç dayanımı göstermiştir. Bununla birlikte, cam elyaf ilavesi basınç mukavemetini düşürmüştür. Ayrıca sonuçlar, SD'nin esas olarak sülfürik aside maruz kalmaya karşı YPÇEK direncini arttırdığını göstermiştir.

ANAHTAR KELIMELER: Elyaf takviyesi, Mekanik özellikler, Çimento esaslı yüksek dayanımlı Kompozit, Asit saldırısı.

ABSTRACT

MSc Thesis

EFFECTIVENESS OF HYBRID FIBER REINFORCEMENT ON ENHANCEMENT OF THE MECHANICAL PROPERTIES OF CEMENT BASED HIGH STRENGTH COMPOSITES EXPOSED TO ACID ATTACK

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The high strength concrete having an improved compressive strength can be produced by addition of the fibres which eliminates inherent weakness of brittle failure due to lack of tensile strength. This thesis presents an experimental study on enhancement of the mechanical properties of high performance cementitious composites by the use of either single type (steel or glass) fiber or hybrid steel-glass fibers with different volumetric ratios. Moreover, the effect of partial replacement of ordinary cement with silica fume (SF) on the fresh and hardened properties HPCC was also investigated. Another stage of the experimental program is evaluation of the effect of aggressive sulfuric acid (H_2SO_4) exposure on HPCC. Hence, understanding the role of SF and steel-glass fiber reinforcement on the performance of HPCC under acidic environments is the main aim of the thesis. In the experimental program, fourteen mixes in two series were prepared. The first series was based on only cement as the binder, while the second series consisted of 85% OPC and 15% SF. Unreinforced plain mix was considered as a control group. The percentages of fibres by the volume of mixtures were 0.5% and 1.0%. Water to binder ratio was fixed as 0.25 for HPCC production. A series of destructive and non-destructive tests were done at different ages 28, 56 and 90 days of moist curing. For acid attack a number of samples were exposed to 7% sulfuric acid solutions for one month and two months after 28 days of curing. The tests on the non-exposed specimens were carried out for comparison. The experimental results indicated that specimens with a hybrid combination of 0.5% steel-0.5%glass fiber with 15% SF exhibited a higher flexural strength and lower capillary water permeability. Also, specimens with 1.0% of steel fiber and 15% SF showed higher compressive strength at all ages. Nevertheless, addition of glass fibers decreased compressive strength. Furthermore, the results showed that SF mainly enhanced the HPCC resistance against sulfuric acid exposure.

KEYWORDS: Fiber reinforcement, Mechanical properties, Cement based high strength composites, Acid attack

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SYMBOLS AND ABBREVIATIONS

ACI	American HPCC Institute
ASTM	American Society for Testing and Materials
B	Binder
C	Cement
C3A	Calcium aluminate hydrate
$Ca(OH)_2$	Calcium Hydroxide
$CaSO_4.2H_2O$	Gypsum
C-S-H	Calcium Silicate Hydrates
d	diameter of fiber
DL	Dimension Loss
ECC	Engineered Cementitious Composites
Fc	HPCC compressive strength
Fcr	HPCC flexural strength
FRC	Fiber Reinforced HPCC
GF	Glass Fiber
GFRC	Glass Fiber Reinforced HPCC
H_2SO_4	Sulfuric Acid
HF	Hybrid Fiber
HFRC	Hybrid Fiber Reinforced HPCC
HPCC	High Performance Cementitious Composites
HFRCC	High Performance Fiber Reinforced Cementitious Composites
l	length of fiber
MR	Modulus of Rupture
OPC	Ordinary Portland Cement
ρ	Density of HPCC
Q	Quartz
RPC	Reactive Powder HPCC
S	Sand
SF	Silica Fume
SiO_2	Silicone dioxide
SP	Superplasticizer
SSD	Saturation Surface Dry
StF	Steel Fiber
UHSC	Ultra-High-Strength HPCC
UPV	Ultrasonic Pulse Velocity
Vf	Volume fraction
W	Water
W/C	Water-to-Cement Ratio
WL	Weight Loss

1. INTRODUCTION

1.1. General

Concrete is the most widely used building substance compared to other available materials, because it has the lowest strength-to-cost ratio. Concrete is defined as the mixture of cement, sand, aggregates, water and sometimes additives. Each material has a significant role in overall performance of concrete. It is an artificial material. In beginning, it is soft, ductile or fluid and gradually with time, it will turn solid. Concrete possesses many desirable characteristics such as high strength, low cost, constituent availability, workability and durability under normal environmental factors. There are several applications of concrete, it is used for building of multi-story structures, water tanks, highway pavement, dams, offshore structures and etc. Concrete mix design is termed as the way of choosing suitable constituents of concrete and finding their relative amount with the purpose of making concrete with the necessary strength, workability and durability.

Concrete is a heterogeneous material so it has some inherent weakness like low chemical and acid attacks, permeable to moisture, and low tensile strength. It is subjected to erosion. Cementitious system as concrete is created by the arrangement of various parts such as aggregates, pores, and micro cracks. The grades can be of different sizes and shapes. The concrete behaviour depends on these inclusions when subjected to the load i.e., the distribution and continuity of various impurities. Weakness in concrete caused by small cracks of mortar aggregate junction. These small (micro) cracks growth and finally in brittle fracture in normal concrete when subjected to the load (Anand and Jose, 2018).

The deficiencies of concrete are classified by plenty of researchers, some of them made considerable works to enhance the concrete performance, particularly durability and moisture permeability, these are the major criteria which are considered by the investigators. The present pozzolanic concrete literatures present that the porosity of concrete decreased by using mineral admixtures by replacing cement content partially with admixtures if cement content is partially replaced by some mineral admixture as silica fume (SF), metakaolin, rice husk ash, fly ash, and ground granulated blast furnace slag. The request of mixed cement has increased worldwide to make impermeable denser concretes with enhancing concrete strength like compressive, flexure, and tensile. These admixtures allow concrete to display greater harmful resistance against aggressive solutions such as chemicals, acids, etc. (Ayub et al., 2014).

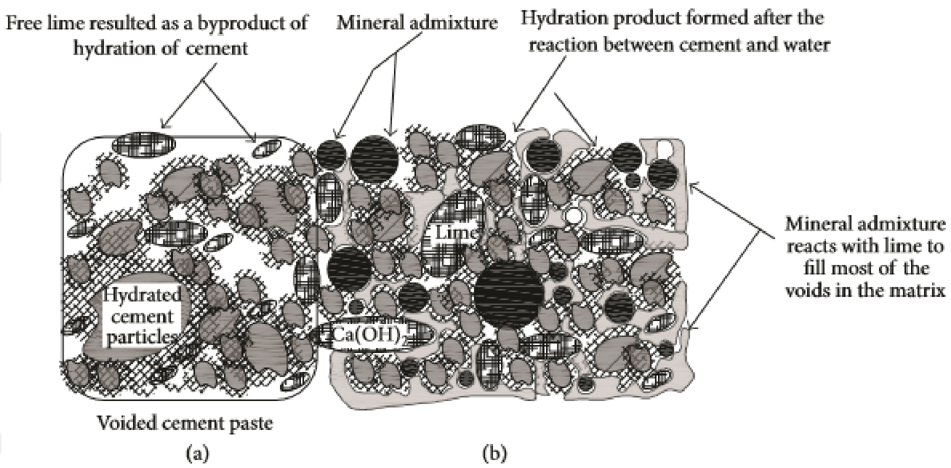

Figure 1.1. (a) Production of lime as a by-product of Portland cement hydration resulting into a porous paste. (b) Pozzolanic reaction between admixtures and lime to fill the spaces (Ayub et al., 2014)

Investigation is made by researchers during the last two to three decades keeping in view the stability of structures that required a high-quality concrete with enhanced durability, tensile strength and other concrete characteristics. Requiring these properties draws searching for complementary cementitious materials. Study of any appropriate substance in replacement of cement partially that is completely sustainable enhancement and minimal environmental impact possible. The using of high strength & high-performance cement is now in common practice in the fast development of infrastructure in the world. Researchers confirmed that SF, ground granulated blast furnaces slag, fly ash, etc., are appropriate and commonly used cementations materials for partial cement replacement (Kumar and Dhaka, 2016).

During the last 30 years, development in science and technology of concrete materials has greatly exceeded that of the 150 years. A new class of concrete is ultra-high-strength concrete (UHSC) is that has been the result of such progress. The compressive strength of the new class of concrete is higher than 100 MPa. This new type of concrete has good properties, advanced for special environment; the properties are enhancement in tensile strength, resistance to various external factors, durability, and etc (Yew, 2012).

The enhancement of high performance cement based composite (HPCC) substances have undergone a number of stages. The number of researchers established the influence of steel fibres in decreasing brittleness of concrete. This progress has continued with expansion of a diversity of other fibres like carbon, glass fibres and hybrid fiber in the last years, that combine either diverse fibre kinds or lengths (Li, 2008). The weaknesses of concrete like low crack growth resistance, brittleness, etc are handled by introduction of reinforcement by randomly distributed short discrete fibers (steel, polypropylene and nylon). The definition of (FRC) is a compound gained by the addition of single type or a combination of fibers to the mix. The addition of single kind of fiber alone helps to prevent or decrease the impacts of only certain undesirable characteristics. Previous studies show that use of more than one kind of fibers as termed of hybrid fibers in a appropriate proportion may help to enhance more concrete characteristics amongst the fibers (Yew, 2012).

High Performance Fiber Reinforced Cementitious Composites (HFRCC) may be considered a type of substance different from conventional and FRC in that various degrees of tensile strength and ductility. This class of materials should be observed as fibre reinforced cement mortars or pastes therefore it should be noticed that the matrix of this type of substance contains fine aggregates without coarse aggregates. (Figure 1.2.) shows schematic indication of variances between the tensile response of conventional concrete (CC), FRC, and HFRCC, as subjected to uniaxial tension load (Li, 2008).

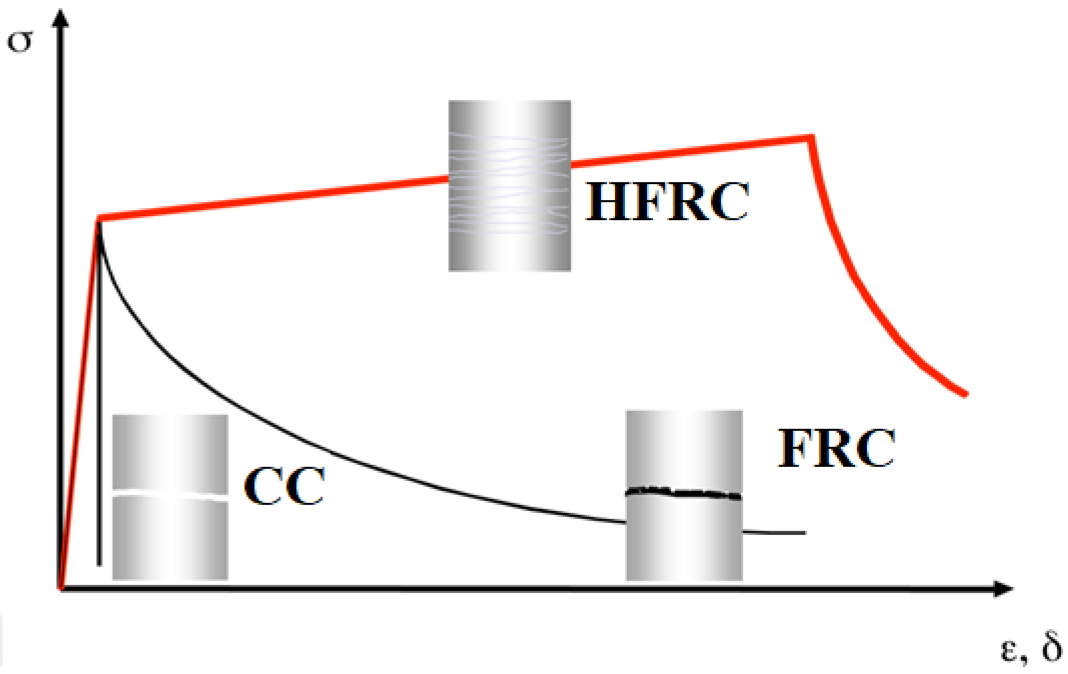

Figure 1.2. Schematic indication of variances between the tensile response of conventional concrete (CC), FRC, and HFRCC, such as subjected to uniaxial tension load. (Li, V.C., 2008)

In the world, the large number of structures, like sewerage systems continuously exposed to corrosion from various chemical solutions, like sulphuric acid however many concrete infrastructures have considerable long-life expectations. Regrettably, this attack leads to entrance of acidic ions into structures can eventually cause significant degradation to concrete infrastructures, that will later lead to expensive maintenances or sometimes, whole replacement of the entire structure (Joorabchian, 2010).

Sulfuric acid may be considered as the most aggressive chemical solutions to concrete structure which is depending on its formation manner and concentration, can lead to serious damage and degradation to concrete which come into interaction with it. This type of aggressive acid probably formed in groundwater and soils during the iron sulfide oxidation in the form of marcasite or pyrites (Richardson, 2002). Many industries such as iron and steel, waste aggressive acids, could be dumped into sewerage systems which will subsequently lead to attack on underground concrete installations. The most common type of sulphuric acid corrosion in concrete structures occurs in sanitary sewerage system structures. In food processing plants, Sulphuric acid also lead to degradation in the floor of the plants (Kaempfer and Berndt, 1999).

Manufactured HPCC with good resistance to microbiological and chemical corrosion of sulphuric acid may also be a unique idea and solution. This purpose could be obtained by adding various types of chemical admixtures, mineral additives and etc. Then, the samples of HPCC could be tested by using various ways in research laboratories to estimate their performances in terms of tensile and compressive strengths, appearance, weight loss, etc (Joorabchian, 2010).

1.2. Problem statement

The statement of problems of HPCC and objectives of the thesis are listed below:

1. An intensive effort has been made to present the inherent deficiencies of conventional concrete.
2. To produce HPCC more than 100 MPa mixes depend on traditional concrete mix formula.
3. To find the effectiveness of hybrid glass-steel fibres on enhancement of the mechanical characteristics of HPCC through the investigation of mechanical properties.
4. To find the effectiveness of sulfuric acid on the mechanical characteristics of HPCC with and without fibres and mineral admixtures.

1.2. Outline of Thesis

This research is displayed in five parts. The introduction of this study is presented in chapter one, which defines the general and the problem statement, principal objectives, and outline of thesis. A review of literature on the concrete and its inherent deficiencies is described in chapter two. The effect of hybrid fibre reinforcement on enhancement of the mechanical characteristics of HPCC was defined and studied. Suitable literatures in the field of engineered cementitious composites

(ECC) and reactive powder concrete (RPC) have been reported and reviewed. Finally, the effects of aggressive solutions like sulfuric acid of HPCC was presented.

The methodology details which were adopted to carry out the material preparation, materials properties, classification, testing procedures and test apparatus are showed in chapter three. The enhancement of concrete and tests were done to show their mechanical and physical characteristics are clarified. Different types and amounts of fibers to be used. Acid effect on HPCC was explained.

The experimental outcomes and discussion on the characteristics of fresh and hardened of HPCC with and without fibers are presented in chapter four. The final chapter is adopted to the recommendations and conclusions derived from an analysis of the results in this investigation.

2. LITERATURE REVIEW

2.1. General

Concrete is a popular construction composite despite of the inherent weakness as low tensile strength, brittleness, low resistance to acids and permeability. Recently plenty of investigators have been able to control the deficiencies of concrete and concretes with higher strength levels and low permeability have been showed because of the requirement of high strength concretes in construction industries. Hybrid fibers reinforcement and RPC are a new class of high strength cementitious composites which attain high ductility, impermeability and high level of strength through the introduction of small amount of short fiber reinforcement and excellent durability with advanced mechanical and physical properties.

2.2. Concrete

Normal concrete is composite material that contains cement, aggregates, water and sometimes admixture as described Singh and Rai (2018). It is used as major construction substance in most of structures due to good properties. One vital constraint of normal concrete, even of good quality, is the presence of micro-cracks, capillaries, and micro-capillaries.

Anand and Jose (2018), reported that concrete is a significant non-homogenous construction substance and brittle in nature. When compared to other available materials, it has the lowest strength-to-cost ratio. Fresh concrete can be cast into any shape and strength according to our need. Nowadays it is actually easy to put concrete by pumping and everything. All of these reasons make concrete such a popular building substance. Concrete has some deficiencies despite of good properties. Concrete sometimes is permeable to chemicals and has low tensile strength. Also, it is subject to corrosion. Cement mash is made like concrete by complicating the arrangement of various impurities such as aggregates, micro cracks, and pores. The grades could be of various shapes and sizes. The concrete behaviour depends on these inclusions when subjected to the load i.e., the continuity and distribution of various impurities. Weakness in concrete caused by small cracks at the mortar aggregate junction. These micro cracks spread and unite together to produce macro-cracks and lead to brittle fracture in normal concrete when subjected to the load. This occurs caused by low tensile strength and ductility of concrete. These cracks happen during stiffness due to various kinds of shrinkage. The initial cracks width occasionally more than a few microns. When subjected to load these small cracks expand, and new larger cracks are produced. Failure begins due to cracks in concrete that are controlled by tensile properties. Several ways have been used to solve these problems. It includes prestressing, reinforcing, etc.

Chandramouli et al. (2010), investigated that the most widely used construction substance is concrete. Under usual environmental factors it has many desirable characteristics as high compressive strength, durability and stiffness but usually conventional concrete is weak in tension and brittle material. Normal concrete has two principal weaknesses, low strain at fracture and tensile strength. Reinforcing concrete usually controls these shortcomings.

Karakurt and Arslan (2017), reported that concrete has several advantages due to its fresh and hardened properties however; the weakest points of this widely used construction material are brittleness and lower tensile strength. Technical concrete properties can be enhanced by addition different substances. Today, the necessity of using concrete in different areas has led to some enhancements in concrete technology.

Sukumar and John (2014), estimated that over seven billion tons of concrete is produced annually in the world, so it is the most widely used building substance. Concrete is cracked for a diversity of reasons. The cause of the crack may be due to, environmental, economic or structural reasons, but due to the natural weakness of the substance to attack tensile forces most cracks are formed. When it is restrained the concrete has shrunk and will crack again. The reinforcement of steel fibres is now known as control of cracking by making the concrete more ductile and tougher.

2.3. Fiber-reinforced concrete (FRC)

Fiber-reinforced concrete (FRC) is a class of concrete incorporating relatively short, discontinuous, discrete fibers as defined by Yew (2012). Normally, the addition of fibers is not for enhancing the strength of concrete, although significant increasement in strength will occur. But, the major effect of dispersed short fibers in concrete is to prevent cracks from spreading in concrete that are caused by their weakness in tensile strength.

According to Kumutha and Vijai (2010), the idea of adding fibres isn't new. Since ancient times, fiber has been used as reinforcement. Historically, straw was added in mud bricks, horse hair in mortar. For the first time asbestos fiber was added to concrete in the early twentieth century and in the fifties of the twentieth century the idea of composite materials appeared and fibre-reinforced concrete (FRC) was an important topic. In 1960s, steel fibre, glass fibre and polypropylene fibers had been used in concrete, and a new investigation of FRC goes on today. Fibres are generally added to concrete to eliminate drying and plastic shrinkage cracking and reducing the bleeding of water by lowering the concrete permeability.

Feng et al. (2018), reported that however concrete tensile strength is relatively weak in contrast with compressive strength, concrete is widely used building substances. The application of concrete in building and construction is limited due to this inherent deficiency. Adding substances with enhanced mechanical, durability and dynamic properties, (FRC) is ideal to prevent disaster and mitigate of blast application as it requires energy absorption capacities and good blast resistance. Fibre also helps prevent fine cracks which begins to develop during the compound hardening by the fibres bridging the cracked sections. The fibres added are mostly steel, polymer and carbon fibres.

Mermerdaş et al. (2019), reported that in order to enhance concrete structural integrity and mechanical characteristics, fibrous substances have been used to concrete. Fibers have been added as reinforcing agents since ancient times, and the idea is not new. The concept of reinforcement concrete with fibers and composite materials entered the field of interest decades ago and was one of the hot topics. Starting from 1960, many researchers have investigated the impact of using multiple types of fibres (steel, synthetic and glass fibres) to strengthen OPC concrete, and tried to observe the effectiveness of fibres on the durability properties.

Kanagavel and Arunachalam (2015), estimated that several concrete infrastructures are frequently exposed to short period dynamic loads in addition to static loads like earthquakes, wind gusts, influence from missiles and machine vibrations. Normal concrete fails suddenly under impact loading and in a brittle manner. To eliminate this deficiency, fibres have been used to concrete and enhanced mechanical characteristics. Addition of fibers reduce the drying shrinkage and improve flexural toughness, tensile strength, impact strength, durability, shear strength, etc.

Patil and Burile (2013), reported that brittle failure is one of the most deficiency of cement concrete and total loss of loading capacity, as it begins to fail. The application of the material is limited by this weakness, it can be removed by the inserting a small quantity of randomly short distributed fibres (steel, natural and glass fibre) also can be practiced among other things that handle concrete weaknesses, like low durability, high shrinkage cracking, low growth resistance, etc.

Selin-Ravikumar et al. (2015), confirmed that Fiber Reinforced concrete (FRC) have short uniformly distributed fibers which are randomly oriented. Fibers like natural, glass, steel, and synthetic fibers, each of them gives different properties to concrete. Fibres in concrete are used to eliminate cracking caused by plastic and drying shrinkage. Also, concrete permeability decreased by the addition of fibres. Some kinds of fibres make greater influence, shatter, and abrasion resistance of concrete. Usually, adding fibers to concrete cannot replace steel reinforcement and do not enhance its strength. The concrete strength may be decreased by addition of some kinds of fibres to concrete. The fibers quantity which is added to concrete is showed as a percentage of the total volume of the complex, expressed “volume fraction (V_f)”. The value of V_f is between 0.1 – 3 %. The aspect ratio (l/d) is determined by dividing length (l) by its diameter (d) of fiber. The fibres have a significant influence to enhance the tensile strength of the substance by carrying the load if fiber's modulus of elasticity is higher than the mortar or concrete. However, too long fibres that tend to flocculate in the mixture and produce consistency problems. When the weak concrete matrix is reinforced with steel fibres, is greatly enhanced, making the matrix perform as a composite material with characteristics that differ totally from normal concrete.

As many researchers Chandramouli et al. (2010), also described (FRC) is class of concrete made principally of cements, fine and coarse aggregates and short discrete fibers. FRC is a new substance. It is a composite substance which including small fibers that distributed randomly in the matrix, either artificial or natural, with high tensile strength. The cracking strength of concrete is enhanced and the fibers working as crack arresters due to the existence of these homogenously dispersed fibres. Fibres appropriate of reinforcing concrete having been produced from glass, steel and organic polymers. Plenty of the recent applications of FRC include the use of fibres ranging from about 1% of the volume of concrete.

Wafa (1990), indicated that experience shows that min content of cement of 400 kg/m^3, and (W/C) between 0.4 and 0.6 are wanted to cover the great surface area of the fibres with paste. FRC mixes are usually categorized by higher cement factor, smaller size coarse aggregate, and higher fine aggregate content when compared to normal concrete. The fibre mix usually needs more vibration to combine the mix. External vibration is preferred to eliminate segregation of fibers. Also, they are confirmed that an exposure of fiber steel mortar to external weathering atmosphere of industrial areas for ten years displayed no significant effect on the strength characteristics. Corrosion has been found limited only to fibres already exposed to the surface. The steel fibrous mortar has been submerging in sea water for 10 years with a loss of 15 percent compared to a decrease in the strength of plain mortar by 40 percent.

Vairagade and Kene (2012), reported that concrete is categorized by nearly-brittle failure, once failure is initiated, the quasi-whole loss of loading capacity. The application of the substance is limited due to this deficiency, also it can be removed by the using of small quantity of short fibres (natural and synthetic as steel, glass fiber) that randomly distributed also may practice among other things to treat weaknesses in concrete, like low durability, high shrinkage cracking and etc. Fibres are able to eliminate surface cracking by making bridges, which increases the impact resistance of the concrete.

Civici and Saylan (2016), illustrated that concrete is one of the most used structural substance recognized for its brittle properties. The research of gaining ductile feature on concrete was recently studied. Inclusion fibres in concrete is one of these works. The fibers in concrete have different kinds like steel, glass, wood and synthetic. Fiber concrete achieved with a mix of cement, water, aggregate and fibres is often used in construction of airport pavements, bridge decks, parking areas that are subject to cavity and erosion surfaces. FRC is preferred over normal concrete due to its high impact strength, cavitation resistance, tensile strength and toughness.

Ravikumarand and Thandavamoorthy (2011), reported that it has been a substantial demand in the addition of fibres to concrete over the decades, for enhancing some properties like ductility and tensile strength. Fibrous concrete is also used to modify existing concrete structures. Indeed, approximately 65 per cent of the fibers produced worldwide are currently used in concrete. Provides increasing toughness, enhanced load-carrying capacity and tighter crack control. Various types of fibers are available on the market for reinforcing concrete such as steel, glass, aramid, acrylic, nylon, carbon, polypropylene, polyethylene, polyester, etc. In addition, natural fibers such as wood and sisal.

Sukumar and John (2014), showed that the randomly oriented fibres help control the spread of small cracks that exist in the matrix, firstly by enhancing the resistance of structure to crack itself, finally by bridge across the small cracks created after applying the load on the matrix, thus avoiding its expansion to the major cracks (Figure 2.1.).

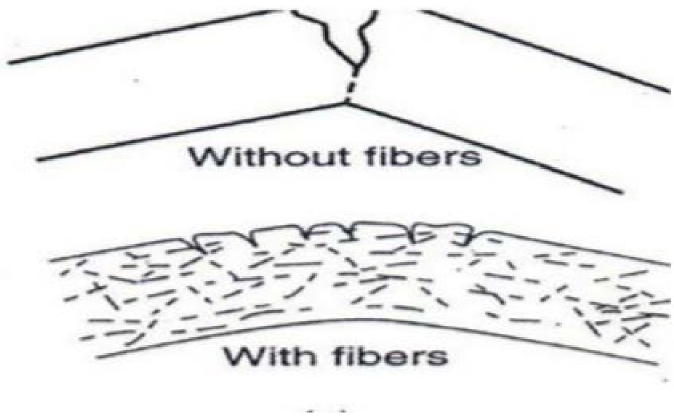

Figure 2.1. Mechanism of failure mechanism and fiber influences (Sukumar and John, 2014)

Deshmukh et al. (2012), presented that the concrete will grow the cracks without any fibres because of plastic, drying shrinkage and due to the volume changes of concrete. Elastic deformation of concrete will form by the development of these fine cracks. Conventional concrete is recognized by the properties of low modulus of rupture, strain capacity and also brittle substance and having the values of strain capacity and modulus of rupture is low. In order to enhance these properties, fibres are used in normal concrete. Adding fibres to normal concrete will reduce the water bleeding and also eliminate the cracking due shrinkage.

Kushartomo and Ivan (2017), reported that the toughness and strength of concrete can be developed by the using of fibres in to concrete. The length, direction, and the strength of the fibres influence concrete toughness and strength. The minimum fibre length is critical length that required to maintain stress or tension equal to the fibre's strength. Using of longer or shorter fibre outside the critical length will cause the non-optimum capacity and strength of the fibre to maintain tension. Flexural strength of FRC is influenced by aspect ratio fibres volume in the concrete mix.

2.3.1. Glass fiber

Amer et al. (2018), reported that glass fibre are produced from molten glass of a certain composition. The word (glass) in glass fibre mentions to various kinds of glass products. Glass fibre is a multipurpose industrial substance that is used recently. It can be simply manufactured using raw substances, obtainable in indefinite amounts. Glass fibers are made of silica (SiO_2) and Some other components such as (calcium, aluminum, …. etc.) are supplemented to silica base for reducing the temperature and imparting characteristics, that may be useful in some specific applications. The concrete tensile strength is enhanced by the addition of S-glass fibres due to high concentration of silica, which enhances its tensile strength. Table 2.1. presents the percentage of oxide for multiple kinds of common and commercial glass fiber substances.

Table 2.1. Chemical compositions of glass fibres in wt% (Amer et al., 2018)

Type of GF	percentage composition (%)										
	Sio_2	Al_2O_3	Fe_2O_3	TiO_2	B_2O_3	CaO	MgO	Na_2O	K_2O	ZnO	ZrO_2
A.	67.5	3.5	-	-	1.5	6.5	4.5	13.5	3	-	-
C.	64.3	4.1	-	-	5	13.4	3.3	9.6	0.5	-	-
D.	74	-	-	-	22.5	-	-	1.5	2.0	-	-
E.	55	14	-	0.2	7	22	1	0.5	0.3	-	-
R.	60	24	0.1	-	0.3	9	6	0.5	0.1	-	-
S.	65	25	-	-	-	-	10	-	-	-	-
ECR.	58.2	11.6	0.1	2.5	-	21.7	2.0	1.0	0.2	2.7	-
AR.	61	1.0	-	-	-	5	1	14	3	-	15

According to Kushartomo and Ivan (2017), the first using of glass fiber as a HPCC reinforcement was in Russia in 1940s and then in the early 1970s was familiarized in the United Kingdom for building industry. The mix between cement matrix and fiberglass is defined as the Glass Fibre Reinforced Concrete (GFRC). This mix preserves the chemical and physical identity of fibre and of cement matrix synergistically and attains a mixture of characteristics that cannot be attained separately.

Tajne and Bhandari (2014), showed that the great deal of research is recently being done concerning the addition of glass fibre as reinforcement in concrete. This is because of less weight, easy and rapid installation, and also decreases the dead load of the structure. The light weight and tough substance also reduce the transportation costs, allows flexibility in design, and decreases the impact on environment. Superior strength enhances the ability to afford seismic loads.

Ravikumar and Thandavamoorthy (2011), reported that glass fibers are useful, this is due to low weight and high surface area. While, the surface area is increasing the chemical attack to the surface increases. Glass fibres enhance the material strength by growing required power for deformation and increase the toughness by improving power demand to expand the crack. Another advantages of glass fibre are fire-resistant and high tensile strength and properties, thus reducing damage loss during fire of concrete structures. FRC is a new substance. The cracking strength of concrete is increased by existing of these small uniformly dispersed fibers and these fibres act as crack arresters. Also, FRC has higher fire resistance than normal concrete. So, glass fiber concrete has a better fire resistance property. Many of the current applications of FRC include the use of fibres ranging around 1-5%, by the volume of concrete.

Deshmukh et al. (2012), confirmed that concrete is a tension weak construction substance, that is frequently crack ridden connected to hardened states, drying shrinkage and plastic shrinkage. Furthermore, concrete suffers from low resistance for cracking, low tensile strength and limited ductility. In order to enhance these weaknesses, and efforts have been done to research the influence of adding glass fibres to OPC concrete. From the experimental outcomes and its investigation, it is clear that adding 0.1% glass fibres to concrete provides better results in durability and mechanical properties.

Amer et al. (2018), reported that glass fibre is a very advanced engineering substance due to its well fire, temperature, and chemical resistance characteristics. Recently, these materials are used in many complex applications, such as reinforcement of rubber and sealing substances, and as a concrete reinforcement substance in airport runways, parking, walls, pavements, septic tanks, slope stabilization and pipes.

2.3.2. Steel fiber

Kumutha and Vijai (2010), presented that reinforced concrete with steel fibres is a compound substance in which discrete steel fibres throughout the concrete matrix are distributed randomly. Investigate conducted extensively on steel fibre reinforced concrete has demonstrated that adding steel fibres to normal cement concrete enhances its flexural strength, ductility, toughness, cracking resistance, durability, etc. Steel fibres have been used to enhance the strength and fracture properties of concrete. The adding enhanced the ductility and increased the strain capacity.

Zheng et al. (2018), showed that with the vital progress in engineering structure, high performance concrete like FRC has gradually been applied in a significant structure. Among these high-performance concretes, it is clear that steel fiber reinforced concrete is widely used in the current engineering area for the advantages of low cost, easy production, and performance enhancements, However, the research confirmed that irregular fusion of steel fibre would influence the concrete uniformity mixing, consistency and also result in fibre bonding, which ultimately impacts of mechanical characteristics.

Sumathi and Mohan (2019), reported that using of steel fibre-reinforced concrete over the past three decades were modified and widespread, so it is difficult to classify it. The applications are tunnel linings, pavements, shotcrete and slabs.

Nis (2018), showed that plain concrete is a non-homogeneous brittle substance, strong in compression conversely weak in flexure and tension. Recently, the usage of steel fibre in concrete manufacturing is also developed to control this inherent weakness. Reinforced concrete with steel fibres has superior flexural and tensile performance in relation to normal concrete dependent on the kind and quantity of steel fibres. Furthermore, the control of crack width and ability of crack bridging improves interest in the addition of steel fibres to concrete, particularly in post-cracking stage. Researchers reported that the most used fibre sorts in building manufacturing are steel fibres. The performance of steel fibre is impacted by three various characteristics: (1)

steel fibre shape (straight, hook-end) and surface deformation; (2) steel fibre aspect ratio (l/d); (3) surface treatment. Surface deformation is usually made to increase the bonding between the matrix and the fibres. The aspect ratio of fibre l/d varies between (50-100) in structural applications. Under same l/d of fibre, the better crack bridging is obtained by using large number of fibres (short fibres). While higher fibre matrix bond area is obtained by using larger fibre l/d.

It has been known that adding uniformly tiny and dispersed fibres to concrete enhances their mechanical properties under static and dynamic loading and helps to arrest cracks as reported Ravikumar and Thandavamoorthy (2011). Round steel fibres are the most common type used to improve the flexural, impact and fatigue strength of concrete. The addition of this fibres also enhances the ductility and toughness of concrete. Steel fibres have been used in various types of structures such as road overlays, earthquake resistant structures, bridge decks and airfield pavements.

According to Nis (2018), stirrups in both beams and columns have been replaced with steel fibres as shear reinforcement in places that shear stresses are critical. In heavy structural elements, the transverse reinforcements are used in high seismic areas in order that attain ductile behaviour. Though, these excessive reinforcements might cause a problem placing concrete in strict areas. The number of transverse reinforcements is reduced by the using of steel fibres as a solution for the placement of concrete. However, the workability problems in concrete are caused by this quantity of steel fibres.

According to Khan et al. (2017), with the increaseent of steel fibre content in concrete, the flexural to compressive strength (f/c) ratio developes as illustrated in Figure 2.2.

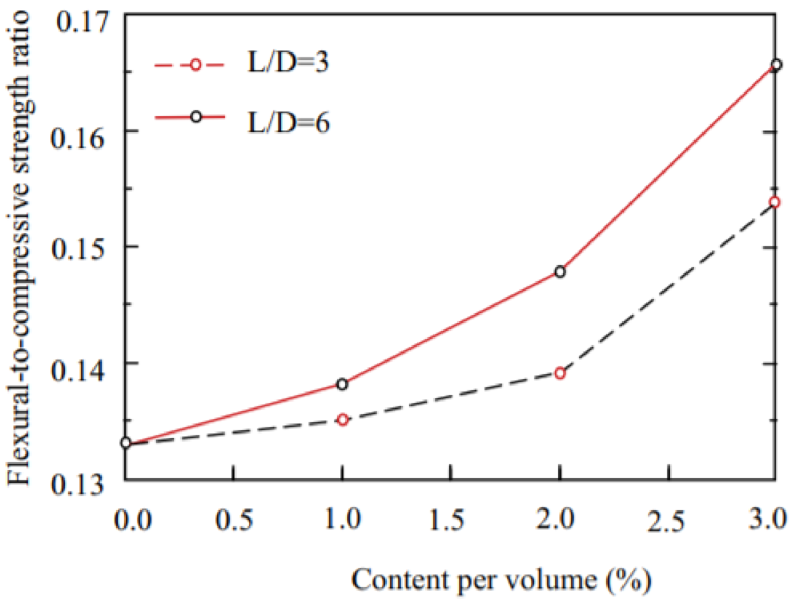

Figure 2.2. Impact of steel fibre content of the flexural strength of high-performance cement composite (Khan et al., 2017)

Sukumar and John (2014), confirmed that the usage of steel fibres to concrete not only enhances strength characteristics, but then also enhances ductility. Research has shown over the years that fibre reinforcement has appropriate strength and ductility to be used as a complete replacement for traditional steel bars in some kinds of structures; slabs, walls, foundations. The technology available today made it possible to consider fibre reinforcement without using conventional steel bars in load carrying structures. If the fibres can be used without steel reinforcement bars, then the reinforcement portion of the construction work will be eliminated. Thus, the construction costs will be reduced significantly.

Nis (2018), presented that straight and hooked-end type steel fibers are generally used for structural applications. By forming a single crack, normal concrete breaks down under flexural or tensile loading. However, the reinforced concrete with steel fibres resists the extra crack holes and several cracks noticed before failure. This is by the ability of steel fibres to arrest small cracks and thus avoid the production (mechanism of arresting micro cracks); and in the case of more stresses, the width of small cracks exceeds and turn into larger cracks. The steel fibres bridge the cracks after large cracks creation, and avoid more crack widening (mechanism of bridging cracks).

Figure 2.3. Steel fiber 6mm length (Hamiruddin et al., 2018)

Sumathi and Mohan (2019), showed that the adding of 1% steel fibres to concrete enhances the compressive strength by 25 to 30 %, at the age of 28, 90 and 180 days of normal curing after compared to plain concrete. Concrete with 1% steel fibre yielded well outcomes among different percentages of fibres and was discovered to be a better value in terms of ultimate load carrying capacity and ductility improvement.

2.3.3. Hybrid fiber

Hybrid fibers are the blend of more than one various type of fibers as defined Vineetha and Aravind (2017), if more than one sort of fibers is rationally mixed in a common matrix to create a compound that drives profits from each of the single fibres. Using of short discontinuous fiberes have a significant function in the enhancement of concrete mechanical properties. It reduces brittleness, enhances modulus of elasticity, cracks initiation control and its development. There are many applications of hybrid fiber reinforced concretes such as runways, roads and pavements, overlays and toppings, ground supported slabs, tanks and pools, machine foundation.

Vairagade and Kene (2012), confirm that the addition of more than one kind of fibres in an appropriate mixture may enhances the complete characteristics of concrete. Hybridization is a mixture of fibres. The blend of more than one kind of fibres (various fiber geometries and/or types) is becoming more public, with the purpose of improving the total behaviour of the system. The goal is that the act of these hybrid systems will outperform each type of fibre alone. That is, there will be a synergy. Synergy is categorized into three collections, according to the mechanisms involved:

1. Hybrids depend on the fiber-forming response, where one of the fibres is ductile and affords toughness at high strains, while other fibre is stiffer and offers strength.
2. Hybrids depend on sizes of fibres, where one of fibers is large which can capture the spreading micro-cracks; the other fiber is smaller and control microcracks at initial loading stages for enhancing the durability of the concrete.
3. Hybrids depend on function of fibers, where one kind of fiber is proposed to enhance the characteristics at early ages, while the second type supplies toughness or strength in the hardened composite (improve mechanical properties).

Vineetha and Aravind (2017), showed that adding of the hybrid fibre to the concrete at 7 and 28 days enhanced compressive strength of concrete. The increased of bonding and bridging impact of fibers with the matrix enhances concrete compressive strength. It has been observed that maximum value of the fibres in concrete is 1%. Concrete compressive strength decreases when the percentage of volume of fiber increases beyond its optimum value, this is due to the balling effect of fiber or increased interference of fibres with each other. This may create voids in the mixture, that drives to reduce the whole weight of the mixture and then mixtures compressive strength decreases. On the other hand, it has been noticed that the consistency decreased by increasing volume of fibers. This is because of hydrophilic properties of fibres. Workability can be reduced by the usage of admixtures to the matrix.

Singh and Rai (2018), defined hybridization is the using one or more various types of fibers in concrete, the combination of different material property is used to form a composite composition and usually termed as a hybrid. The hybrid composites enhance the overall concrete performance. Mechanical characteristics of concrete enhance in a limited range when concrete is reinforced with a single type of fibre, on the contrary, superior properties are attained in case of the fiber reinforced concrete when concrete is reinforced with two or more types of fibers. Researchers presented that the use of various types of fibres with various lengths can enhance concretes tensile strength and also for control of the cracks for both micro and macro-cracks.

Shrivastava and V.K. Shrivastava (2018), confirmed that hybrid fiber reinforcement is very effective for enhancing the strength characteristics, cracking and consistency will be enhanced if suitable design and construction methodology is adopted.

Sarangi and Sinha (2016), reported that in FRC include synthetic, natural, glass, or material fibres each with their original properties. More than two various sorts of fibers are added proportionally to concrete in a hybrid to create a compound material which has individual benefits of synergistic fibers. Hybridization of both synthetic and natural fibres can give potential advantages in enhancing concrete characteristics. At the same time, it reduces the cost of concrete production.

Kanagavel and Arunachalam (2015), reported that the overall performance of the composite can be improved in hybrid fibre systems improved, beyond the sum of the single achievement. Also, it is best found that the blend of various sorts of hybrid fibres in concrete gives better mechanical properties and enhances the engineering performance of concrete.

Feng et al. (2018), presented that to supply hybrid reinforcement, the smaller fibers bridge micro cracks and prevent the growth of cracks then the tensile strength can be enhanced but the other sort of fiber is larger, it can greatly improve composite toughness because it can arrest diffuse macro cracks. In practical terms, hybridization with two various fibres combined into a concrete matrix, the hybrid fiber reinforced concrete can supply more excellent engineering characteristics because the existence of first fibre enables the more efficient add of the potential characteristics of the second fibre. Moreover, HFRC exhibits enhanced structural behavior when compared to plain concrete, qualities like scabbing under impact loadings and less spalling.

Ravikumar and Thandavamoorthy (2011), exhibited the experimental program on hybrid fiber reinforced high performance concrete using three kinds of fibres steel fibre, glass fibre and polyester fibre of a famous brand. Silica fume (SF) is a mineral admixture was added as a partial replacement of cement in concrete and the use of super plasticizer (SP) to obtain the required consistency. Comparison of normal concrete with reinforced concrete with steel fibre and exhibited important strength enhancement of the HFRC because of the inclusion of both SF and fibres.

2.4. High strength concrete

Annadurai and Ravichandran (2013), has studied that the high-strength concrete incomes respectable impact, cavitation and abrasion’s resistance. High-performance and high-strength concrete are manufactured by upsurging the binder amount and dropping the water/binder ratio. It is widely used all over the world due to its economic benefits. Most of high strength concrete applications to date have been in long span bridges, multi-story buildings, and some different structures. The main application of high strength concrete was in multi-storey structures in and shear walls and columns, which resulted in an increase in the area of rented floors space on lower floors and decrease dead weight of the structures.

According to Patil and Burile (2013), the mechanical characteristics of concrete can be improved by changing in its components such as cementitious substance, water and aggregate and also by adding some special elements. Concrete is well matched for a wide range of applications still concrete has several shortcomings such as low ductility and brittleness, low tensile strength, low impact strength, low post cracking capacity and not suitable of large deformations.

Selin-Ravikumar et al. (2015), reported that concrete possesses appropriate workability properties and high strength, so it is a substance widely used over the world. In the field, efforts have been made of concrete technology to enhance such concretes with unusual properties. Researchers are still trying to enhance the performance of concretes through adding single or hybrid fibres and other admixtures in concrete up to determined proportions.

Kim et al. (2018), reported that high strength fiber reinforced concrete characteristics, including tensile properties and durability are superior to those normal concrete due to enhance particle size distribution and minimizing the microstructural porosity of concrete by using fillers with fine aggregates. Furthermore, steel fibres are including within the high strength fibre reinforced concrete.

The requirement of high strength Concretes is essential in today's construction industries. There are different types of high strength concrete technology such as engineered cementitious composites (ECC) and reactive powder concrete (RPC).

2.4.1. Engineered cementitious composites (ECC)

Engineered cementitious composites (ECC) can be taken into consideration a group of substances with a series of tensile strengths and ductility's that can be modified liable on the requirements of a specific infrastructure. ECC also signifies a group of substances with various functions furthermore to the common properties of fine multiple cracking and high tensile ductility as defined (Li, V.C., 2008).

Soe et al. (2013), also defined ECC is a cement-based substance that contains a mixture of cement, fly ash, water, sand, chemical admixtures and reinforced with short fibers erratically distributed with a fraction of the volume of fibers up to 2%. ECC materials are a kind of high-act fiber-reinforced cementitious composites, known for their superior mechanical characteristics. The ECC is considered a very promising substance for building defending and distrustful structures, excellent ability to absorb high energy and influence shutter resistance. The mechanical characteristics of ECC rely on the sort, volume fraction, geometry of ingredients utilized in the mix, and mainly, the properties of the fibers greatly influence the mechanical characteristics of substance.

Pan et al. (2012), reported that recently, a kind of high-performance fibre reinforced cementitious composites has been settled for applications in construction industry. It is called ECC. This family of substances is categorized by high ductility in range of 3% to 7%, a relatively low fraction of fibers of about 2% and a tight crack width about 60 micro meters. The mechanical properties of fibre reinforced cementitious composites principally depend on several parameters as properties of fibre, interface characteristic and matrix. Figure 2.4. exhibits a width control tight crack and its typical stress-strain curve of ECC.

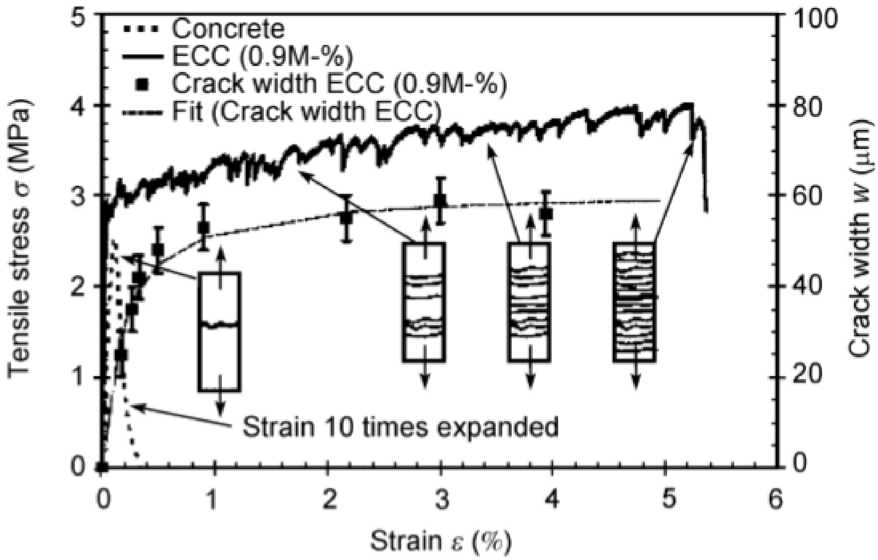

Figure 2.4. Tight crack width control and tensile strain hardening behaviour (Pan et al., 2012)

Figure 2.5. presents the difference between normal concrete and ECC, for normal concrete flexural member, it frequently does fail by brittle fracture in the mid of the span with high-pitched softening when the displacement upsurges but for ECC flexural member, the initial cracking load is alike to the load of the concrete flexural member. Though, with increased load, the first crack of the member does not open because of the effect of bridging of fibres at the cracked section. By increasing external load, it drives to added matrix cracking close to the main initial crack. For minor cracks, the bridging force between the matrix and fibers is comparatively small because of slighter opening of the crack.

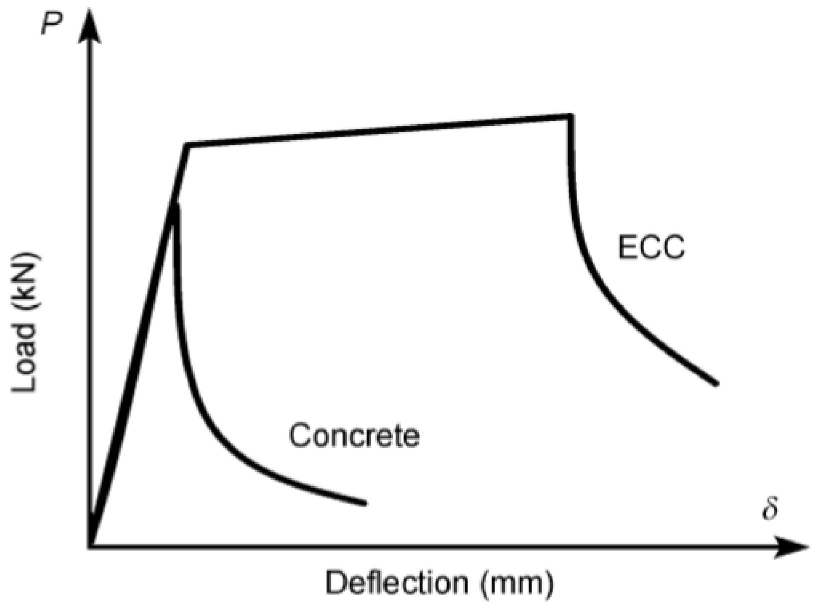

Figure 2.5. Schematic load-displacement curve for concrete and ECC beams (Pan et al., 2012)

According to Khan et al. (2017), using of fine materials like ground quartz, silica fume and various other popular substances, is obligatory in the making of durable and high-performance cementitious composite. The synergetic reaction between various groups of cement, chemical admixtures and fine materials at very low levels of water-to binder ratios helps to produce a high performance cementitious composite (HPCC).

Yuan et al. (2019), confirmed that single or hybrid fiber of various sizes are usually intended for concrete to improve strength and ductility. The hybrid fibre-reinforced composites benefited from each of the separate fibres and show a synergetic answer. There are many ways of hybridization include fiber types (tensile strength, modulus) and hybrids with various aspect ratios (diameters, lengths). Hybrid depend on fibre aspect ratios improved fracture toughness and results in a higher strength of the composites, which controlled microcracks and macrocracks, respectively.

Annadurai and Ravichandran (2013), reported that fiber - reinforced cement-based composites was established with the purpose of resolving structural complications essential with today's typical concrete, as their propensity to flop in a brittle manner under excessive loading and its deficiency of durability in long-term time. This special part of concrete possesses the individual ability to flex and self-strengthen before fracturing.

2.4.2 Reactive powder concrete (RPC)

Abdelalim et al. (2008), defined reactive powder concrete (RPC) is a very new group of cement based high strength compounds that attains excessive levels of compressive strength. The new requests for engineers and researches have been opened by the introduction of the RPC. In 1994, for the first time RPC was advanced in France as a new type of cement based high strength composites. RPC obtains the level of flexural strength between 30-60 N/mm2 and compressive strength between 120-200 N/mm2. Additionally, it is categorized by its high durability. By applying special conditions, the compressive strength of RPC is exceeded 200 N/mm2 as post set heat treatment and peripheral pressure before or through setting if necessary. The last ten years construction industry was developed so RPC was invented to serve various structural purposes.

RPC mix composed of high cement content, fine sand, SF, quartz (Q), and super Plasticizer (SP) but the coarse aggregate was eliminated. This is depending on the fundamental that materials with lowest internal voids will own a greater load-carrying capacity and show well structural performance. The absence of coarse aggregate reduced the heterogeneity between the aggregate and the cement matrix and thereby enhancing the microstructure and the performance. RPC is generally known as concrete not as mortar although the matrix does not contain coarse aggregate. Cement content has an important character to determine the strength of RPC. This factors impact was inspected by researchers and 800-1090 kg/m3 cement content was used by them.

Silica fume (SF) is added to RPC for pozzolanic reaction, increasing density and enhance the interfacial transition zone between sand and cement matrix. Kurdi et al. has studied the impact of SF content. The outcomes of their experimental training showed that the ideal content of SF for RPC is around 25% by weight of cement.

El-Hefnawy and Abbas reported the curing impact of RPC production. Their outcomes showed that applying heat treatment at 100 ºC to RPC for three hours, 24 hours after casting, resulting in a four-times enhancement in compressive strength than untreated. This enhancement enlarged to six times by the extension of heat-treatment to 24 hours.

According to Algburi et al. (2019), RPC is oversensitive to brittle failure like high strength concrete. The usage of fibres is the best system to increase the ductility of the RPC. Steel fibres have long been used for this purpose.

Aravindhan and Vijayakumar (2016), reported that RPC can supply a combination of ultra-high strength, high ductility cementitious composite with reinforcement by including a short steel fibre and advanced mechanical and physical characteristics with excellent durability so it is recognized as a revolutionary material. It contains of a special type concrete where the microstructure is improved by accurate gradation of all particles in the mixture to obtain the maximum density. The characteristics of pozzolanic are widely used for refined SF and improved Portland cement chemistry to make the highest strength hydrates. It was advanced at the Bouygues laboratory, France at mid-1990s. The 810 MPa and over Strengths were also noted. Since the high cement content in RPC is usually by as much as 700-1000 Kg/m3, the cement option could be a critical factor influencing RPC performance. In the use of concrete technology, SF has four major functions as follows:

(a) Voids between the large class elements like cement were filled by SF.
(b) Enhancing the durability and resistance of concrete, by reducing the permeability of concrete.
(c) The lime resulting from the primary hydration reacts with SF and producing secondary hydration.
(d) Reducing the expansion generated by alkali-aggregate and making the HPCC more abrasive force resistant.

Aravindhan and Vijayakumar (2016), reported that quartz (Q) is the main form of pure silica in nature and density is 2.65 g/cm3, also hardness is seven on the Mohr's scale and it is a very hard material. Quartz powder is used as micro filler, that can fill the gap between cement and SF. Flexural strength ranged between (25-50) MPa. The flexural strength of RPC is higher conventional concrete. SF supplies substantial enhancement in mechanical properties as the compressive, flexural strength, besides of other important enhancement in impermeability and durability.

According to Kushartomo and Ivan (2017), RPC is a kind of high ductility and strength concrete which contains only fine aggregate. Its microstructure has been produced by suitable particle size distribution of the substances confined in a concrete mix to enhance concrete density. RPC consists of extremely fine aggregates for instance SF, sand, cement, various kinds of fibres, and superplasticizer SP. The RPCs compressive strength between 200 to 800 MPa.

Anusiya and Oviya (2017), showed that RPC is a new substance. The composition of RPC is Portland cement, a dosage of superplasticizer, low water-to binder ratio, and the existence of very fine SF and crushed quartz and also coarse aggregate is eliminated. Coarse aggregate in conventional concrete is totally changed with fine quartz sand. The RPC exhibits very good granular compactness and porosity is reduced by low water content of the concrete. The RPC and high strength concrete durability was determined by measuring the corrosion, absorption of water and the mass loss of concrete after exposure to sulphate and acid.

Anusiya and Oviya (2017), reported that the RPC concept was advanced by P.Richard and M.Cheyrezy for the first time. At Bouges' laboratory in France, RPC was first invented in the initial 1990s by researchers. The first application of RPC in the world is the sherbooke bridge in Canada. It was built in July 1997. Mechanical characteristics have been achieved by reducing the ratio of water/binder and frequently adding SP and SF. RPC is a class of concrete utilizing four main bases:

1. Enhancement of the homogeneity of substance by eliminating coarse aggregates.
2. Increased compactness by compaction and granular optimization.
3. Possible enhancement of the microstructure with the idea of heat treatment.
4. Ductility accomplishment of the substance by adding of steel fibers.

RPC applications have some economic benefits although the costs of manufacturing of RPC are usually higher than for conventional concrete. By incorporating short steel fibres, the use of steel bar reinforcement can be eliminated. Moreover, ultra-high mechanical performance of RPC reduces concrete thickness, which saves material and cost.

2.8. Acid Effects

The concrete has been taken three forms due to the acid attack. First, formation of dissolved ions because of the reaction between hydration products and acid which is leading to damage of solid material. Then, insoluble salts are formed, in the matter of some acids, some of which take part to reason extension and cracking. Lastly, some acid gives complexes containing aluminium, calcium, iron and silicate ions that make much higher concentrations of these ions in the solution than was the case, once more deriving to dissolution.

In urban areas due to high population, increased number of factories and hazardous wastes, the durability of the structures under chemical attacks becomes significant as reported Gülşan et al. (2018). The hot topic among researchers is the degradation of normal concrete under chemical attacks and ongoing studies continue to prevent the concrete degradation under chemical exposures. In earthquake zones as well as chemical attacks, structures are subjected to axial load, shear force and bending moment. In such a case, the structures are exposed to seismic loads after a loss of mechanical strength due to chemical attack and the structures failure becomes inevitable.

According to Olonade et al. (2014), durable concrete when exposed to the environment retains its original shape, quality and serviceability. Acidic is one of these environments, to which concrete can be exposed. Acid exposure on concrete may come from various sources like bacterial contamination and air pollution.

Mahdikhani et al. (2018), confirmed that studies have showed that degradation of concrete occurs when it is exposed to acidic solution, because acid enters into concrete and interacts with the compounds of concrete.

Salman and Zghair (2018), reported that Portland cement concrete is decomposed slowly or rapidly by acid solutions depending on the concentration and sorts of acid due to the concrete being not a complete acid resistance. The weakest portion of the cement hydrate is Calcium hydroxide Ca $(OH)_2$, but calcium silicate hydrates C-S-H gel is also attacked. Concrete is attacked with PH less than 6.5 liquids but attacks are only severe with a pH less than 5.5, less than 4.5 the attack is very severe.

Izzat et al. (2013), reported that the pH values of OPC usually above 12.5 so it is extremely alkaline and can be simply exposed with acid solutions. When OPC is exposed to acid, the pH value of the solution reduces, the equilibrium is disturbed and due to hydrolytic decomposition the hydrated OPC compounds are changed. At less than 12.5 of pH value, portlandite is the first ingredient that to start dissolving. If pH is less than stability limits for cement hydration composites, then the equivalent hydrates lose calcium and decompose into amorphous hydrogel. The last outputs of exposure to acid are the corresponding calcium salt of the acid as well as hydrogels of ferric oxides, silica and alumina.

Türkel et al. (2007), notified that the hardened Portland cement binders' integrity is extremely based on high levels of alkalinity contain that ordinarily settle the gel composite responsible for cementitious characteristics. The binder alkaline components $Ca(OH)_2$, C-S-H, C-A-H interact with acids which reduce alkalinity degree. In most cases, the alkaline acids may be completely neutralized. These chemical variations are disastrous and matrix disintegration. Since Portland cement contains a high percentage of Ca $(OH)_2$ emitted while hydrating calcium silicates, it is the weakest cement type to acidic attack.

Marcos-Meson et al. (2019), reported that when cement-based substances exposure to low-pH solutions endorses the dissolution of the phases of the chief hardened cement paste and some aggregates (i.e. calcium-based), which leads to alkalinity loss and basic pore solution, increased porosity and a corrosion of the matrix's mechanical characteristics. This phenomenon is commonly known as 'corrosion of concrete or cement". The filtration of melted calcium, hydroxyl, alkali and other ions show in the pore solution, as a consequence of the gradient concentration of the ionic species (Figure 2.6.). The free OH- and alkali (i.e.(a)+) are increasingly disbursed by neutralizing the H+ ions and acid radicals (i.e.(X)-) that circulate in the pore solution, and produce water and salts molecules.

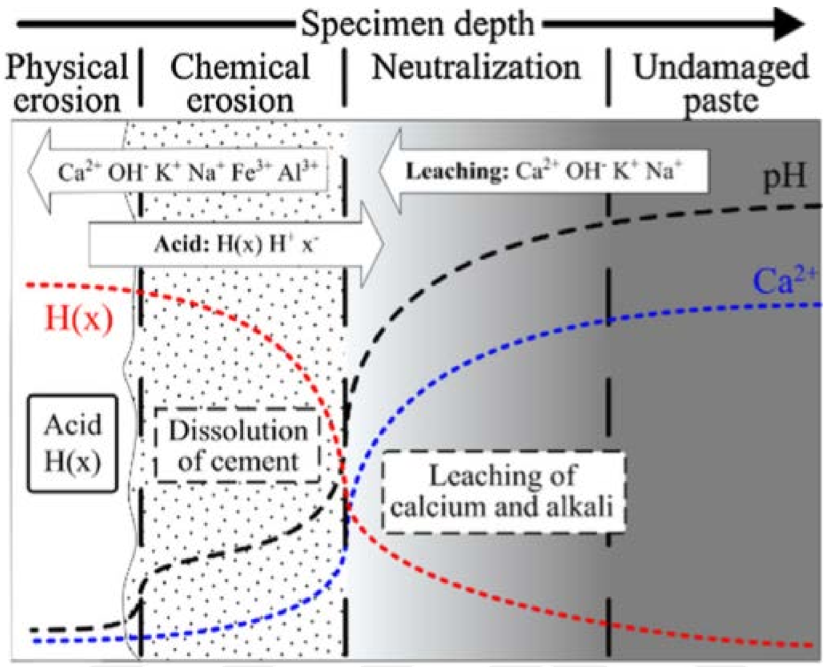

Figure 2.6. Cement paste dissolution and neutralization for a given acid H(x). (Marcos-Meson et al., 2019)

Makhloufi et al. (2014), showed that sulphuric acid reacts with calcium carbonate leads to the gypsum deposition “$CaSO_4.2H_2O$”. These gypsum coverings have been considered in natural rocks like marble and limestone. $CaCO_3$ and Ca $(OH)_2$ are dissolved by the H+ ions of the sulphuric acid, while the instantaneous reaction of Ca2+ with SO42- causes degradation because of the gypsum deposition on the surface of cementitious substance. The solubility of calcium salts and the ability of acid to isolated the components of the cementitious substance also play a substantial role in the deterioration of these substances.

Izzat et al. (2013), showed that the creation of gypsum and ettringite are the chemical reactions that may take part to the procedure of expansive degradation mechanisms. According to previous studies the calcium sulphate (gypsums) production, drives to softening (reduce in density) and increases the concrete volume. The main indicator of degradation of OPC are the weight loss and the expansion of samples since the acid exposure is a surface phenomenon. The alkalinity of cement itself is a base of acidic exposure completely. The main cause of acid attack is the acid-alkali reaction in the cement network. The first composite has been attacked by acid is calcium hydroxide Ca $(OH)_2$ and this reaction is the major cause for the hydrolytic disintegration in OPC.

Taku et al. (2015), found that concrete works can be in constant contact with chemicals that refute the durability of infrastructures in such an environment like in case of chemical factories, acid rains or acidic soils, etc. Acid attack is one of the important substances that could affect the concrete strength gain rate. The foundation of structures can be damaged and thus can lead to the failure of the whole infrastructure.

Olonade et al. (2014), proved that acid decreases concrete alkalinity by reacting with the hydration products of the concrete so acidic environment is harmful to the durability of concrete which leads to create ettringite and gypsum. The Equations (1) and (2) show this neutralization phenomenon, it is the chemical reaction of with sulfuric acid. Both ettringite and gypsum have low strength, but they have larger volumes of composites that they replace. This consequences in internal pressures, production of cracks and finally, the loss of strength. Thus, the concrete becomes weak to aggressive attack.

$$H_2SO_4 + Ca(OH)_2 \text{ ----- } CaSO_4.2H_2O \text{ (gypsum)} \qquad (2.1)$$

$$3CaSO_4 + 3CaO.Al_2O_3.6H_2O + 25H_2O \text{ ---- } 3CaO.Al_2O_3.3CaSO_4.31H_2O \text{ (ettringite)} \qquad (2.2)$$

According to Taku et al. (2015), that the rate of degradation of concrete is affected by many factors when exposed to acidic substances such as cement paste porosity, acid concentration, acid solubility, fluid transport out of the concrete, the quality of concrete, movement of water on the concrete surface, aggregate and cement types and etc. Researchers reported that acidic curing environment has a damaging impact on the flexural, compressive strengths as well as unit weight of concrete. Both proportion concentration of acid and curing age increases the reduction in strength of concrete in the normal water curing. There is a near linear relationship between weight and strength loss with increased acid content.

Türkel et al. (2007), reported that the sources of aggressive acid are wide may be due to urban activity it originates from industrial processes and also, natural exposure conditions such as sulfuric acids and carbonic waters and sulfurous in peat waters can source acid attacks but free acids in natural waters are seldom. Soils may contain luminous acids. Important amounts of free acids can be found in factories and plants. In these situations, the acid concentration contacts with concrete infrastructures, can range to very high values. It is notified that by upsurging the acid concentration of solution the pH values of the acidic solutions were slightly decreased (Table 2.2.) aggressive influences of strong acids frequently is related to pH.

Table 2.2. PH values of various aggressive solutions (Türkel et al., 2007)

	Concentrations and pH values of inorganic acids			
Acid type	0·05(M)	0·075(M)	0·100(M)	0·125(M)
Hydrochloric	1·3	1·2	1.0	0·9
Nitric	1·2	1·1	0·9	0·8
Sulfuric	1·2	1·0	0·9	0.8

Hasan et al. (2016), showed that underground concrete structures are generally subjected to different chemical materials, including sulfate, that are found everywhere in soil, seawater and groundwater. It has long been known that sulfate attack normally leads to the creation of expansion product, such as gypsum, ettringite, and thaumasite, which are produced by sulfate ions that interact with cement hydration product, resulting in spalling, cracking, expansion and strength loss of concrete. The concrete structures degradation is caused by the sulfate attack from the concrete surface and the extent of the damage can be expressed by the amount of expansion by the attack or as a function of the depth of attack and the progress rate.

Salman and Zghair (2018), reported that the most harmful of natural threats to concrete structures are Sulphuric acid fluids. Mostly, they originate from industrial processes, but they are because of urban areas activities. There are great amounts of acids in sewerage systems.

Barbhuiya and Kumala (2017), showed that the most aggressive acids to work on concrete is sulphuric acid (H_2SO_4) due to a mixture of sulphate and acid attack. The degradation of the concrete sewage pipes due to the aggressive sulfuric acid attack is a worldwide problematic around the world. Concrete structures in industrial areas are subjected to sulfuric acid because of industrial waste often containing a large quantity of sulfuric acid. The creation of gypsum resulting from the chemical reaction due to sulfuric acid attack in concrete causes volume increase. Gypsum also reacts with (C_3A) to create ettringite. Ettringite sources inner pressure in concrete due to the increase in volumes approximately seven times more than the initial composites which creates cracks. Finally, the corroded concrete loses its mechanical strength which takes part to more spalling, cracking and eventually leads to whole destruction.

Kawai et al. (2005), confirmed that it was found that the time of exposure of acid solution to that HPCC was exposed is approximately proportional to the concrete erosion depth and the rate of degradation of concrete due to the sulfuric acid exposure depends on the acids PH. Regarding the mechanism of degradation of concrete due to aggressive sulfuric acid, researchers reported that sulfuric acid entering into mortar or concrete interacts with cement hydrates as $Ca(OH)_2$ to create gypsum and the increasing volume mainly and reasons expansion of reaction products.

Tsubone et al. (2016), reported that concrete degradation was investigated due to sulfuric acid exposures in sewer and waste water treatment plants. To estimate this kind of degradation, the immersion of concrete specimens in sulfuric acid solutions are generally tested, and the physical dials of the degree of degradation can be the weight loss and erosion depth of the samples, while the penetration of sulfate ion is used as a chemical indicator.

According to Mahmoodian and Alani (2017), the corrosion process undergoes several chemical processes: the sulphate in the wastewater goes into sulphide (Figure

2.7.), before the sulphide is raised into the air in the form of gas, where the hydrogen sulphide is oxidized on moist surfaces into sulfuric acid. The PH of new concrete pipe is usually high about 11 to 13. Some compounds of cement as calcium hydroxide, which neutralizes the acid and cause a very strong acid exposure. The properties of the cementitious materials and the rate of sulfuric acid generation determine the corrosion rate of the sewer pipe wall. When sulphides are created and sulfuric acid is formed, reacts with hydration products of concrete and converts to calcium sulphate, normally recognized by its mineral name, gypsum. Especially when wet, gypsum offers little structural support. It is normally existing as a white pasty mass on concrete surfaces. when gypsum is battered, the concrete loses its bond and starts to spall, revealing new surfaces. Until the pipeline fails this process will continue.

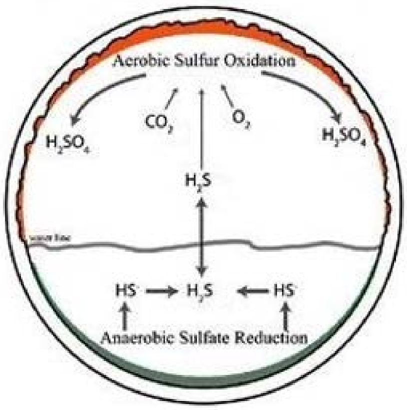

Figure 2.7. Corrosion process in concrete sewers (Mahmoodian and Alani, 2017)

Gutierrez-Padilla et al (2009), showed that for concrete specimens for 64 days exposure in 0.5%, 0.2% and 0.05% sulphuric acid solution estimated that the corrosion ranges of 2.19, 0.76 and 0.18mm/year. Mahmoodian and Alani (2017) confirmed that the concrete degradation can be determined by percentage of weight loss in relation to exposure time under laboratory conditions. Also, considered that their study could be useful for research in the field of modelling concrete degradation sewerages as well as service life estimate.

Min and Song (2018), reported that destructive sulfuric acid is principally resulting from acid rain, sewage treatment systems and industrial environment;

moreover, the physical and chemical interactions between cement hydration products and aggressive sulfuric acid are main sources for the failure of the durability concrete infrastructures.

Hassan et al. (2016), informed that modulus of elasticity and compressive strength of concrete exposed to aggressive sulfuric acid are lower than original concrete because concrete subjected to sulfuric acid suffers from internal micro cracking. With rising the duration time of exposure, the modulus of elasticity and compressive strength decrease.

Marcos-Meson et al. (2019), notified that great number of parameters, as: the (w/b) ratio, the type of cementitious materials, aggregate reactivity and specially the kind and acid concentration affects the shape of the PH profile through the uncracked concrete depth. A recent study showed that strong acids like sulfuric acid at PH = 2 to 4, make a sharp reduction of the pH and a narrow neutralization front While, weaker acids as boric acid at PH = 5 to 6, would make a wider neutralization front with a smooth decrease in the PH. For lower concentrations or weaker acids, the chemical erosion depth will decrease significantly, and it is highly dependent of the stability of the formed salts and secondary reactions, see (Figure 2.8.).

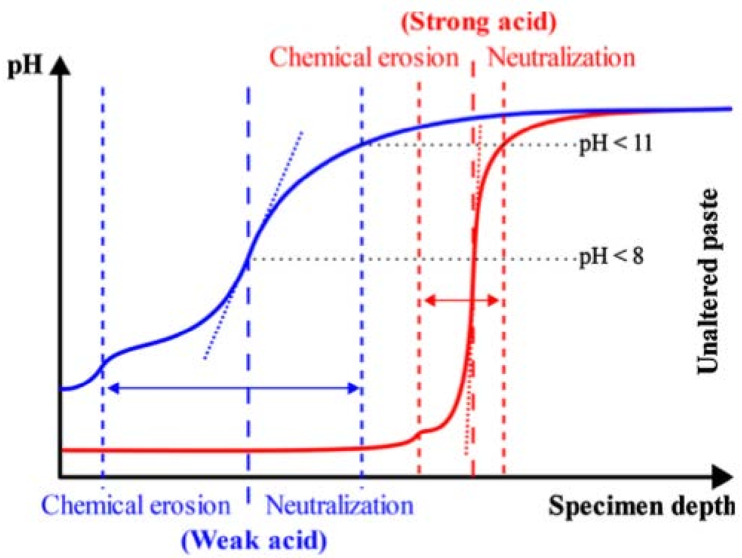

Figure 2.8. Symbolic PH profiles for concrete subjected to weak and strong acids (Marcos-Meson et al., 2019)

Olonade et al. (2014), reported that the reducing of concrete cubes weight is observing gradually. This impact can be referred to the curing influence in sulfric acid solution (Figure 2.9.). Presents the plot of average concrete cubes weight versus the different media curing ages.

Figure 2.9. Ca $(OH)_2$ leaching from concrete samples in the H_2SO_4 solutions at 90-day curing (Olonade et al., 2014)

According to Marcos-Meson et al. (2019), factors affecting the deterioration cement paste due to expose to acids are:

1. Exposure type: The degradation progress of cement paste is greatly impacted by the sort of exposure and consequently the chemical erosion of the concrete and corrosion of the steel.
2. The quality and type of binder: The degradation of concrete due to exposed to acids is largely impacted by the quality and sort of binder and of the cement matrix. An effective use of SF was proposed in restricting the entrance of chemical erosion front. It is suggested to refine the pore-structure as the governing mechanism. Though, opposing outcomes recommend a lower performance of SF in ternary blends under acid attack. Generally, it has been shown that lower w/b ratios make a denser microstructure with a high acid attack resistance.
3. Type and quantity of fibers: There are plenty of studies focusing on the impact of fiber content on the degradation of reinforced concrete with steel fibres subjected to acids.

Marcos- et al. (2019), reported that the adding of steel fibers was recorded to reduce the prevalence of the chemical-erosion and reduce the rate of weight-loss rate acid-showing steel fiber reinforced concrete, especially in case of sulfuric acid exposure, where the secondary sulphate attack provides a cracking expansion deepens the acid exposure. There are conflicting outcomes regarding the effectiveness of steel fibers in relation to other fibers (such as glass and polymers): most studies indicate an enhanced performance of steel fiber reinforced concrete relative to glass or plastic fibers for uncracked concrete; whereas for cracked steel fiber reinforced concrete, severe corrosion of steel fibers bridging cracks was stated. The general degradation mechanism responsible for acid exposure on steel fiber reinforced concrete may follow the scheme presented in Figure 2.10.

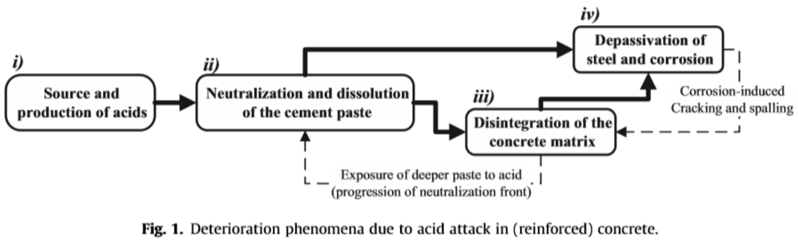

Figure 2.10. Degradation phenomena by acid exposure in (reinforced) concrete (Marcos-Meson et al., 2019)

Also, Marcos-Meson et al. (2019), has studied that the exposure of the aggregates to the acidic environment caused by gradual dissolution of the cement paste. Two scenarios are considered at this phase: i) the existence of acid-resistant aggregate like quartz, which is insoluble in the acidic environment and therefore will not lead to the deterioration of the presence of acid-soluble aggregates, like dolomite or limestone. The dissolution of cement matrix and acid-soluble aggregate will contribute to the reestablishment of neutral and calcium balance in the pore solution; while conversely, it will upsurge porosity and thus facilitate ion transport. It is shown that the balance between these two variable quantities can enhance the resistance of acid-erosion of the concrete, because some acid-soluble aggregate like limestone will offer slower rates of chemical-erosion for the concrete compared to acid-resistant aggregate. The addition of fiber reinforcement was proposed as being active in limiting the prevalence of the erosion front by reducing the spreading of cracks in the matrix and preventing concrete spalling.

Amudhavalli and Mathew (2012), showed that the concrete containing silica fume was more resistant against acid exposure. The reason behind this is the filling effects of sf which make the concrete dense and prevent the entry of acid into the concrete.

3. MATERIAL and METHOD

3.1. Introduction

This chapter describes various tests for ingredient substances and engineering characteristics utilized in this investigation. The experimental work consists of 14 high performance cement based composite (HPCC) mixtures that containing various types of fibers with different ratios and replacement of cement with mineral admixtures. All works were done of the civil engineering departments laboratory at Harran university. The substances, mix designs, mixing, casting, curing in different conditions and test methods were explained in details.

3.2. Materials

3.2.1. Cement

Ordinary Portland cement CEM I 52.5 R was used in the experimental program as the main binding material. Cement was manufactured by KAHRAMANMARAS company in bags according to Turkish Standards (TSEN 197-1). The weight of each bag is around 50 kg. The OPC used must be of the same batch for the whole series of test. The chemical composition of cement is presented in (Table 3.1.).

Table 3.1. Chemical composition of cement

Compositions (%)	Portland cement
CaO	63.28
SiO_2	18.91
Al_2O_3	5.02
Fe_2O_3	3.12
SO_3	2.90
K_2O	0.68
Na_2O	0.14

3.2.2. Silica Fume (SF)

The American concrete Institute (ACI) describes SF as extremely fine nanocrystalline silica that is manufactured as a by-product in electric arc oven of the creation of elemental silicon or alloys including silicon (ACI 116R). Generally high-strength concrete contains one or more supplementary cementitious materials like SF, metakaolin, blast furnace slag, fly ash, etc. SF as a partial replacement for Portland cement by volume and a specific gravity of 2.2 has been used for the creation of high strength concrete. The SF used for this research was obtained by local supplier. It enables to achieve extremely high compressive strength ranges between (70-120) MPa. SF also reduce the permeability of HPCC and lubricates the HPCC. The suggested amount of (5-15) % adding by cement weight with very low water/binder ratios. Though, this can be varied depend on the desired HPCC properties. The chemical composition of the SF utilized in this work is showed in (Table 3.2.).

Table 3.2. Chemical composition of SF

Compositions	Silica Fume
CaO (%)	0.45
SiO_2 (%)	96.36
Al_2O_3 (%)	0.71
Fe_2O_3 (%)	1.31
SO_3 (%)	0.41
K_2O	1.52
Na_2O	0.45

SF enhances HPCC by two mechanisms: -

Pozzolanic impact:

When adding SF to HPCC, it stays initially inert. Once water interacts with Portland cement in the mix, hydration occurs with the formation of two productions, as given below:

$$OPC + H_2O \text{ -------------- } CSH \text{ (Calcium silicate hydrate) } + Ca(OH)_2 \quad (3.1)$$

In the existence of SF, silicon dioxide from SF reacts with the calcium hydroxide which results in supplementary CSH in many of the voids around hydrated cement particles as follows:

$$Ca(OH)_2 + SiO_2 + H_2O \text{ ---------------- } CSH \quad (3.2)$$

In HPCC the quantity of $Ca(OH)_2$ can be reduced by pozzolanic reaction. $Ca(OH)_2$ is weak and does not contribute the strength of HPCC. It forms a soluble salt when combine with carbon dioxide which will leak over the HPCC causing an architectural problematic called efflorescence. Additional CSH for HPCC provides not only enhanced bond, flexural and compressive strength but also makes a matrix denser, mostly in areas which would have stayed as small voids expose to the possibility of harmful substances entering. Also, HPCC is more susceptible to chemical, sulphate attack and adverse alkali-aggregate reactions when there are large quantities of $Ca(OH)_2$ in the HPCC.

Micro filler impact:

SF is very fine substance, with the diameter 100x finer than cement (Figure 3.1). The surface area is extremely large because of SF particles are too small. The ranges of 15% SF replacement of cement are estimated by the ACI 234R, Guide for the usage of SF in HPCC, there are around 2,000,000 particles of SF for each particle of Portland cement. This prevents bleeding and a weak transition area between paste and aggregate found in conventional concrete. This micro filler impact will significantly enhance the aggregate to paste bond of HPCC and reduce permeability compared to normal concrete.

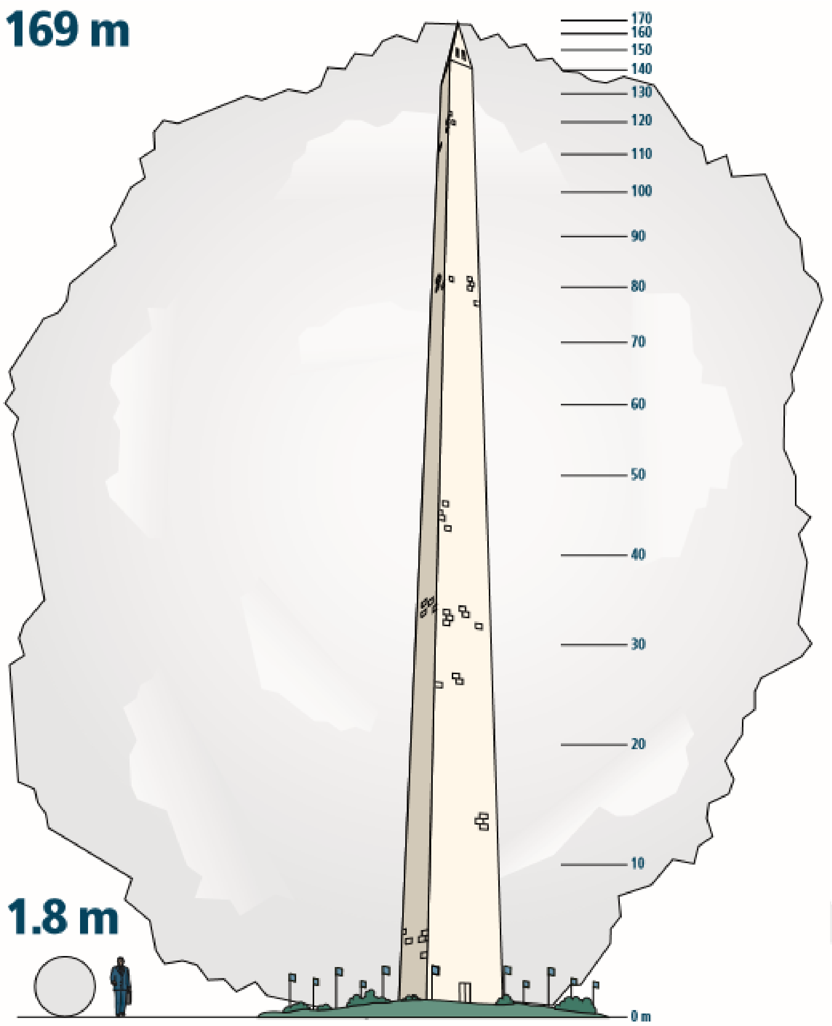

Figure 3.1. Comparison of SF with cement particles. If a person (1.8m) is the size of a SF, then the size of the Washington Monument(169m) would be the size of cement grain (Holland, 2005)

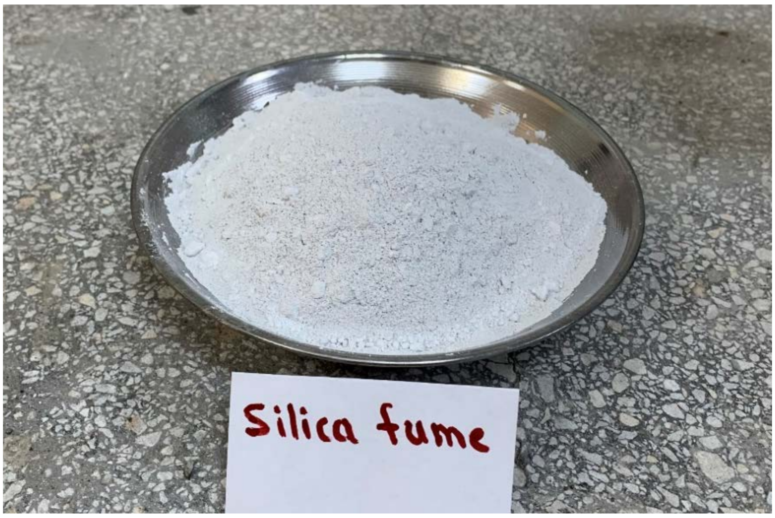

Figure 3.2. Silica fume.

3.2.3. Fine aggregates

3.2.3.1. Sand

Fine aggregate is a significant constituent of HPCC, that is frequently took out from the river. Local river sand with a maximum size of 4mm was used in this research, the sand grade from (0-4mm). The sand was stored in laboratory conditions, the specific gravity of sand is 2.66.

3.2.3.2. Quartz

The main form of clean silica is quartz and is an extremely hard substance, its hardness equal to 7 on Mohr’s scale and specific gravity is 2.65. The largest size of particles is 2mm and also it is used in the manufacture of HPCC. It is in a form of yellowish-white high purity silica sand and was supplied from POMZA EXPORT company in 20 kg bags. The river sand and quartz used in this investigation are shown in Figure 3.3.

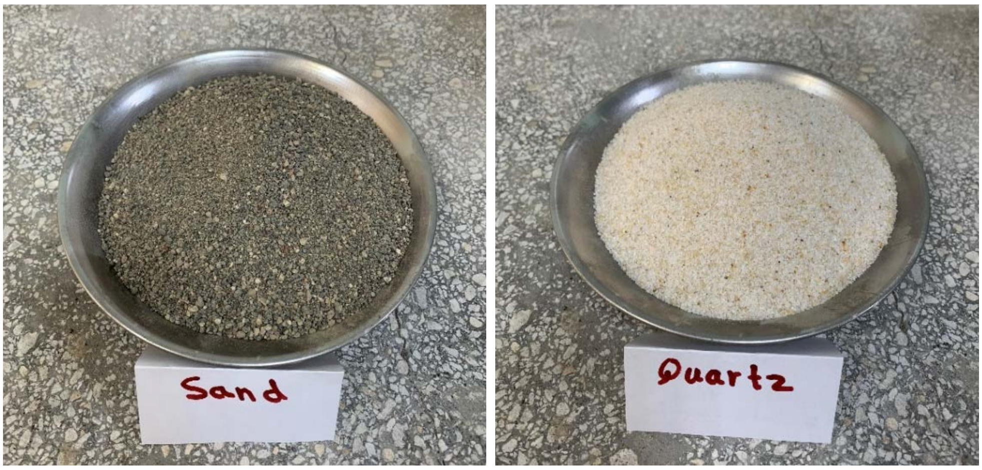

Figure 3.3. River sand and quartz

The river sand and quartz sand were combined in the ratio of 1.1binder (B):0.39(B) respectively. The sieve analysis of the fine aggregate was done to attain a fine aggregate according to ASTM C136. The grading of fine aggregate is presented in Table 3.3. and Figure 3.4. that indicates that the grading of the fine aggregates conforms to the necessities of ASTM C33.

Table 3.3. Grading of the fine aggregates: river sand and quartz

Sieve Size (mm)	Percentage Passing
4	100
2	96.88
1	68.37
0.5	26.56
0.25	8.29

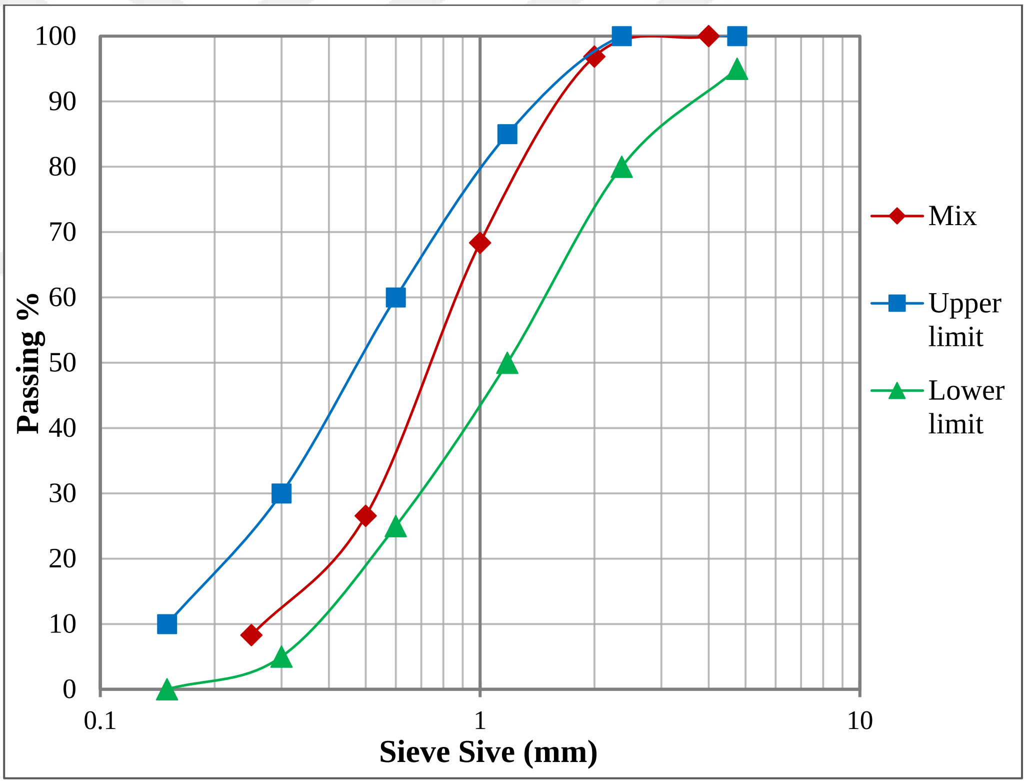

Figure 3.4. Particle size distribution of fine aggregates according to ASTM C 33 (2003)

3.2.4. Water

The tap water was used in this research for HPCC mixing and curing. The distilled water was obtained from Harran University-Environmental Engineering Department for preparation of acid solution.

3.2.5. Fibers

There are two kinds of fibres used in this experimental study. These fibres are obtained from Spinteks is a fabric product manufacture in Turkey. The first type of fiber is steel fiber with length about 6 mm, straight type and golden color. The specific gravity of steel fiber is 7.85. The second type is glass fiber with length about 3 mm and white color. The specific gravity of glass fiber is 2.60. The steel and glass fiber were used during mixing separately with the same volume ratio. Also, the hybrid of two fibers was used to obtain the main goal of study for enhancing mechanical properties of HPCC. All these fiberes is seen in Figure 3.5. Furthermore, their characteristics are presented in Table 3.4.

Table 3.4. Physical properties of fibers

Fiber type	Length, mm	Diameter, mm	Specific gravity
Steel fiber	6	0.2	7.85
Glass fiber	3	0.01	2.60

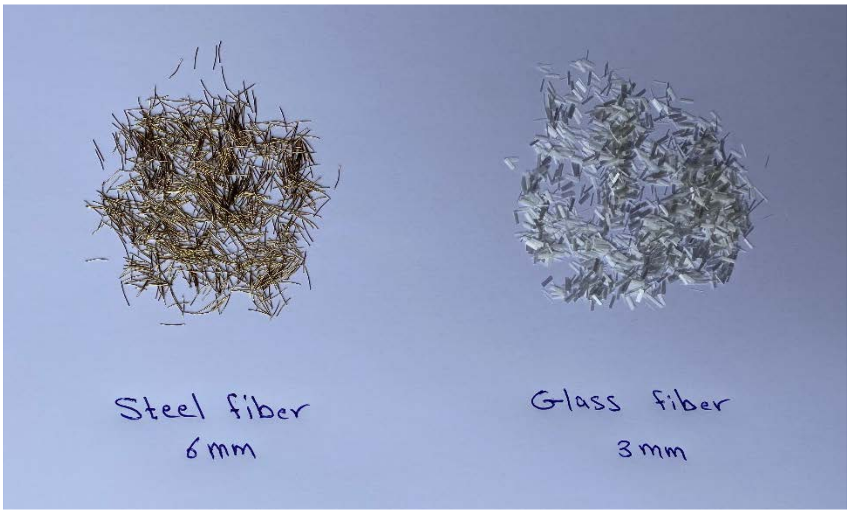

Figure 3.5. Steel fiber (6mm) and glass fiber (3mm)

3.2.6. Superplasticizer

The inclusion of fibers resulted in decrease in the workability. To enhance HPCC workability, high-range water reducer (Superplasticizers, SP) are added to a HPCC mix. Unfortunately, Superplasticized HPCC entraps more air than normal HPCC, but most of this air is normally gone through casting process by using vibrators. In present study, the solution of Master Glenium Gunas 51 procured from BASF Company was used with a specific gravity of 1.07 to improve the workability of fresh HPCC and to support the strength enhancement of hardened HPCC. The properties of SP are presented in (Table 3.5.).

Table 3.5. Characteristics of superplasticizer

Properties	Superplasticizer
Name	Glenium 51
Color tone	Dark brown
State	Liquid
Specific gravity (kg/l)	1.07
Chemical description	Polycarboxilate ether

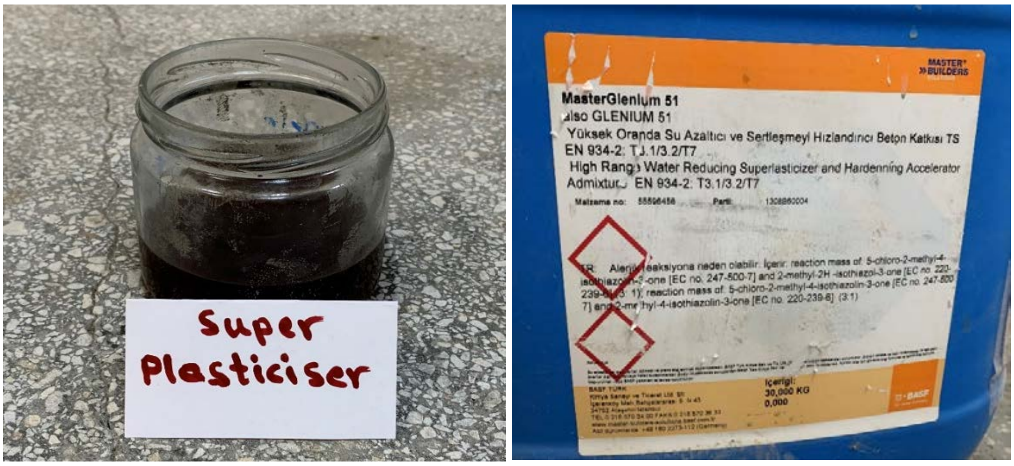

Figure 3.6. Superplasticizer

3.3. Experimental study

The experimental study in the research principally concentrates on effect of hybrid fiber reinforcement on development of the mechanical properties of HPCC and the resistance of various HPCC samples to aggressive sulphuric acid exposures. The pore structure and porosity of various HPCC mixes are also estimated by performing a water sorptivity test. Large spectrum of tests, such as compressive strength, flexural strength, ultra-pulse velocity UPV, visual inspection, weight loss and dimension loss test are examined as a part of the experimental program.

3.3.1. Mix design and proportion

The selection of constituents and their properties can be defined as mix design. It includes the procedure of selecting the correct amount of cement, water, fine and coarse aggregate and mineral and chemical admixtures to manufacture HPCC which is as economical as probable with certain minimum characteristics like strength, a required consistency and durability.

The mixing stage has significant role in the production of HPCC and effects on the homogeneity, workability and hence the strength of the mix. Unsuitably combined mix may reason failure as early setting or not hardening both of failure causes inapplicability of HPCC.

In order to manufacture a desirable HPCC mix that satisfies the necessities of a particular project, trial mixes must be done with various binder's quantities and chemical admixtures. The production of these mixtures will assist in finding the appropriate amounts of SP to obtain the specified flow. It should be observed that the trial mixes also aid to understand whether the sorts and quantities of binders and aggregates in the mixtures meet the necessities of the study. The selection of mixtures constituent was summarized as following depend on outcomes of some trial mixtures in a preliminary study:

- Cement used as a based binder (B); two series of mixtures were prepared. In the first series cement (C) is an only binder was obtained by 859.7 kg/m^3 but the second one C was partially (15%) replaced by SF. C and SF were obtained by 717.9 kg/m^3 and 126.7 kg/m^3 respectively.
- Fine aggregate consists of two parts: River sand (S) and Quartz (Q). S was used 110% by mass of B with the size of 0-4mm and Q was used 39% by mass of B with size 2 mm.
- Drinking water (W) was used 25% by mass of B.
- SP was used 2.5% by mass of B.
- Steel fibre StF and Glass fiber GF were added separately and as a hybrid form with range of 0.5 and 1.0 by total volume of the mixture.
- Totally 14 mixtures were prepared.

The following tables below presents the mixtures proportion:

Table 3.6. Mix proportions 859.7 kg/m3 Cement based

#	Mix ID	Cement C	Fine Aggregate		Water W		Superplasticizer SP		Steel Fiber		Glass Fiber	
			Sand	Quartz								
		[kg/m^3]	[kg/m^3]	[kg/m^3]	[W/B %]	[kg/m^3]	[%]	[kg/m^3]	[%]	[kg/m^3]	[%]	[kg/m^3]
M1	Control-SF0	859.7	945.7	335.3	0.25	214.9	2.5	21.5	0	0	0	0
M2	S-0.5-SF0	859.7	945.7	335.3	0.25	214.9	2.5	21.5	0.5	39.25	0	0
M3	S-1.0-SF0	859.7	945.7	335.3	0.25	214.9	2.5	21.5	1.0	78.5	0	0
M4	G-0.5-SF0	859.7	945.7	335.3	0.25	214.9	2.5	21.5	0	0	0.5	13
M5	G-1.0-SF0	859.7	945.7	335.3	0.25	214.9	2.5	21.5	0	0	1.0	26
M6	H-0.5-SF0	859.7	945.7	335.3	0.25	214.9	2.5	21.5	0.25	19.6	0.25	6.5
M7	H-1.0-SF0	859.7	945.7	335.3	0.25	214.9	2.5	21.5	0.5	39.25	0.5	13

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Table 3.7. Mix proportions 717.9 kg/m^3 Cement and 126.7 kg/m^3 SF based

#	Mix ID	Binder (B)		Fine Aggregate		Water W		Superplasticizer SP		Steel Fiber		Glass Fiber	
		C	SF	Sand	Quartz								
		[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[W/B %]	[kg/m^3]	[%]	[kg/m^3]	[%]	[kg/m^3]	[%]	[kg/m^3]
M8	Control-	717.9	126.7	929.1	329.4	0.25	211.2	2.5	21.1	0	0	0	0
M9	S-0.5-SF15	717.9	126.7	929.1	329.4	0.25	211.2	2.5	21.1	0.5	39.25	0	0
M10	S-1.0-SF15	717.9	126.7	929.1	329.4	0.25	211.2	2.5	21.1	1.0	78.5	0	0
M11	G-0.5-SF15	717.9	126.7	929.1	329.4	0.25	211.2	2.5	21.1	0	0	0.5	13
M12	G-1.0-SF15	717.9	126.7	929.1	329.4	0.25	211.2	2.5	21.1	0	0	1.0	26
M13	H-0.5-SF15	717.9	126.7	929.1	329.4	0.25	211.2	2.5	21.1	0.25	19.6	0.25	6.5
M14	H-1.0-SF15	717.9	126.7	929.1	329.4	0.25	211.2	2.5	21.1	0.5	39.25	0.5	13

3.3.2. Sample preparation: mixing, casting and curing

3.3.2.1. Mixing

The mixing process has a significant impact on the consistency and homogeneity and hence mixture strength. In this investigation a sensitive balance 0.1gm was used for weighing substances and for the mixing process a revolving electrical mixer with a maximum capacity of 20 litres was used as shown in Figure 3.7a. and b., respectively.

(a) (b)

Figure 3.7. (a) Sensitive balance 0.1gm; (b) Revolving electrical mixer max. capacity 20lit

Before mixing process, the mixer should be free from excess water and clean and the inner surface of the pan was moistened slightly to minimize water attraction from the mixture. Also, the materials should be prepared, weighted and packed in suitable containers as shown in the Figure 3.8.

Figure 3.8. All materials before mixing

The fine aggregates include sand and quartz were dry mixed with cement and SF for three minutes to obtain a homogenous mixture, and then mix with 2/3 of the whole water for three min. Later, the remaining water and SP were mixed carefully and then added to the mixture gradually and mixed continuously for another 2 or 3 min finally fibers were added to the mixture and mixed for 3 min to complete the entire mixing process. Figure 3.9. shows dry mixing and final mixing.

Figure 3.9. Dry mixing and final mixing

3.3.2.2. Casting

Before casting, two types of molds were prepared, cube molds with 50x50x50 mm dimensions and prisms with dimensions of 40x40x160 mm. The molds should be cleaned from dust or foreign materials and lubricated properly to help demolding process after hardening of HPCC. Also, it should be ensuring that all the bolts are fully tight to keep exact dimension during casting. After mixing process the molds should be filled with HPCC sample in two layers, every layer was compacted for 25 seconds by mechanical vibration on a vibration table to decrease the air bubbles in the mixture. Once, the HPCC samples have been taken and mixed, now the molds should be made to cast quickly as possible. Figure 3.10. shows the casting process. Finally, the top of moulds was levelled for getting uniform shape.

Before curing procedure, the moulds were protected by polyethylene film to avoid moisture loss for 24 hours. Then, curing process was started.

Figure 3.10. Casting process

3.3.2.3. Curing

The curing of HPCC is the procedure of preserving suitable moisture in HPCC within an appropriate temperature range in order to help hydration of cement at early ages. The chemical reaction between cement and water called hydration which results in the creation of different chemicals that contribute to setting and hardening. Curing plays a significant role on in developing HPCC strength and durability of HPCC. In HPCC curing is very necessary because of its low water-cement ratio.

There are different curing methods. In this study after 24 hrs of casting, the casting moulds were removed. Then, the specimens were cured by submerging in water in a container as shown in Figure 3.11., under laboratory conditions for 28, 56 and 90 days.

Figure 3.11. Curing

3.4. Fresh HPCC tests

3.4.1. Fresh unit weight

The term “unit weight” as used here refers to the weight of fresh HPCC per unit volume, as determined by ASTM C 138 . It is attained by measuring the weight of the compacted fresh HPCC in a mould of known mass and volume. The top of mold is wiped of any extra HPCC. Fresh density of HPCC is calculated by using this equation:

$$\rho = \frac{M}{V} \tag{3.1}$$

Where: ρ = density of fresh HPCC (kg/m^3)

M = mass (kg)

V = mold volume (m^3)

3.4.2. Flow test

The flow test is a method to determine consistency of fresh HPCC. As name suggests, in this test the workability of HPCC is measured by examining the flowing property of HPCC. Flow of HPCC was determined according to ASTM C 1437 by using of flow test apparatus which is in the form of a cone with a base diameter of 100 mm, upper surface diameter of 70 mm and 60 mm height as shown in Figure 3.12. First, the flow table and inside of the mold were cleaned from the gritty material or dust and the cone was located in the marked or middle portion of the flow table. The cone was filled by freshly mixed HPCC in two layers, each layer should be tamped 20 times with tamping rod. If HPCC overflows after tamping then level it with the help of a trowel, and excess HPCC should be removed off from the table. Then, the cone was lifted vertically upward and let HPCC stand on its own without support after that directly the table was raised and dropped in a height of 12.7 ± 0.13 mm for 25 times in 15 seconds. Lastly, the dia. of the spread HPCC was measured in about 4 directions and the average was taken. The flow of HPCC is calculated by using the following equation:

$$\text{Flow \%} = \frac{Spread\ diameter\ in\ cm - 10}{10}\ x\ 100 \tag{3.2}$$

Figure 3.12. Flow test

3.5. Sulfuric acid test

Acid attacks on HPCC impart unique set of damage mechanisms and appearances as studied in chapter two compared to other durability issues of HPCC. There isn't any standard in the ASTM which is completely dedicated to estimate the HPCC sulphuric acid resistance. Therefore, this study was carried out according to ASTM C267, that is the standard test way for the chemical resistance of mortars, grouts and polymer concrete. All HPCC specimens were cured in water for 28 days, after which they were immersed in sulfuric acid (H_2SO_4) solution for one month and two months. The HPCC specimens of each group are tested after one month and two months exposure to sulfuric acid and compared to the specimens curing in normal water at same age. The average of three HPCC samples was also reported for each mixture and age. The compressive strength, flexural strength, weight loss (WL), dimension loss (DL), ultrasonic pulse velocity (UPV) and visual inspection test were measured and reporting the results for specimen's exposure to sulfuric acid and specimens keeping in normal water at the same age.

3.5.1. Preparation of acid solution

Fourteen plastic containers with a capacity 20 litres were used to make the acidic solutions. The Germany 2.5-liter sulfuric acid (SIGMA-ALDRICH) product with 95.0% - 97.0% concentration as shown in Figure 3.13. was used to make a solution with high concentration 7% of sulfuric acid by weight and the solution should be stirred properly. Every group of mix had its own acid container to offer similar acidic environments for each group of mixtures.

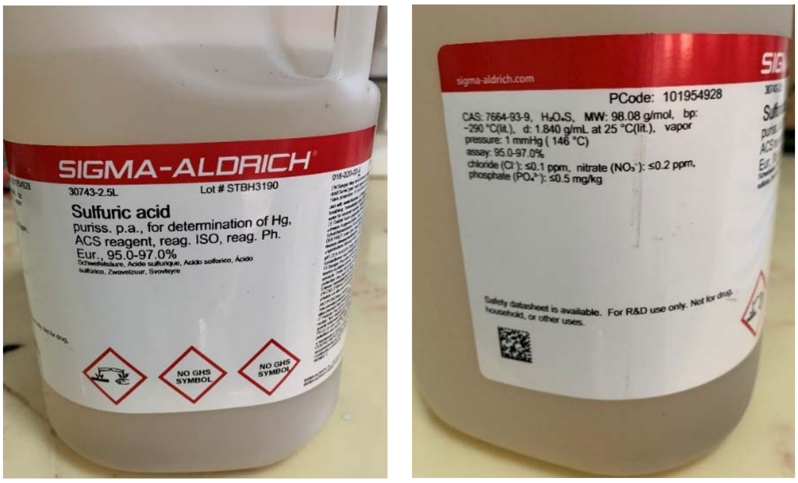


Figure 3.13. Sulfuric acid (H_2SO_4)

3.5.2. Sulfuric acid exposure

Each HPCC mixture consisted of 6 specimens of prisms with dimensions of 160x40x40 mm and 3 specimens of cubes with dimensions of 50x50x50 mm for each container. After 28days of curing, they were immersed in sulfuric acid solution as shown in Figure 3.14.

Figure 3.14. Samples were immersed in sulfuric acid solution

The initial pH of the solution is very low about (1) and it is increased quickly after reacting with HPCC specimens as shown in Figure 3.16a. This is due to high alkalinity of OPC with PH values usually above 12.5. The reaction of HPCC samples with solution will continue until the PH value of acid solutions had been gotten the neutral value (PH~ =7±2). The period of immersion of the samples was divided into two phases. The phases length was one month; hence, the total testing length was two months. After one month, the solution should be renewed with the same concentration this is because of neutralization of PH values after one month as shown in Figure 3.15b.

(a) (b)

Figure 3.15. (a) At the beginning of exposure of sulfuric acid, there is a reaction between HPCC samples and solution because of different in PH values. (b) After one month of exposure, there is no reaction between them because of neutralization of PH values

A special test setup was designed to place HPCC samples inside containers. This is to avoid any problems that may lead to unreliable results in the test. This problem has been detected in preliminary researches of the HPCC resistance to sulphuric acid exposures. It was noted that after sulfuric acid solution attack for a period of time, the HPCC samples will begin to lose elements from their outer surface and gather around the bottom of the specimens, the particles will provide a type of protective layer for the HPCC which makes it difficult to enter sulfuric acid, while in the middle and upper parts of the specimens, the entire HPCC surface is exposed to the sulfuric acid solution. This phenomenon will lead to unreliable behavior of the samples and examining the outcomes of the testing will become complex. To overcome this problem, the specimens were laid on a plastic grid in the containers as illustrated in Figure 3.16. It has openings and allow to drop lose particles to the bottom of the container.

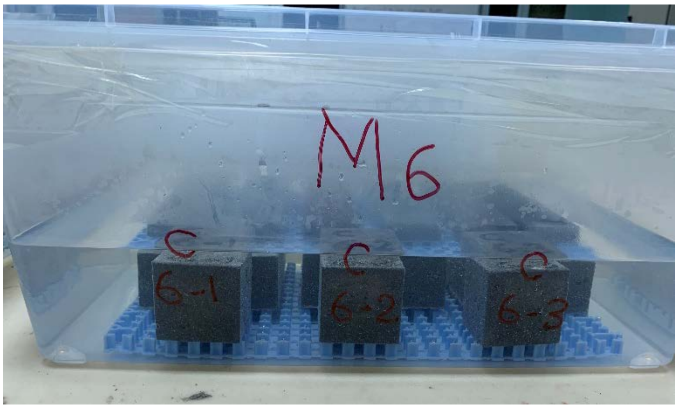


Figure 3.16. HPCC specimens in fresh sulphuric acid solution

3.6. Hardened HPCC tests

3.6.1. Flexural strength test

There are various methods to measure concrete tensile strength, flexural strength is one of them. It measures maximum stress on unreinforced concretes tension face at the failure point to bend. Flexural strength is stated as Modulus of Rupture (MR) in psi (MPa), it is calculated by ASTM C78 standard test methods (third-point loading) or ASTM C293 (centre-point loading).

A Shimadzu AGX Plus machine, a controlled tensile tester with a load frame of 100 KN was used to determine the flexural strength of plain and hybrid fiber reinforced HPCC prisms. The flexural strength in this study was fulfilled in agreement with ASTM C293. the 40×40×160 mm prisms were used for 3-point flexural test. Figure 3.17. displays the universal flexural testing machine. The point loads are applied at the middle of the span.

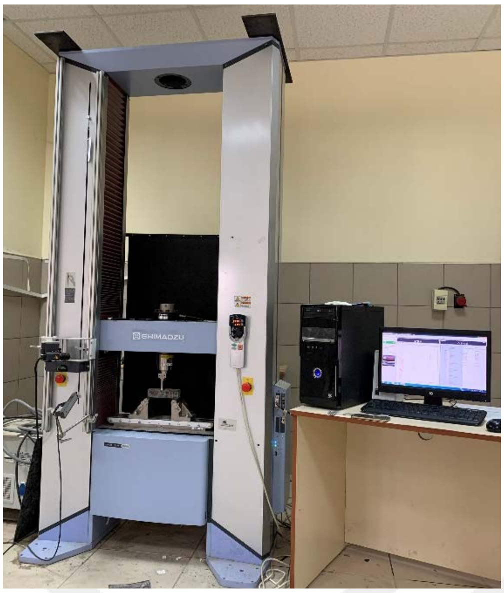


Figure 3.17. Flexural testing machine

All samples that were tested as soon as they were removed from the water while they were still wet. Samples at age of 28 days of normal curing and before and after exposure to sulfuric acid at one month and two months were tested as shown in figure 3.18. The load was putted steadily and without shock the stress at a rate of 1 N/mm^2/min. The flexural strength was determined by taking the average of three specimens at each age test. The flexural strength is calculated by the following equation:

$$\text{Fcr} = \frac{FL}{bd2} \tag{3.3}$$

Where: F_{cr} = flexural strength (MPa)

F = maximum breaking load (N)

L = distance between the lower supporting rollers (mm)

b = base of the specimen (mm)

d = depth of the specimen (mm)

Figure 3.18. Flexural strength testing of specimen before and after acid exposure

3.6.2. Compressive strength test

The compressive strength test was achieved in accordance with ASTM C109 by utilizing a hydraulic testing machine with a load capacity of 3000 KN. It was carried out on the remaining parts of the prism samples after completion of the flexural test for the HPCC samples. The sample is located with a flat, smooth surface in contact with the platens of the testing machine as presented in Figure 3.19. The load was applied to the specimen at a constant stress rate (0.25 MPa/s) until the failure of the sample. The average value of six samples is taken as the compressive strength value at the age of 28 days of normal curing and before and after exposure to sulfuric acid at one month and two months.

Figure 3.19. Compressive strength test before and after exposure to sulfuric acid

concrete is a non-linear substance in the relationship of stress and strain. The strain increases gradually at a high stress rate. In the event of near failure, the movement of the pressure plate of the teste machine increases. The failure approaches in the sample when the loading rate decreases. The maximum load applied to the specimen records. The compressive strength is calculated by using the following equation:

$$\rho = \frac{M}{V} \tag{3.4}$$

Where: f_c = Compressive strength (MPa)

F = Failure load (KN)

A_c = Cross-sectional area of loading surface (mm^2)

3.6.3. Ultrasonic pulse velocity (UPV) test

UPV is the technique that do no harm to the tested concrete element by using mechanical waves, so it is a one of the truly non-destructive tests of concrete. It can be used to reveal internal cracking and other shortcomings as well as changes in concrete such as degradation due to freezing and thawing and aggressive chemical environment.

According to ASTM C597-02 the UPV test is depend on measuring the speed of the sound wave with the density of its propagation. The basic idea that the pulse velocity way has been established is that the pulse velocity of compressional waves across a medium relies on the density and elastic characteristics of the medium, as presented in Figure 3.20. UPV, in km/s or m/s for the HPCC can be determined as given below:

$$V = \frac{L}{T} \tag{3.5}$$

Where: V = Pulse Velocity m/s

L = length of specimen, m

T = Time taken by the pulse to pass the path length, μs

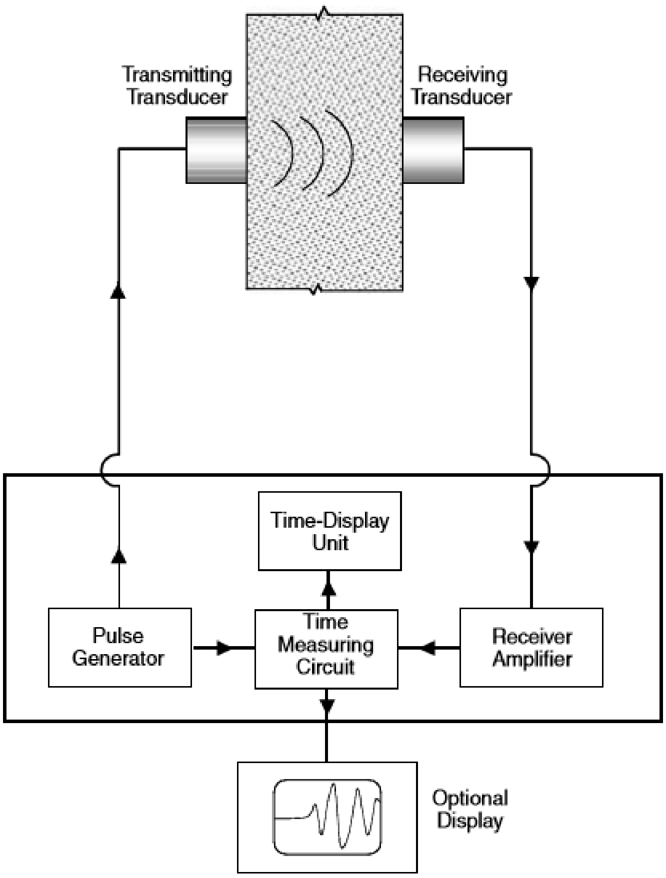


Figure 3.20. Schematic diagram of pulse velocity test circuit (ASTM C597-02)

The transducers may be arranged in three possible configurations, as presented in Figures 3.21a-c. These are direct transmission, semidirect transmission; and indirect or surface transmission. Because of maximum energy of the pulse is transmitted and received with this arrangement, the direct transmission technique, (Figure 3.13a), is the most desirable and acceptable arrangement.

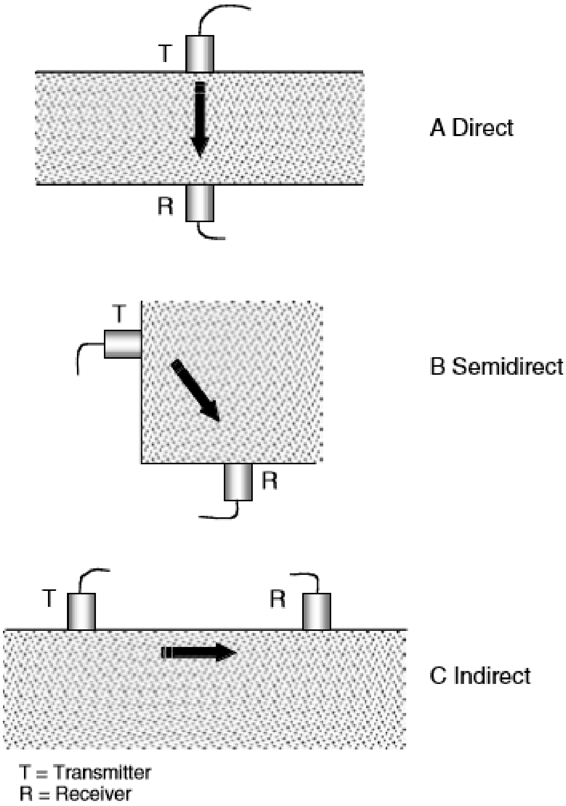


Figure 3.21. Pulse velocity measurement methods; a) Direct method, b) Semidirect method, c) Indirect surface method (ASTM C597-02)

In this study the direct transmission method was used. HPCC cubes with dimensions of 50mm x 50mm x 50mm at 28 days of normal curing and before and after exposure to sulfuric acid at one month and two months were tested. The UPV apparatus was used in this research is shown in Figure 3.22.

Figure 3.22. UPV testing before and after exposure to sulfuric acid

3.6.4. Weight loss test

Weight loss (WL) is a simple and traditional measuring factor in acidic attack tests. However, the results of weight loss can depend on sample size, type of cement, and can have a significant impact on the properties of the reactions products and the degraded cement paste on samples. So, in this research 50x50x50 mm cubic samples were used. After 28 days of curing, three cube specimens of each mixture were taken out of water and left to the laboratory environment for 2 hours to obtain saturated surface dry in laboratory condition, subsequently, the initial weights of specimens were measured and exposed in 7% sulfuric acid (H_2SO_4) solution for 60 days. The HPCC samples from each mixture were taken out of solution at the end of each phase (30 days). After that, they were washed smoothly with tap water to eliminate the porous layer of corrosive products such as soft and crystallized acidic substances or calcium salts on the surface and the samples were in air for 2 hours to attain the same state when their initial weights were calculated. Then the samples were weighed after exposure to sulfuric acid and the percentage of mass loss was measured at the end of each cycle.

(a) (b)

Figure 3.23. (a) Initial weight of HPCC specimen after 28 days of curing. (b) Weight of specimen after one cycle (30 days) exposure to sulfuric acid

3.6.5. Dimension loss (DL) test

Dimension loss is the easy method to obtain the effect of sulfuric acid on concrete. It was carried out on cubes with dimensions of 50x50x50 mm, the dimensions (x, y, z) of specimens were measured by digital Vernier after 28 days of normal curing. The samples were exposed to sulfuric acid for two cycles (60 days). The specimens were taken out and washed then the dimensions also were measured at the end of each cycle. The dimensions are taken in four different places in each direction and the average value is reported. Loss of dimension was determined for 30 days and 60 days of exposure.

Figure 3.24. Measuring dimensions by Vernier

3.6.6. Visual inspection test

ACI 201 defines visual inspection as the concrete examination to determine and define many different conditions that concrete may exhibit during its service period. The visual inspection is usually limited to the surfaces of the concrete structure that are visually accessible.

A visual inspection was performed by taking high-resolution images of corroded samples. Based on previous research, this is a suitable way for comparing sample performance and gaining a better understanding of resistance of the various specimens subjected to aggressive sulfuric acid exposure. In this study visual inspection of different HPCC cubes with dimensions of 50x50x50 mm was done. The surface photos of the specimens were taken for visual observation before exposing to sulfuric acid at the age of 28 days of normal curing and after exposing to sulfuric acid at the end of each cycles (30 days and 60 days acid exposure).

(a)

(b)

Figure 3.25. Visual inspection of HPCC cubes (a) After 28 days of normal curing and before sulfuric acid exposure. (b) After 30 days of sulfuric acid exposure

3.6.7. Sorptivity test

Movement of liquids through interconnecting pores plays an extremely significant role to determine the durability of concrete. The sorptivity test is an easy and fast test for measuring the concrete tendency for absorbing water by capillary suction. It is principally sensitive to the micro-structural characteristics of the area close to the concrete surface and thus reflects the nature and effectiveness of curing. The better durability of the concrete means the lower the water sorptivity index. Sorptivity of HPCC was evaluated as per the procedure given in ASTM C 1585.

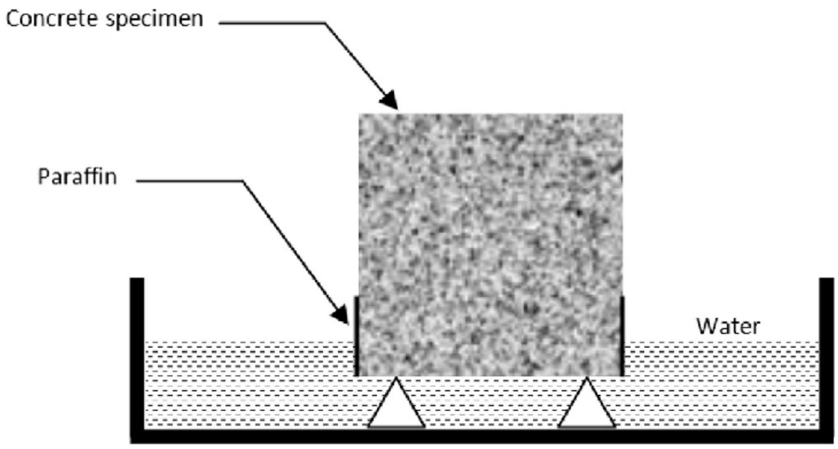


Figure 3.26. Schematic presentation of sorptivity test (Mermerdas, 2015)

In this study sorptivity test was carried out to attain rate of water withdrawal into the pores of HPCC specimen. After casting, the cubes were submerged in water for 28 days curing, then three cubes with dimensions of 50x50x50 mm were prepared after drying in an oven at 105 °C for 24 hours. After that the cubes were taken out into the oven and their sides were coated with silicone seal to guarantee that only water entered the bottom of the sample, then the cubes were submerged in water as presented in Figure 3.29. It should be noted that water level is no more than 3-5 mm above the sample base. The amount of water absorbed was measured at 1, 4, 9, 16, 25, 36, 49 and 64 minutes by weighting the sample on a top pan balance weighting up to 0.1 mg. The surface water on the sample was wiped with tissue or any clothes before each weighting. Sorptivity can be determined by the following equation:

$$I = S.t^{1/2} \tag{3.6}$$

Where: S = Sorptivity in ($mm^3/mm^2/min^{0.5}$)

t = time in min

I = $\Delta w/Ad$ in (mm^3/mm^2)

Δw = change in weight in grams

A = surface area of the sample through which water penetrated in mm^2

d = water density

Figure 3.27. Sorptivity test process

4. RESULTS and DISCUSSIONS

4.1. Introduction

This chapter focuses on the presentation, analysis and discussion of the results obtained from the experimental program. In this chapter, the effects of steel and glass fibers reinforcement as well as incorporation of silica fume on the properties of high performance cement based composite (HPCC) are discussed. The discussion is mainly on the evaluation of resistance of HPCCs against sulfuric acid attack.

4.2. Fresh HPCC test results and discussion

4.2.1. Flow test

The workability of HPCC is a method to find out the response of HPCC and to determine the necessities on site for a desired placement. It is defined by the ease and homogeneity with which the ingredients can be uniformly combined, transported, consolidated, and finished as suggested by well-known standards. It has an important influence on the strength and durability. Moreover, the cost of labour and the final appearance are affected as well. HPCC is said to have a proper as a workability when it can easily be placed and compacted homogeneously, which mean neither bleeding nor segregation is observed.

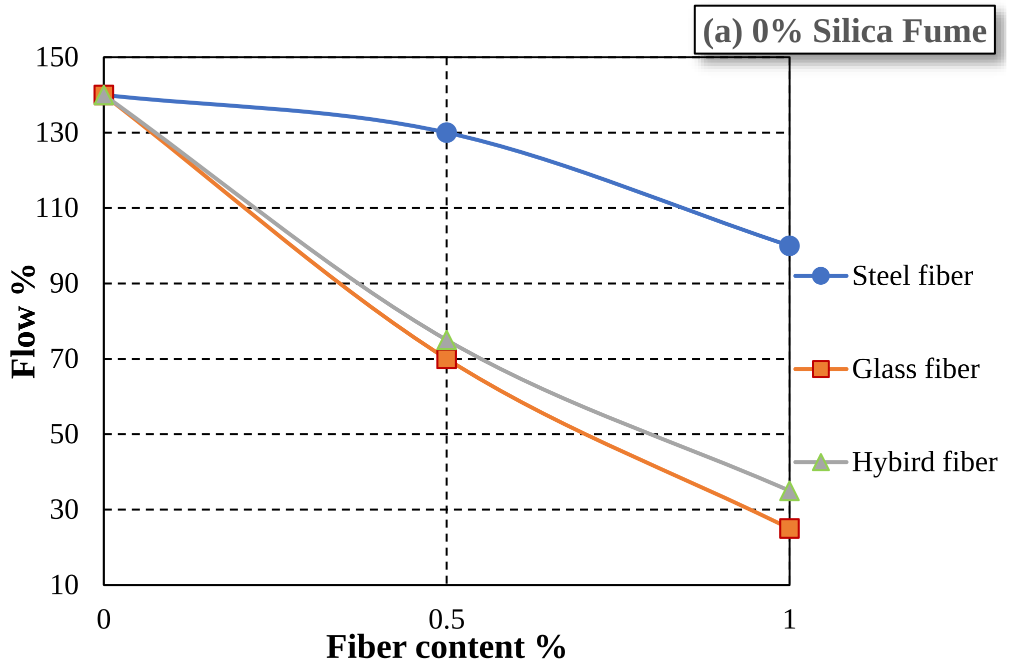
There are different methods to assess the consistency of fresh HPCC. In this study, the flow test was carried out. It was measured by using of flow test apparatus and was calculated as the result of increase in the percentage of average base diameter of fresh HPCC. The results were depicted in the (Table 4.1.). In this study the results of flow of fresh HPCC were influenced by fiber type, orientation, and percentage of fibers and partial replacement of OPC by SF. It was noticed that the highest flow was obtained by M1 the control mixes which does not contain any fiber and SF, but the lowest flow was achieved by M12 the mix which contains 1% of glass fiber and 15% SF.

Table 4.1. Effect of different percentage of various fibers and SF on flow of HPCC

#	Mix ID	Flow %
M1	Control-SF0	140
M2	S-0.5-SF0	130
M3	S-1.0-SF0	100
M4	G-0.5-SF0	70
M5	G-1.0-SF0	25
M6	H-0.5-SF0	75
M7	H-1.0-SF0	35
M8	Control-SF15	90
M9	S-0.5-SF15	80
M10	S-1.0-SF15	60
M11	G-0.5-SF15	40
M12	G-1.0-SF15	15
M13	H-0.5-SF15	55
M14	H-1.0-SF15	30

Figure 4.1 indicates the variation of flow table test results for fresh HPCC mixes. From Figure 4.1, workability based on flow test of the HPCC shows a decreasing tendency when fiber content was increased. This is due to the hydrophilic character of fibers, and their blockage effect on the aggregate particles. Moreover, for the mixes with glass fiber because of increase in the surface area, the workability was also negatively affected. This can be attributed to the fact that the fibers are coated with cement paste around them and hence through increasing the viscosity of mixture, the flow is hindered. Another reason of lower flow is that addition of hybrid fibers may results in a network structure in HPCC, which restrains the mixture from flow. Even though lower flow results in difficult placement, an advantage of lowering the segregation risk can also be attained.

The type of fiber is important in flow behaviour. It was observed that the HPCC with glass fibers has lower flow in comparison to the steel fibers. This may be due to their high ratio of surface area to weight. Also, according to researchers the physical properties of fibers may also affect fresh HPCC's flow.



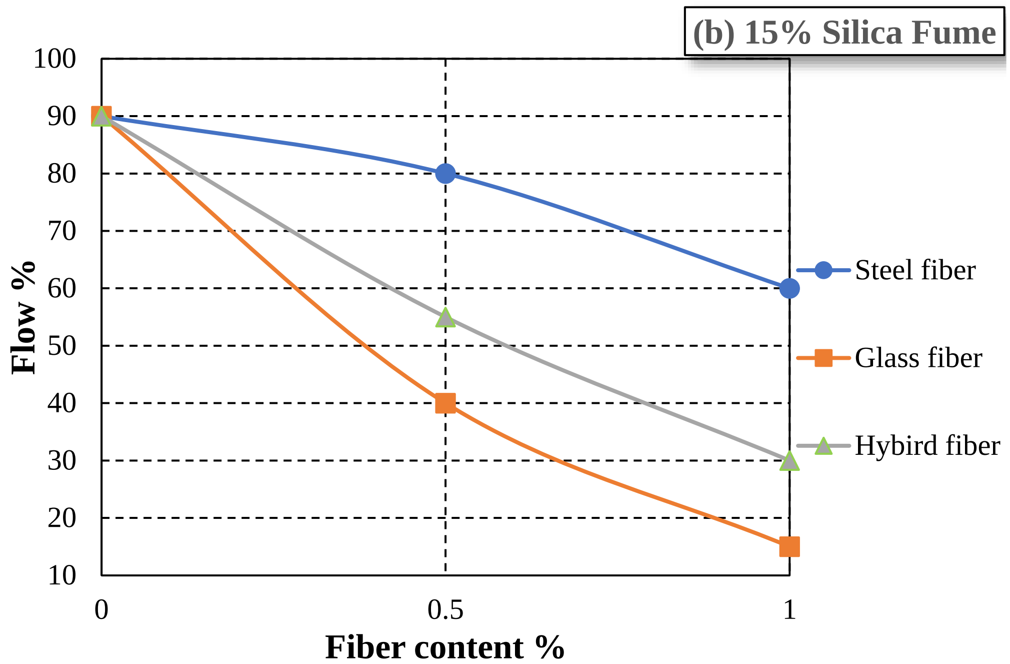


Figure 4.1. Effect of different percentage of various fibers on flow of HPCC. (a) without SF and (b) 15% SF

In order to observe the influence of SF on workability Figure 4.2 plotted by grouping the data according to SF inclusion. Comparing the values for SF and non-SF included mixtures, it is found out that the inclusion of silica fume adversely affected the workability of HPCC as shown in Figure 4.2. It was found that the flowability of the mixes containing SF is less than that of the HPCC without silica fume owing to the introduction of large specific surface area of the cementitious material in the mix. Although the flow decreases, it was observed that fresh HPCC containing SF is more cohesive and less vulnerable to segregation than HPCCs without SF.

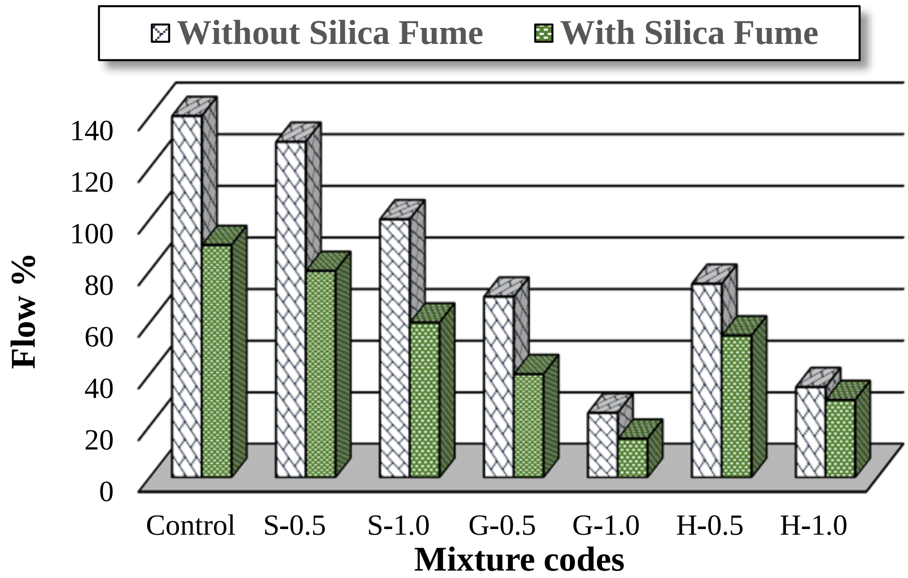


Figure 4.2. Effect of SF on flow of fresh HPCC

In order to provide an essential, the workability to the fresh HPCC, high range water reducing admixture can be used with suitable dosages.

4.2.2. Unit weight

Unit weight was tested in accordance with ASTM C 138. Fresh unit weight was measured directly after casting of HPCC in moulds. Hardened unit weight was determined after demoulding the specimens after 24 hours from casting. The results of fresh and hardened HPCC unit weight values are given in Table 4.2 and 4.3, respectively.

Table 4.2. Fresh unit weight of HPCC mixtures.

#	Mix ID	Fresh unit weight kg/m^3
M1	Control-SF0	2450
M2	S-0.5-SF0	2464
M3	S-1.0-SF0	2474
M4	G-0.5-SF0	2383
M5	G-1.0-SF0	2374
M6	H-0.5-SF0	2407
M7	H-1.0-SF0	2402
M8	Control-SF15	2431
M9	S-0.5-SF15	2456
M10	S-1.0-SF15	2463
M11	G-0.5-SF15	2304
M12	G-1.0-SF15	2287
M13	H-0.5-SF15	2363
M14	H-1.0-SF15	2324

Table 4.3. Hardened unit weight of HPCC mixtures.

#	Mix ID	Hardened unit weight kg/m^3
M1	Control-SF0	2440
M2	S-0.5-SF0	2455
M3	S-1.0-SF0	2465
M4	G-0.5-SF0	2373
M5	G-1.0-SF0	2366
M6	H-0.5-SF0	2399
M7	H-1.0-SF0	2390
M8	Control-SF15	2421
M9	S-0.5-SF15	2447
M10	S-1.0-SF15	2453
M11	G-0.5-SF15	2296
M12	G-1.0-SF15	2279
M13	H-0.5-SF15	2353
M14	H-1.0-SF15	2313

As it can be seen from Table 4.2, the fresh HPCCs' unit weight with different type and percentage of fiber and with and without SF is ranged between 2287 kg/m^3 to 2474 kg/m^3. The HPCC mix with 1% of steel fiber and without SF (M3) has the highest unit weight value of 2474 kg/m^3 and the mix with 1% of glass fiber and with 15% of SF (M12) has lowest unit weight value of 2287 kg/m^3. This phenomenon is due to several factors. In general, the high strength HPCC produced has a density ranging from 1760 to 2410 kg/m³ as mentioned in the study of Almola (2018). The steel fiber reinforced HPCC demonstrates increase in fresh and hardened unit weights compared to the reference mix M1. The increasing in unit weight is because of quantity of steel fiber. Since the density of steel fiber (7850 kg/m^3) much higher than the cementitious material, increasing the amount of steel results in increment of unit weight of HPCC. Additionally, the glass fiber HPCC shows decreased in unit weight when compared to control mix, this reduction in unit weight is because of increasing of glass fiber content incorporated. One reason is that the addition of fibers results in large voids in HPCC as shown in Figure 4.3. Another reason is the density of glass fiber which is relatively lower than plain cementitious composite.

Figure 4.3. The difference between control mix (M1) on the left side and the mixture which contains 1% of glass fiber (M5) on the right side

Moreover, the results reveal that the fresh unit weight of HPCC decreases when cement is partially replaced by SF up to 15%. This can be due the volume occupied by SF as a result of partially replacement of cement.

Hardened unit weight values measured were observed to be very close to fresh unit weight values. These values are not affected as much as by the change of the type and percentage of fibers and partial replacing of cement with SF to the mix. Figures 4.4. and 4.5 demonstrate the effect of fibres and SF on the unit weight of fresh and hardened HPCC respectively.

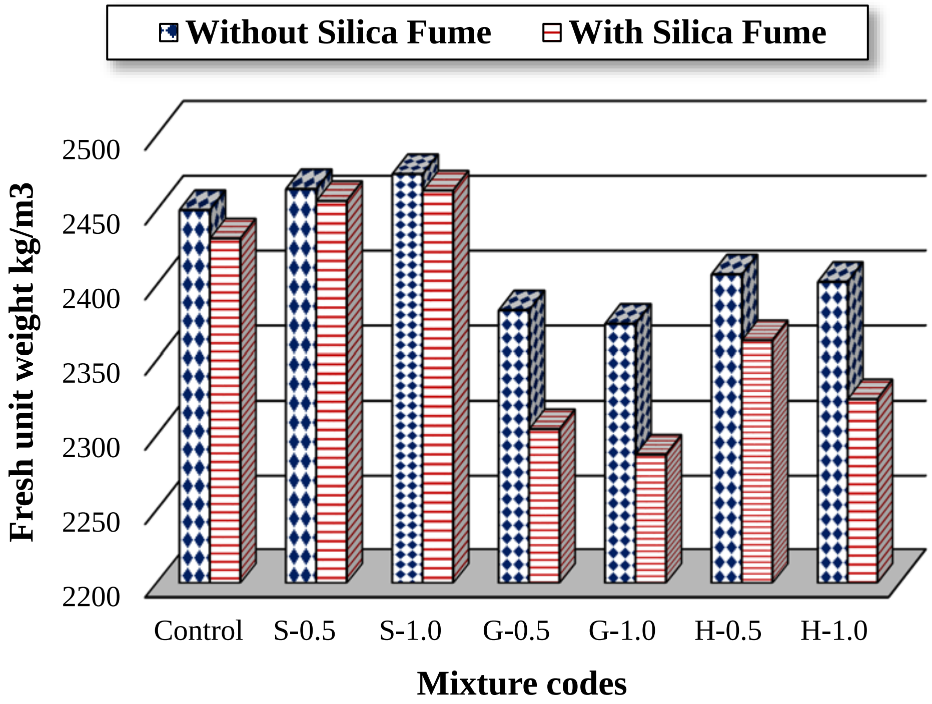


Figure 4.4. Fresh unit weight of HPCC

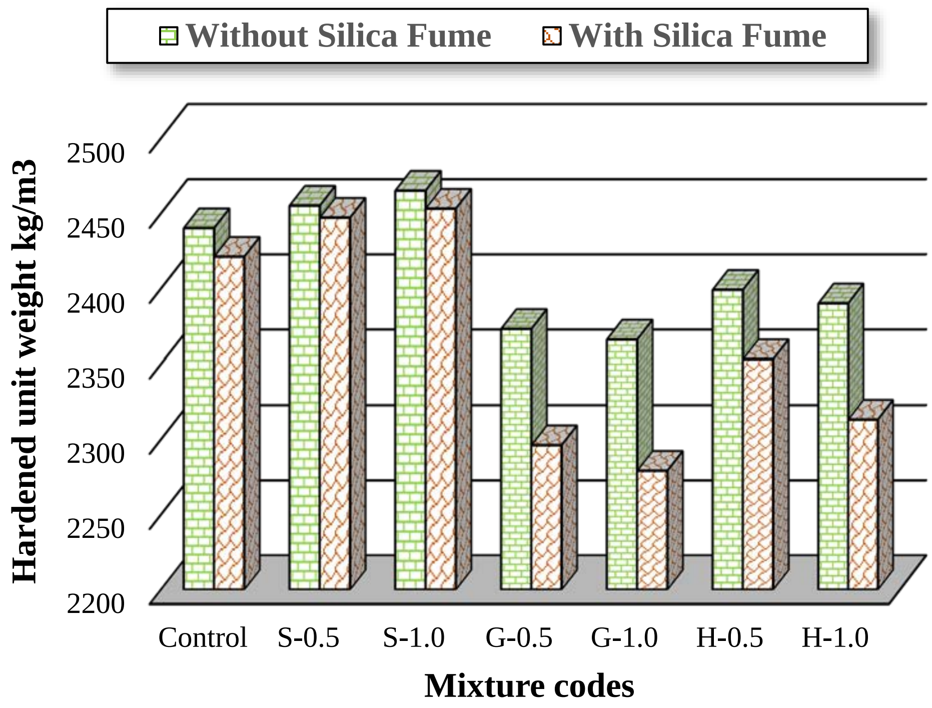


Figure 4.5. Hardened unit weight of HPCC

4.3. Discussions of the test results on hardened HPCC

4.3.1. Flexural strength

Flexural strength is an important criterion to find out the tensile behaviour of hybrid fiber-reinforced HPCC compared to conventional HPCC. Utilization fibres known to enhance tensile behaviour cement based composites. Fibre reinforcement provide not only mechanical enhancement but also better durability.

The flexural strength in this study was carried out in accordance with ASTM C293, totally fifteen prisms with dimensions (40×40×160) mm were tested, three prisms for each mixture at ages of 28, 56 and 90 days of normal curing, one month and two months of sulfuric acid exposure. The average of three samples was determined and the results of flexural strength test were presented in (Table 4.4.), and (Figure 4.6.).

Table 4.4. Flexural strength results

#	Mix ID	Flexural strength MPa			#	Mix ID	Flexural strength MPa		
		28 days	56 days	90 days			28 days	56 days	90 days
M1	Control-SF0	9.39	10.98	11.17	M8	Control-SF15	10.13	11.67	11.98
M2	S-0.5-SF0	10.22	12.05	12.31	M9	S-0.5-SF15	10.69	12.19	13.33
M3	S-1.0-SF0	10.80	12.15	13.64	M10	S-1.0-SF15	11.15	12.63	14.28
M4	G-0.5-SF0	9.50	11.04	11.47	M11	G-0.5-SF15	10.21	11.30	11.90
M5	G-1.0-SF0	11.28	11.59	12.56	M12	G-1.0-SF15	11.64	12.16	12.73
M6	H-0.5-SF0	9.76	11.35	11.88	M13	H-0.5-SF15	10.71	11.58	12.07
M7	H-1.0-SF0	11.61	12.21	12.80	M14	H-1.0-SF15	11.96	12.73	13.17

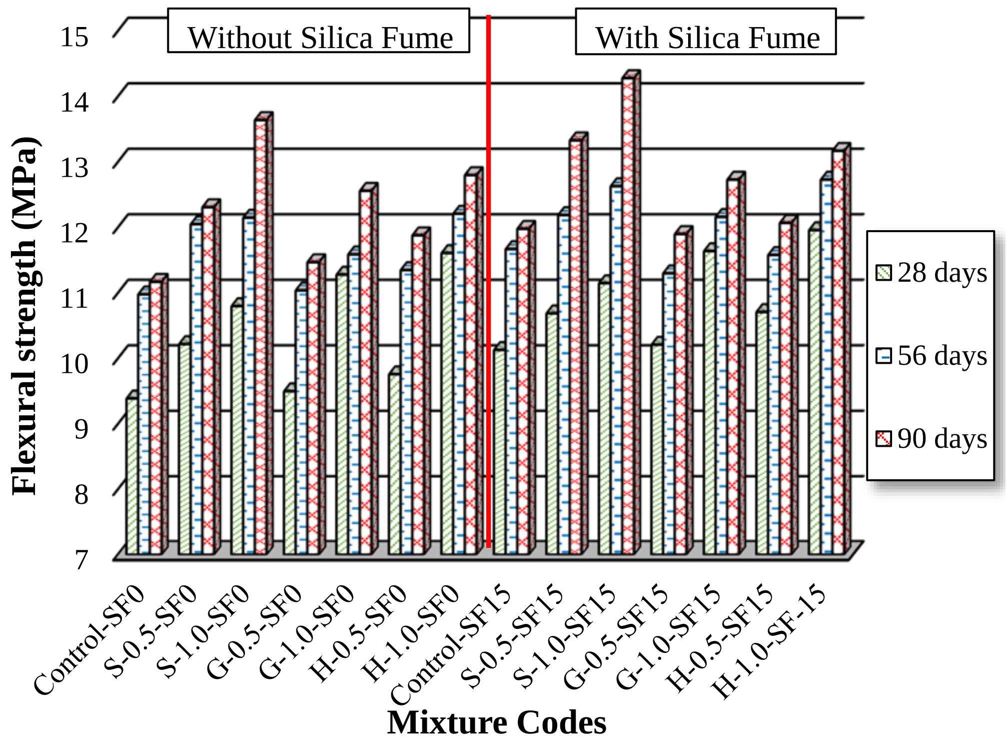


Figure 4.6. Flexural strength results

Based on the results, it was seen that the flexural strength was enhanced by increasing steel and glass fiber separately. In the case of hybrid steel-glass fibre HPCC achieves better results than from single fiber reinforcement at ages of 28 and 56 days. On the other hand, the use of 15 % of SF as replacement of cement exhibits comparable result with the mixture without SF. The addition of SF effectively increased the flexural strength of HPCC.

Figure 4.7 indicates the flexural strength results at 28 days, there was some variation in the strength of the HPCC mixtures, ranging from the highest value of 11.96 MPa to the lowest value of 9.39 MPa. The hybrid 1.0% fiber reinforcement with 15% of SF (M14) had the highest value of flexural strength which stands for was 27.4% increase over the control mix (M1) which had the minimum value.

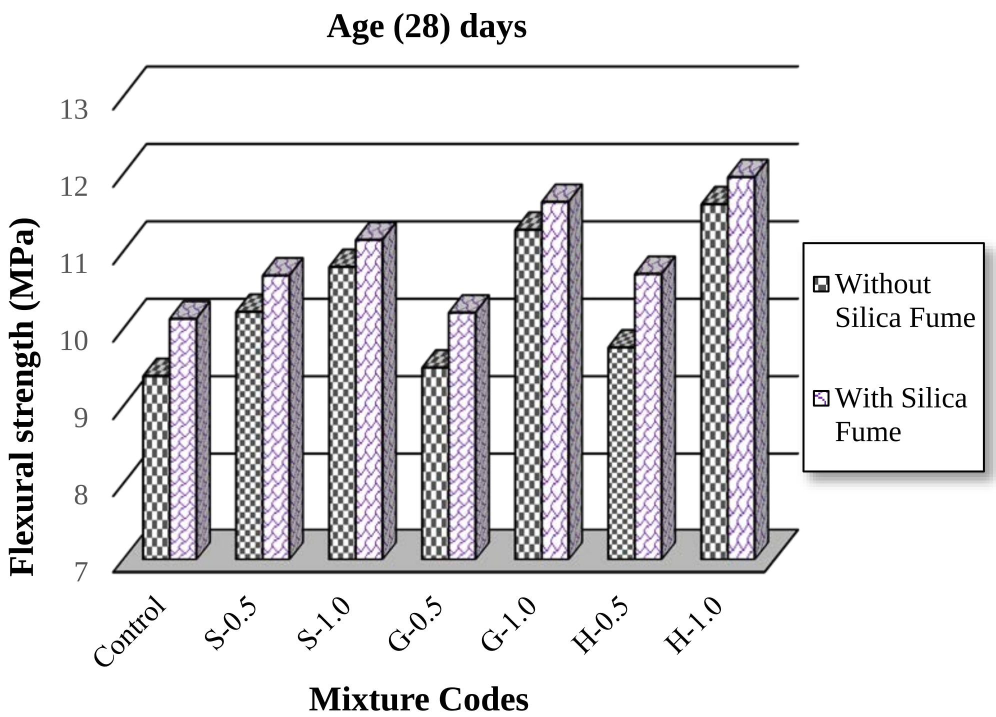


Figure 4.7. Effect of fibers and SF on flexural strength at the age of 28 days

At the age of 56 days of curing, the results ranged from 12.73 MPa to 10.98 MPa as indicated in table 4.4. The minimum value of flexural strength was 10.98 MPa of control mix and the maximum value was 12.73 of the hybrids 1.0% of steel-glass fiber reinforcement with 15% of SF. Figure 4.8, shows indicative flexural strength development when compared to the 28 days results but with different rates. Meanwhile, it was noticed that the HPCC mixture with 0.5% of steel fiber (M2) have the highest development ratio (17.91%) and the mixture with 1% of glass fiber (M5) have the lowest development ratio (2.75%).

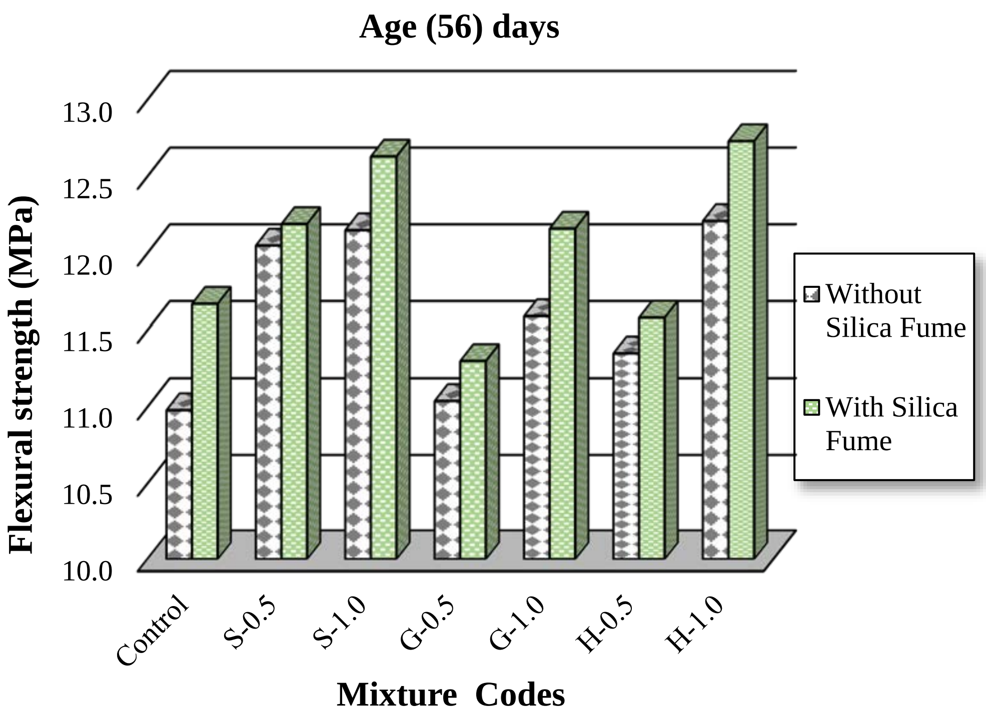


Figure 4.8. Effect of fibers and SF on flexural strength at the age of 56 days

The results of flexural strength tests at the age of 90 days can be seen in the Figure 4.9. The results showed that the maximum flexural strength was 14.28 MPa of the HPCC mixture with 1% of steel fiber and 15% of SF (M10) and the minimum value was 11.17 MPa of control mix (M1). Also, it was found that the flexural strength of HPCCs was developed with various ratios and the highest ratio was 13.06% of mixture with 1.0% of steel fiber and 15% of SF (M10).

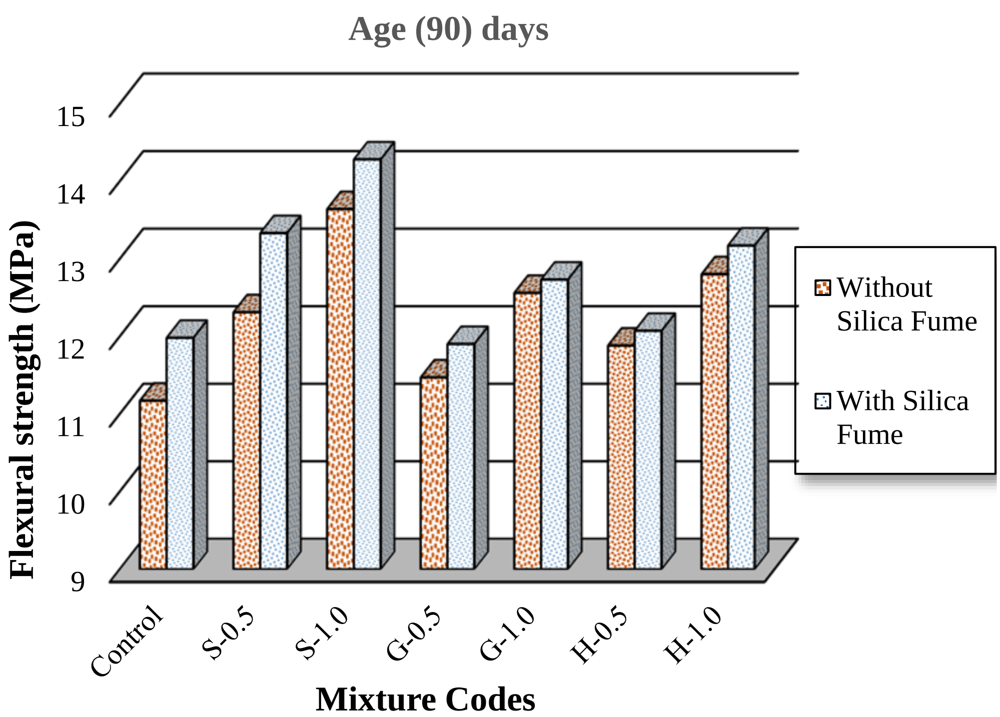


Figure 4.9. Effect of fibers and SF on flexural strength at the age of 90 days

According to the results at all curing conditions, it could be determined that long-term flexural strength development of HPCC which contains steel fiber is more than those containing glass fiber and hybrid steel-glass fiber. As shown in Figures 4.10 and 4.11, the addition of 15% of SF increases flexural strength development.

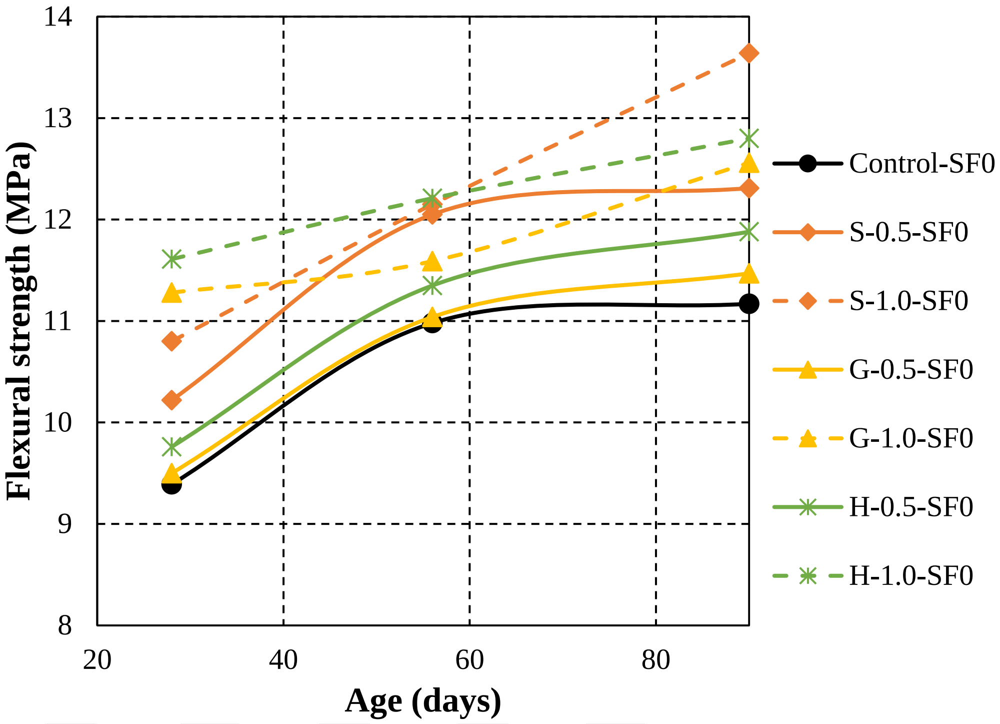


Figure 4.10. Flexural strength development (without SF)

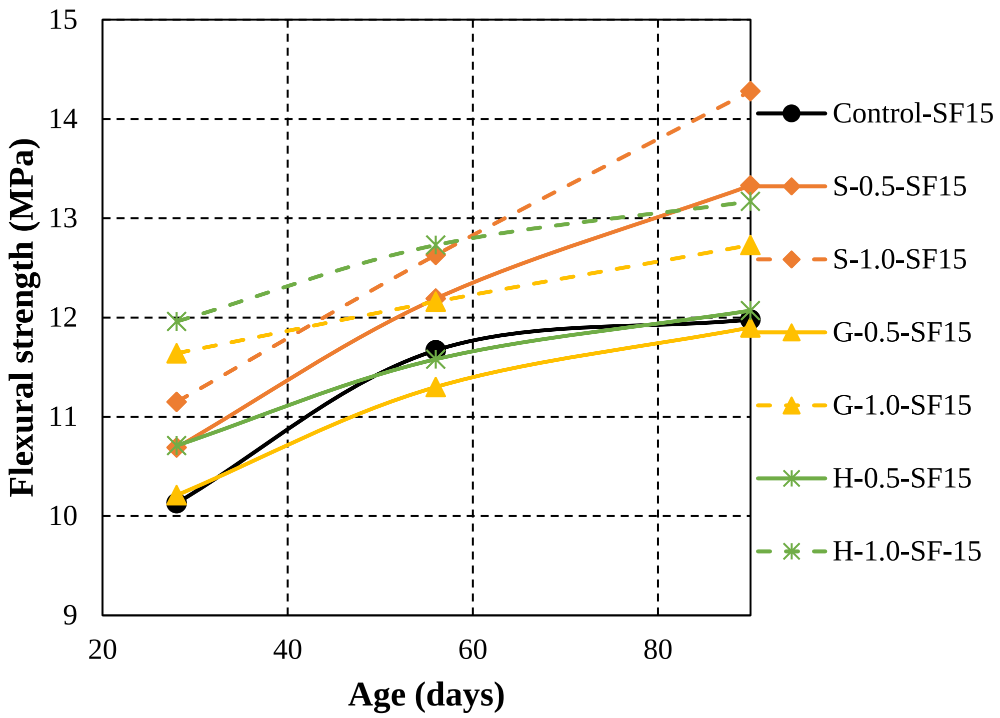


Figure 4.11. Flexural strength development (with 15% SF)

It is known that fibers improve the mechanical characteristics of HPCC. The improvement is obtained mainly from the fibers intersecting the cracks under tensile stress. The fibres hinder separation of the cracked part by stretching themselves. Therefore, via provision of an additional energy-absorbing mechanism, crack propagation which results in damage is prevented. Singh and Rai (2018) presented that the utilization of various fibers with different lengths can improve the tensile strength of HPCC and is influential for controlling micro and macro cracks. It was observed that the use of hybrid fiber gives better results than each of the individual fiber reinforcement.

Fibers are used to prevent a propagation of cracks in HPCC which take place due to the low tensile strength. Unreinforced HPCC specimens fail catastrophically by a single crack. This causes the specimen to be broken to two pieces as seen in Figure 4.12a. Figure 4.12b indicates the specimen didn't split in two pieces even after failure.

(a) (b)

Figure. 4.12. (a) Crack in HPCC element subjected to bending without fibers and (b) with hybrid 0.5% steel + 0.5% glass fiber

On the other hand, a remarkable impact of the using SF was determined. The use of 15 % of SF as replacement of cement effectively increases flexural strength of HPCC. For instance, at the age of 28 days, the result of flexural strength of control with15% SF mix (M8) was 10.13 MPa which was a 7.88% increase over the control mix. The explanation is that the silica fume takes part in three stages, first the pozzolanic reaction, second the physical improvement by micro filling effect and the third is dilution effect.

4.3.2. Compressive strength

In this study, the compressive strength was carried out on the remaining parts of the prism samples after completion of the flexural test for samples. Table 4.5. and Figure 4.13. present the compression strength results performed on the HPCC specimens.

Table 4.5. Compressive strength results

Symbol	Mix ID	Compressive strength (MPa)		
		28 days	56 days	90 days
M1	Control-SF0	80.46	82.15	85.14
M2	S-0.5-SF0	87.35	91.64	94.41
M3	S-1.0-SF0	92.26	95.54	97.46
M4	G-0.5-SF0	72.33	74.47	77.10
M5	G-1.0-SF0	76.83	79.17	83.03
M6	H-0.5-SF0	74.77	75.62	78.59
M7	H-1.0-SF0	81.49	83.19	84.10
M8	Control-SF15	87.06	89.18	93.02
M9	S-0.5-SF15	95.61	102.65	109.23
M10	S-1.0-SF15	103.85	106.86	112.19
M11	G-0.5-SF15	74.29	78.69	82.90
M12	G-1.0-SF15	79.12	81.77	84.64
M13	H-0.5-SF15	82.83	84.85	87.05
M14	H-1.0-SF15	88.63	89.81	91.10

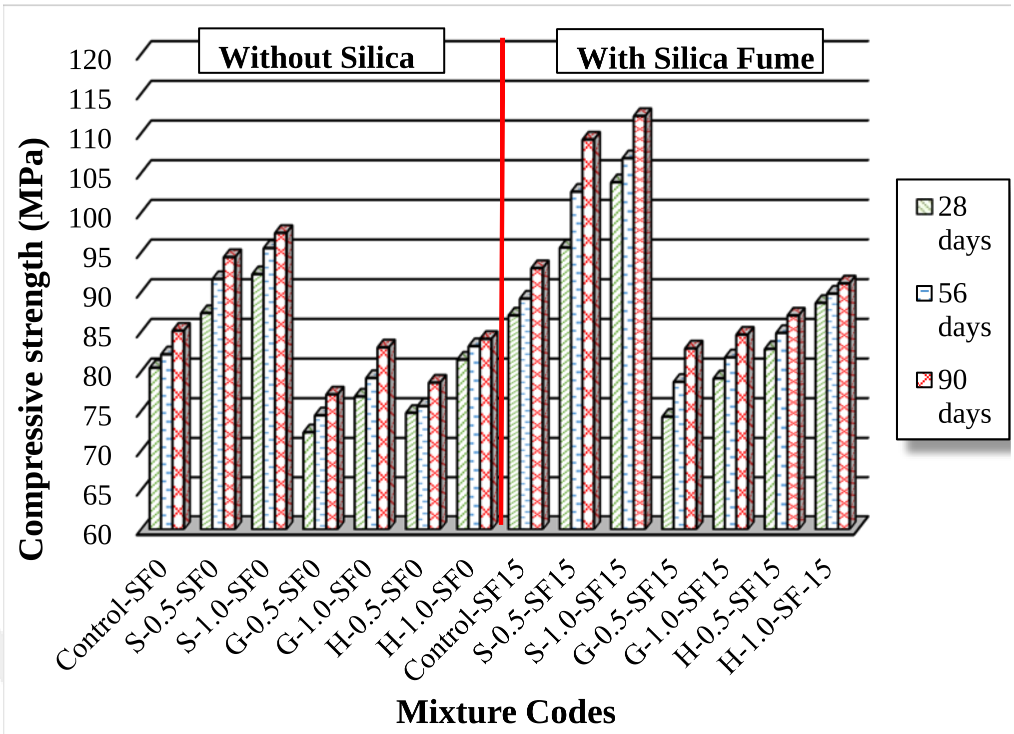


Figure 4.13. Compressive strength results

In this study, 6 specimens from each mix were used in compression test at the ages of 28th, 56th and 90th days. The results indicate that the addition of 0.5% and 1.0% of steel fibers increases the compressive strength but the addition of 0.5% and 1.0% of glass fiber decreases the strength of HPCC. Also, it showed that the addition of 0.5% hybrid steel-glass fiber has adverse effect on the compressive strength of HPCC. Meanwhile, the compressive strength of mixtures increased by adding 15% of SF as a replacement of cement.

According to the results at 28 days, compressive strength of the mix with 1.0% steel fiber and 15% SF (M10) showed the highest value of 103.85 MPa but the mix with 0.5% glass fiber without SF (M4) had the lowest strength value of 72.33 MPa. Generally, the addition of steel fiber increases compressive strength but glass fiber and hybrid steel-glass fiber reduce the strength of HPCC in this study. (Figure 4.14), shows the influence of adding SF to the HPCC and it is seen that the compressive strength increment was observed in all specimens containing 15% of SF.

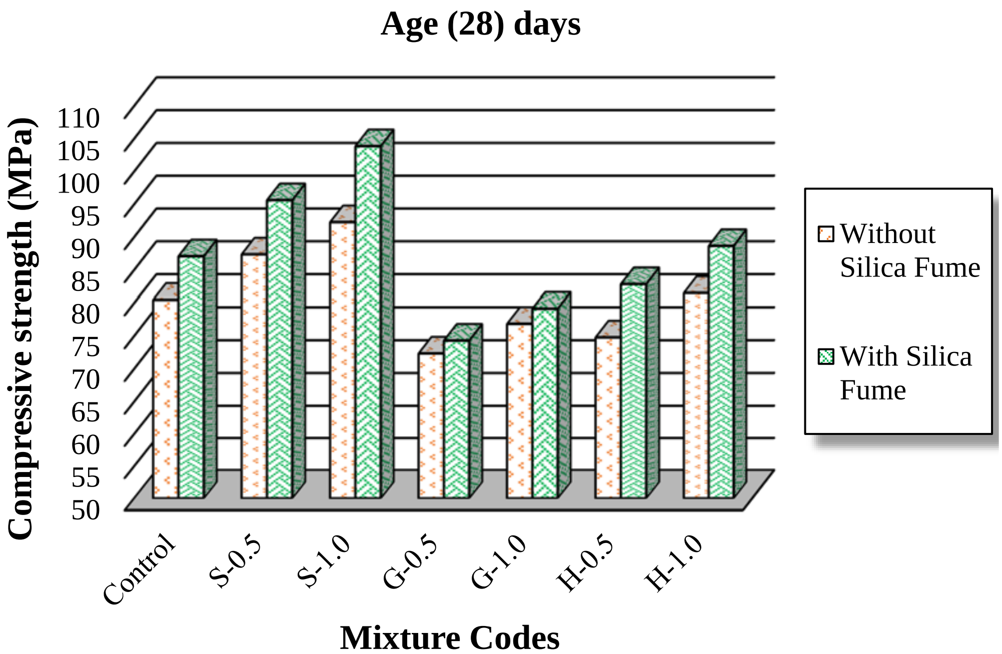


Figure 4.14. Influence of adding fiber and SF on compressive strength at the age of 28 days.

Figure 4.15. shows the results of compressive strength at 56 days in this investigation. The strength results varied from 74.47 MPa to 106.86 MPa. While the minimum compressive strength value of 74.47 MPa was obtained with the mix containing 0.5% glass fiber (M4), the maximum value of 106.86 MPa was reached with the mix containing 1.0% of the steel fiber and15% of SF (M10). When compared to the 28 days results, the mixture containing 0.5% of steel fiber with 15% of SF (M9), demonstrated the highest positive effect on the compressive strength development with 7.36%.

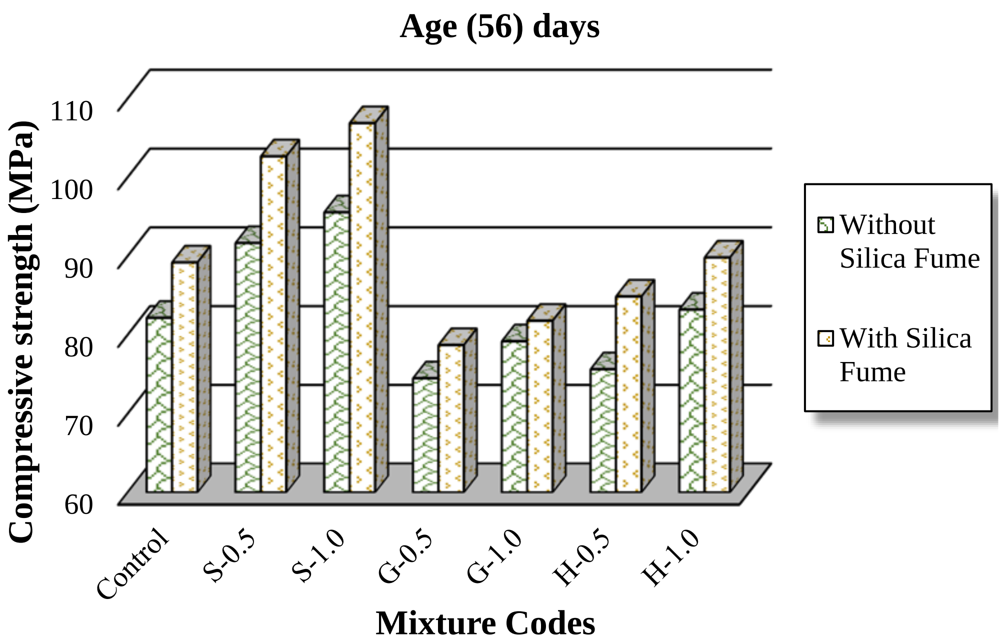


Figure 4.15. Influence of adding fiber and SF on compressive strength at the age of 56 days

With respect to Figure 4.16., the results of compressive strength at 90 days showed that while the maximum strength value was obtained as 112.19 MPa with 1.0% of steel fiber and 15% of SF (M10) mix and the minimum strength value was found as 77.10 MPa with 0.5% glass fiber (M4) mix. Meanwhile, the compressive strength development of all the specimens in different ratios was observed with increasing ages. The highest development ratio of 6.41% was attained with the mixture containing 0.5% steel fiber and 15% SF (M9).

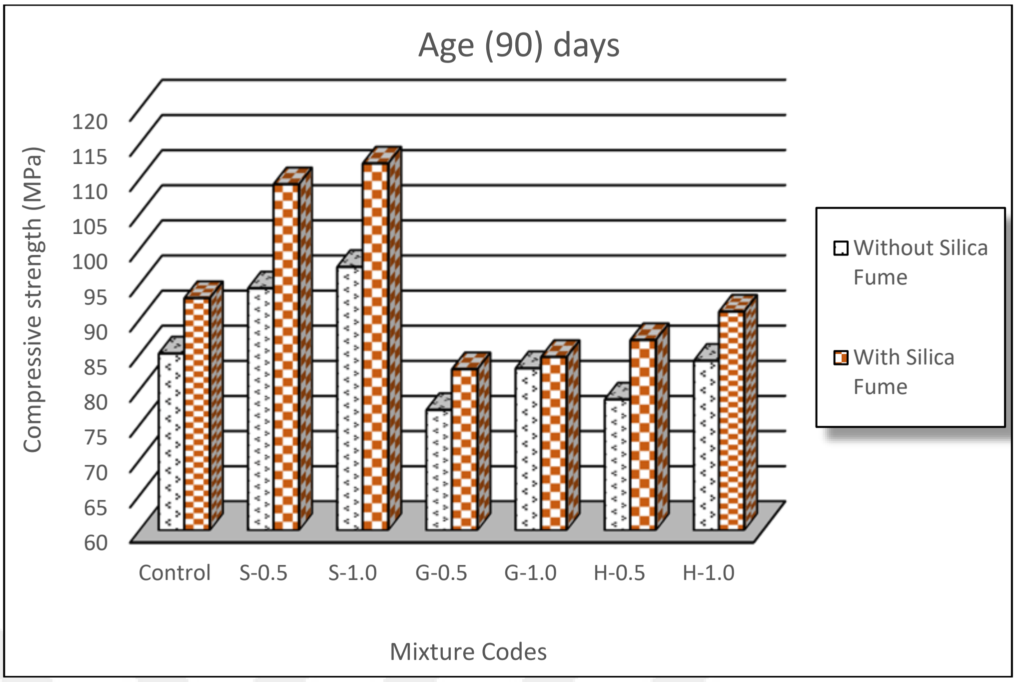


Figure 4.16. Influence of adding fiber and SF on compressive strength at the age of 90 days

The above results indicate that all HPCC specimen strengths developed by time but with different ratio, and the mixture with 0.5% steel fiber and 15% SF had the highest value of development. Figure 4.17. and 4.18. present the development of strength of all mixtures without SF and with 15% SF, respectively at 28, 56, and 90 days.

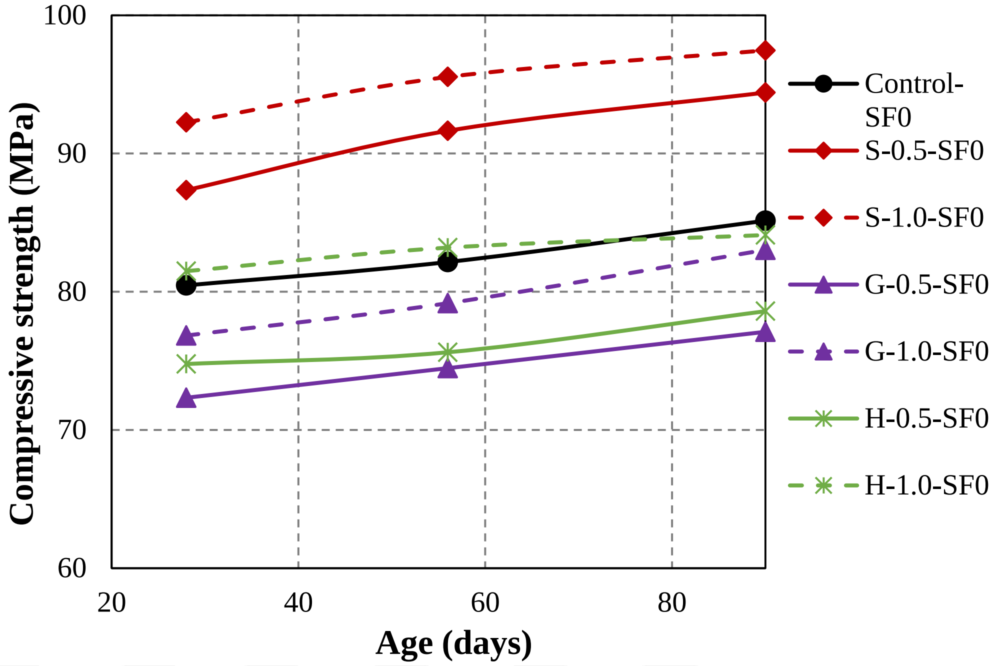


Figure 4.17. Compressive strength development with time (without SF)

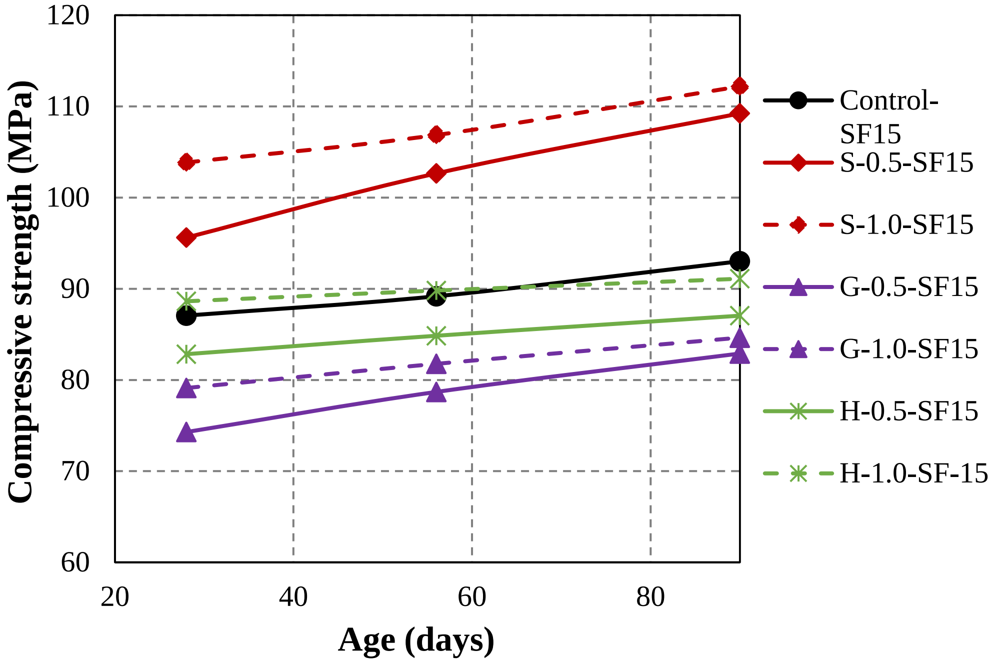
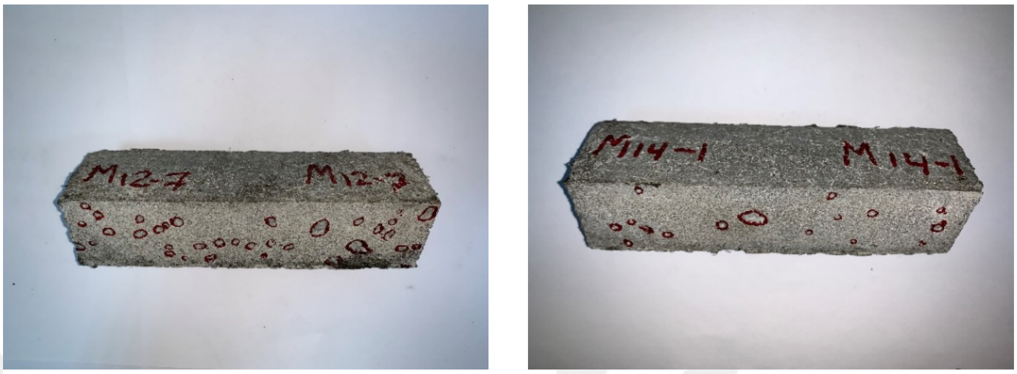


Figure 4.18. Compressive strength development with time (with 15% SF)

Generally, there is a significant enhancement in compressive strength by adding 1.0% of steel fibers to HPCC mixtures. The research results of Sumathi and Mohan (2019) indicated a similar enhancement in compressive strength. On the other hand, it was noticed that the addition of glass fiber decreases compressive strength of the HPCC. The empty voids or pores within the internal structure of glass fiber and hybrid steel-glass FRC (Figure 4.19) reduced the HPCC density, causing decrease of the load carrying capacity of the hardened HPCC sample.



(a) (b)

Figure. 4.19. (a) 1.0% glass fiber HPCC. (b) 1.0% hybrid steel-glass FRC. The voids cause a reduction in compressive strength

Furthermore, it was found that the compressive strength of specimens containing 15% of SF was higher than that of specimens without SF. This can be attributed the highly reactive pozzolanic property and fineness modulus of SF. Johari et al. (2011) stated that using a limited amount of SF enhance the zone between paste matrix and the aggregate due to higher specific surface area and much smaller grains of the SF material when compared to the cement particles.

4.4. Water sorptivity

Sorptivity test is a simple test to determine the tendency of concrete to absorb water by capillary way. In this study three cubes of each mix were tested after 28 days of normal curing and the average value was taken as the sorptivity result. Water sorptivity of the HPCC specimens are presented in (Table 4.6.) and (Figure 4.20.).

Table 4.6. Example of sorptivity calculation

Time (min)	Weight (gm)	Gaining wt. (gm)	Cumulative Gaining wt.(gm)	Vol. of water $(mm)^3$	Surface area $(mm)^2$	Time $(min)^{1/2}$	I (mm^3/mm^2)
0	287.3	0	0	0	2500	0	0
1	287.6	0.3	0.3	300	2500	1	0.12
4	287.7	0.1	0.4	400	2500	2	0.16
9	287.8	0.1	0.5	500	2500	3	0.20
16	287.9	0.1	0.6	600	2500	4	0.24
25	288.0	0.1	0.7	700	2500	5	0.28
36	288.2	0.2	0.9	900	2500	6	0.36
49	288.4	0.2	1.1	1100	2500	7	0.44
64	288.5	0.1	1.2	1200	2500	8	0.48

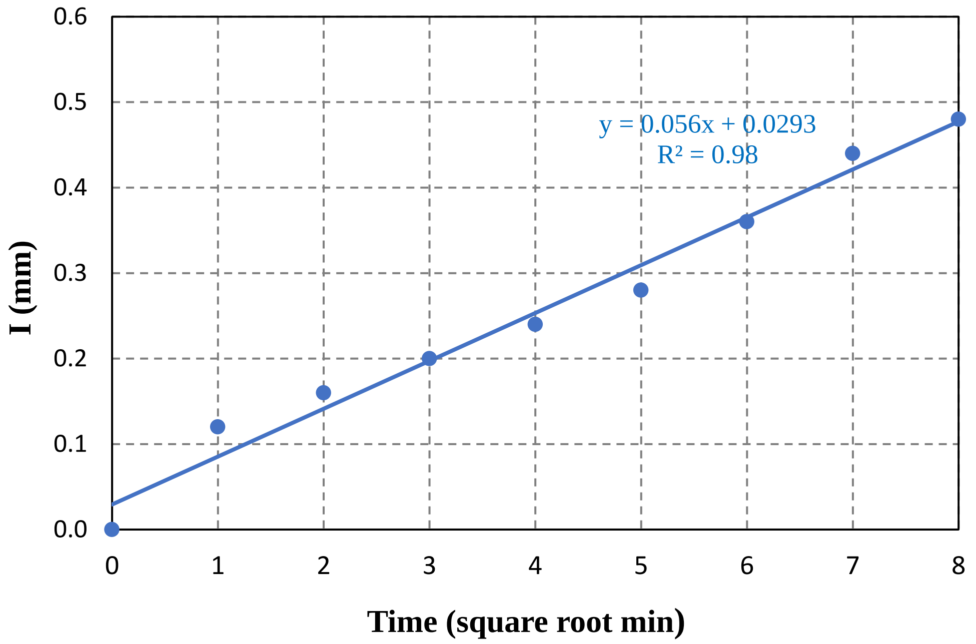


Figure 4.20. Example of sorptivity graph

Table 4.7. Sorptivity results.

#	Mix ID	Sorptivity	#	Mix ID	Sorptivity
M1	Control-SF0	0.0527	M8	Control-SF15	0.0273
M2	S-0.5-SF0	0.0487	M9	S-0.5-SF15	0.0236
M3	S-1.0-SF0	0.0525	M10	S-1.0-SF15	0.0307
M4	G-0.5-SF0	0.0467	M11	G-0.5-SF15	0.0331
M5	G-1.0-SF0	0.0524	M12	G-1.0-SF15	0.0253
M6	H-0.5-SF0	0.0489	M13	H-0.5-SF15	0.0202
M7	H-1.0-SF0	0.0469	M14	H-1.0-SF15	0.0198

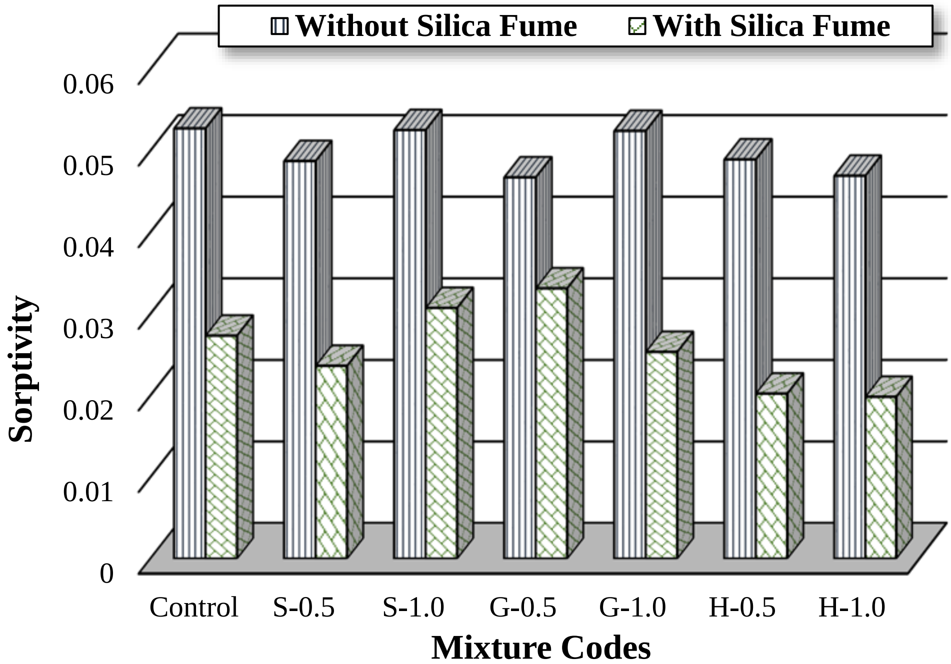


Figure 4.21. Sorptivity results

Table 4.7. and Figure 4.21. show that control sample, with only Portland cement, (M1) has the highest sorptivity value (0.0527 mm/min$^{1/2}$) but the specimen with hybrid 1.0% steel-glass FRC with 15% SF (M14) has the lowest sorptivity value (0.0198 mm/min$^{1/2}$). Generally, the average of sorptivity values is 0.0498 mm/min$^{1/2}$ for the mixtures without SF and 0.0257 mm/min$^{1/2}$ for mixtures with 15% SF. According to the results it was observed that SF modified with hybrid 1.0% steel-glass FRC has low absorption. Moreover, based on the absorption results, there is a significant change in the results due to replacing 15% of Portland cement with SF. This may due to the fact

that SF reduces the permeability of HPCC and makes the microstructure of HPCC denser. Similarly, Diaz and Delvasta (2005) and Shekarchi et al. (2009) announced that addition of silica fume improves water absorption properties of the Portland cement-based materials due to a decrease of permeable voids. In addition, fibers usage has a positive effect on the HPCC relating with permeability and water absorption values.

4.5. Impact of sulfuric acid attack

For each HPCC mixture, 6 prisms and 3 cubes were immersed in a high concentration H_2SO_4 solution (7% by weight) to provide an accelerated acid attack regime. As mentioned in Chapter 3, HPCC specimens were exposed to two subsequent 30-day (i.e. 60 days) exposure periods in aggressive H_2SO_4 solutions. Each one of HPCC specimens had their own acid bath to get similar acidic environments. After the first exposure period (1-month), the solutions were refreshed.

The performance of the HPCC specimens that were exposed to the sulfuric acid solutions was assessed by different aspects. Changes in physical and mechanical properties were observed. As stated in previous chapter, the compressive strength and flexural strength of three prisms were measured and the average values were recorded at the end of each cycle of exposure. Besides, the obtained result was also compared to the samples which were kept in normal curing for the same age. For physical inspection, the weight and dimensions of the cubic samples were monitored monthly through the entire testing period. UPV measurements were carried out to monitor void structure and compared to the non-exposed specimens. Additionally, the appearance of the degraded samples was examined through visual inspection.

4.5.1. Flexural strength loss due to acid attack

The flexural strength results of HPCC specimens which were immersed in 7% sulfuric acid solution and percentage of reduction in strength values are shown in (Table 4.8 and 4.9.) and (Figure 4.22. and 4.23.), The reduction in flexural strength of

HPCC specimens which were immersed for one month and two months' time intervals in aggressive sulfuric acid solutions compared with the flexural strength of HPCC samples that kept in water at the same age.

Table 4.8. Flexural strength loss (without SF) after exposure to a 7% sulfuric acid for two cycles

#	Mix ID	Flexural strength MPa					
		Reference samples kept in water	1-month sulfuric acid exposure	Reduction %	Reference samples kept in water	2-months sulfuric acid exposure	Reduction %
M1	Cont.-SF0	10.98	10.44	4.92	11.17	7.49	32.95
M2	S-0.5-SF0	12.05	10.06	16.51	12.31	7.45	39.48
M3	S-1.0-SF0	12.15	9.42	22.47	13.64	8.12	40.47
M4	G-0.5-SF0	11.04	8.69	21.29	11.47	7.21	37.14
M5	G-1.0-SF0	11.59	9.36	19.24	12.56	8.05	35.91
M6	H-0.5-SF0	11.35	9.20	18.94	11.88	7.36	38.50
M7	H-1.0-SF0	12.21	9.50	22.19	12.80	7.64	40.31

Table 4.9. Flexural strength loss (with 15% SF) after exposure to a 7% sulfuric acid for two cycles

#	Mix ID	Flexural strength MPa					
		Reference samples kept in water	1-month sulfuric acid exposure	Reduction %	Reference samples kept in water	2-months sulfuric acid exposure	Reduction %
M8	Cont.-SF15	11.67	11.43	2.06	11.98	9.26	22.70
M9	S-0.5-SF15	12.19	11.06	9.27	13.33	9.72	27.08
M10	S-1.0-SF15	12.63	10.96	13.22	14.28	9.90	30.67
M11	G-0.5-SF15	11.30	10.08	10.80	11.90	9.13	23.28
M12	G-1.0-SF15	12.16	10.67	12.25	12.73	9.74	23.49
M13	H-0.5-SF15	11.58	10.56	8.81	12.07	8.83	26.84
M14	H-1.0-SF15	12.73	11.23	11.78	13.17	9.91	24.75

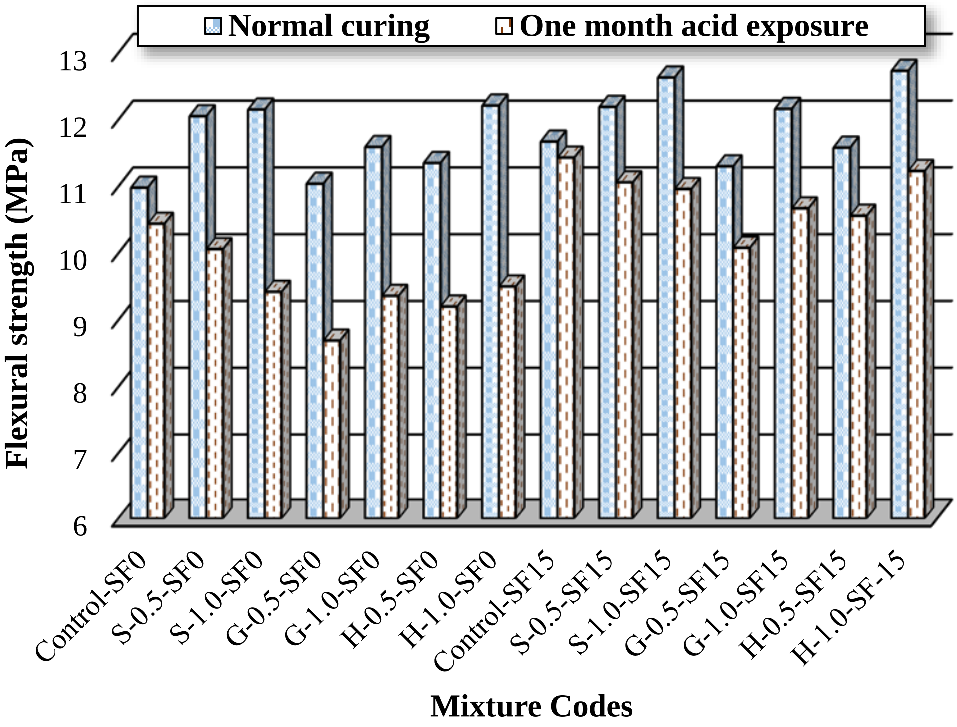


Figure 4.22. Reduction of flexural strength due to exposure of sulfuric acid for one month

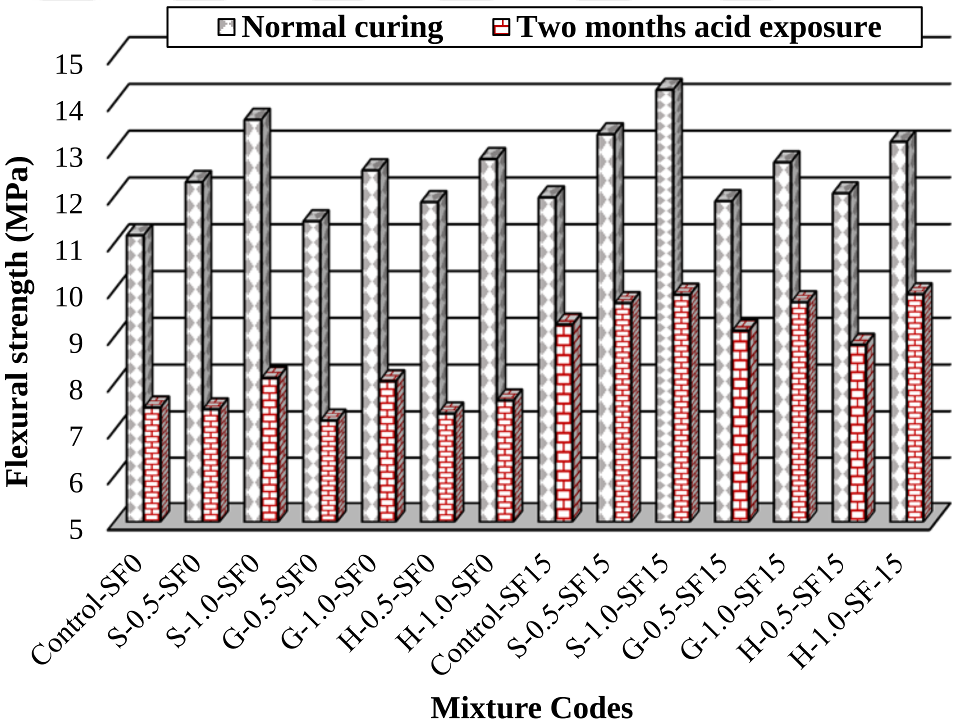


Figure 4.23. Reduction of flexural strength due to exposure of sulfuric acid for two months

(Figure 4.13. and 4.14.) represent the results of the flexural strength measurements of HPCC specimens subjected to the condition with a 7% sulfuric acid solution at the end of each cycles. The results confirm that the reduction of flexural strength for two months of immersion is much higher than those immersed for one month as expected. Additionally, the better acid resistance is achieved for the mixtures containing 15% SF. The mixture of control+15% SF (M8) has shown better performance than the other mixtures, as its flexural strength reduction was reduced by 2.06% and 22.70% after one month and two months of immersion respectively. However, the reduction rate of mixture with 1.0% of steel fiber+ 0% SF (M3) is higher than the others, it has lost 22.47% and 40.47% of its strength after one month and two months of acid exposure. This can be associated with the reaction of sulfuric acid with steel fibers which causes corrosion and helps penetration of acids into HPCC samples. Note that due to the loss of materials and surface irregularities, determining the accurate value of the flexural strength becomes a difficult task.

The results of reduction of the flexural strength in this study had been affected by multiple factors such as time of immersion in sulfuric acid, the type and percentage of fibers and binder used.

It can be seen from the results that the flexural strength reduction increased with increase in time of immersion. Thus, the rate of reduction is highest at two months of acid exposure. The reason for this is due to the chemical reaction between the hydration products of HPCC and the surrounding acid as shown in Figure 4.24. Kurashige [2002] submitted that the penetration of sulfuric acid into HPCC result in reaction with calcium hydroxide and cause gypsum formation. As a result, the solid volume increases and lead to expansion of reaction products. On the other hand, the result of this study shows that at the high concentrations of sulfuric acid, adding 15% SF improved resistance of HPCC against the sulfuric acid impact and the erosion depth of specimens containing SF was smaller than that of specimens without mineral admixtures as shown in Figure 4.25. This is related with lower calcium hydroxide amount in HPCC containing mineral admixtures due to its consumption by pozzolanic reaction. Consequently, using SF positively effects the volume stability of HPCC decreasing the gypsum content derived from the reaction between calcium hydroxide and sulfuric acid. Amudhavalli and Mathew (2012) stated that usage of SF has a positive impact on acid resistance due to the filling property of the fine material.

Figure 4.24. Cubic sample after two months immersion in 7% sulfuric acid solution. White particles (gypsum) were observed due to the reaction between some compounds of HPCC with sulfuric acid

Figure 4.25. Prism sample after one-month exposure to sulfuric acid and the erosion depth is small for specimens containing SF

4.5.2. Compressive strength loss

The results of compressive strength of HPCC specimens which were immersed for two consecutive 30-day (i.e. 60 days) time intervals in 7.0% aggressive sulfuric acid solution and percentage of reduction in strength values are presented in Table 4.10 and 4.11. It was observed that the reduction increases with increasing of exposure time. (Figure 4.24. and 4.25.), show the reduction in compressive strength of specimens were immersed for two-time intervals in aggressive sulfuric acid solutions and compared with the strength of reference samples were kept in water at the same age.

Table 4.10. Compressive strength loss (without SF) after exposure to a 7% sulfuric acid for two cycles

#	Mix ID	Compressive strength MPa					
		Reference samples kept in water	1-month sulfuric acid exposure	Reduction %	Reference samples kept in water	2-months sulfuric acid exposure	Reduction %
M1	Cont.-SF0	82.15	49.03	40.32	85.14	46.77	45.07
M2	S-0.5-SF0	91.64	53.20	41.95	94.41	44.28	53.10
M3	S-1.0-SF0	95.54	58.51	38.76	97.46	53.12	45.50
M4	G-0.5-SF0	74.47	42.52	42.90	77.10	31.92	58.60
M5	G-1.0-SF0	79.17	43.54	45.00	83.03	29.61	64.34
M6	H-0.5-SF0	75.62	45.18	40.25	78.59	28.93	63.19
M7	H-1.0-SF0	83.19	46.72	43.84	84.10	37.17	55.80

Table 4.11. Compressive strength loss (with 15% SF) after exposure to a 7% sulfuric acid for two cycles

#	Mix ID	Compressive strength MPa					
		Reference samples kept in water	1-month sulfuric acid exposure	Reduction %	Reference samples kept in water	2-months sulfuric acid exposure	Reduction %
M8	Cont.-SF15	89.18	54.12	39.31	93.02	46.63	49.87
M9	S-0.5-SF15	102.65	69.96	31.85	109.23	57.14	47.69
M10	S-1.0-SF15	106.86	73.48	31.24	112.19	63.38	43.51
M11	G-0.5-SF15	78.69	48.57	38.28	82.90	40.13	51.59
M12	G-1.0-SF15	81.77	49.55	39.40	84.64	40.43	52.23
M13	H-0.5-SF15	84.85	57.17	32.62	87.05	42.33	51.37
M14	H-1.0-SF15	89.81	54.59	39.22	91.10	45.57	49.98

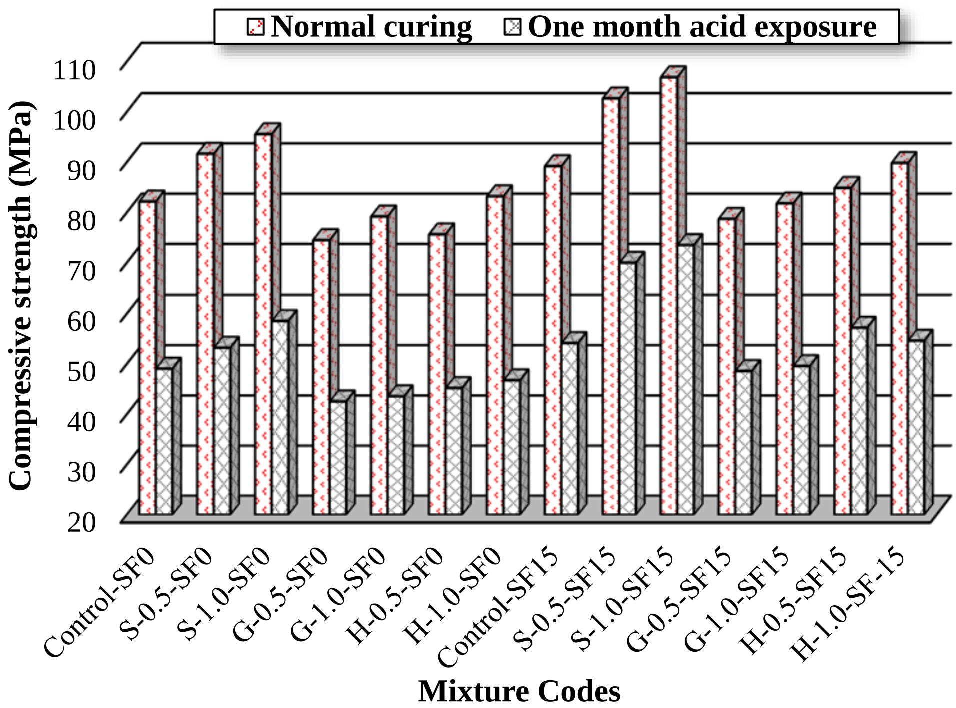


Figure 4.26. Reduction of compressive strength due to exposure of sulfuric acid for one month

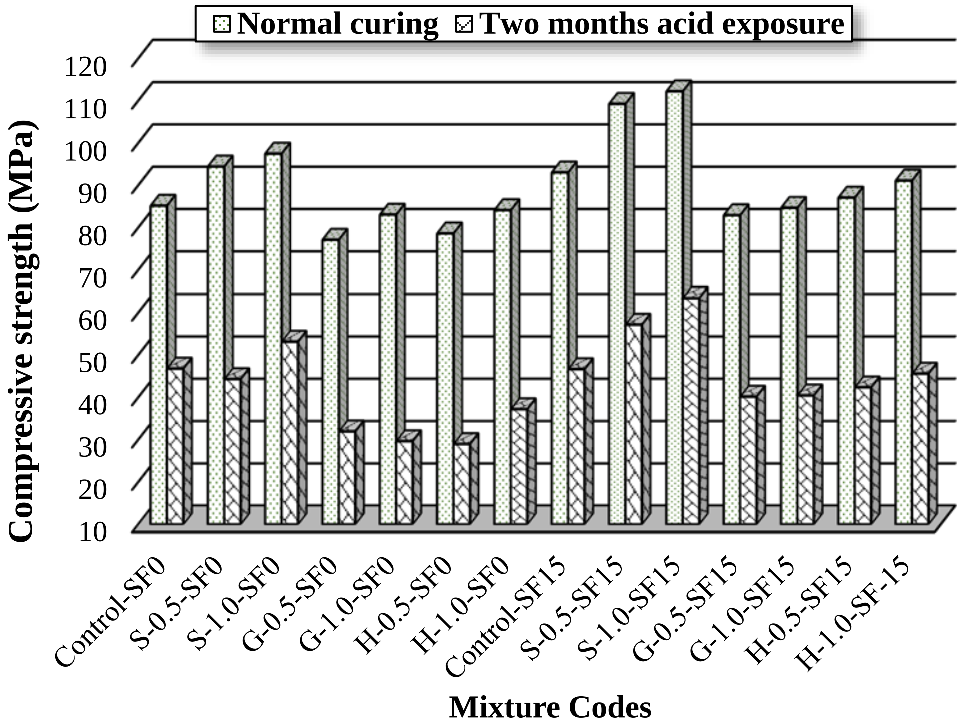


Figure 4.27. Reduction of compressive strength due to exposure of sulfuric acid for two months

The average compressive strength of the degraded samples was evaluated at the end of every phase of exposure to the sulfuric acid solutions and compared with the reference samples at each age as shown in table 4.10. and 4.11. Note that due to the loss of materials and surface irregularities, determining the accurate value of the strength becomes a difficult task. Figure 4.28. shows the compressive test of the degraded sample after one-month immersion in 7.0% sulfuric acid concentration.

Figure 4.28. Compressive strength the of degraded sample

Figure 4.24. and 4.25. illustrate the HPCC specimens that are immersed in a 7% sulfuric acid solution which have undergone considerable strength loss after one month and two months of exposure, respectively. The average strength reduction of specimens was 38.92% for one-month sulfuric acid exposure, and 52.27% for two months acid exposure. As expected, the rate of loss was increased by increasing the exposure time this is due to the increasing chemical reaction between the hydration products of HPCC and the surrounding acid so time of exposure had a significant effect on the reduction in compressive strength. Figure 4.29. shows the difference in strength loss between two cycles of sulfuric acid exposure.

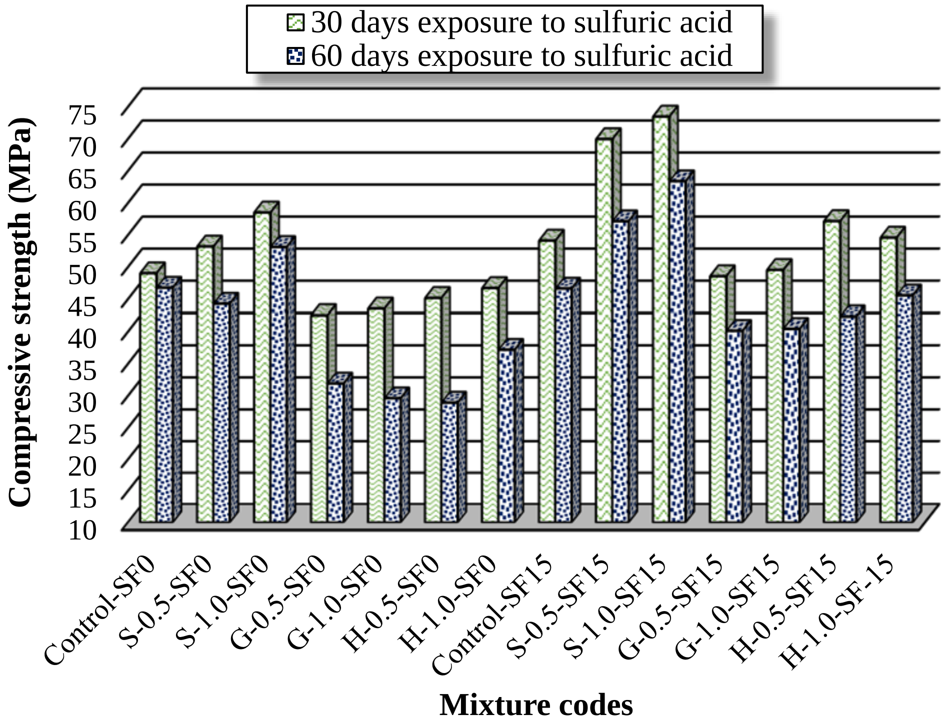


Figure 4.29. The difference in reduction of strength between 30 days and 60 days exposure to sulfuric acid

The contribution of 15%SF in improving the resistance of HPCC specimens to the invasion of sulfuric acid can be clearly noticed from the results of (Figures 4.26., 4.27.) and (Table 4.11.), the average reduction in compressive strength were 35.98% and 49.46% for specimens containing 15% SF, and 41.86% and 55.08% for specimens without SF after one-month and two-months sulfuric acid exposure, respectively. The reason for this, SF is very fine powder and fills the voids between particles. According to Aravindhan and Vijayakumar (2016), SF Produces secondary hydration with the lime resulting from the primary hydration and improves the durability and resistance of HPCC, by reducing the permeability of the cement paste matrix.

According to the results, the maximum reduction in compressive strength was observed for the mixture with 1.0% of glass fiber after immersion in sulfuric acid. The reduction in strength of specimen with 1.0% glass fiber (M5) was 45% after one cycle of acid exposure and 64.34% after two cycles of acid exposure. As presented before, there are a lot of voids or pores in the glass fiber mix structure this may lead to penetration of acids into interior structure and increase degradation of concrete.

4.5.3. Ultrasonic pulse velocity loss

The UPV test was carried out of mixtures after 28 days curing and immersion in sulfuric acid for one cycle and two cycles of acid exposure and the results of this study are shown in (Table 4.12.), and (Figure 4.30.).

Table 4.12. Ultrasonic pulse velocity test results

Mix ID	Exposure to sulfuric acid (days)			Mix ID	Exposure to sulfuric acid (days)		
	0	30	60		0	30	60
Control-SF0	3660	3580	3400	Control-SF15	3670	3600	3430
S-1.0-SF0	3680	3430	2050	S-1.0-SF15	3680	3600	3520
G-1.0-SF0	3680	3540	3250	G-1.0-SF15	3680	3550	3470
H-1.0-SF0	3680	3400	3210	H-1.0-SF15	3680	3650	3520

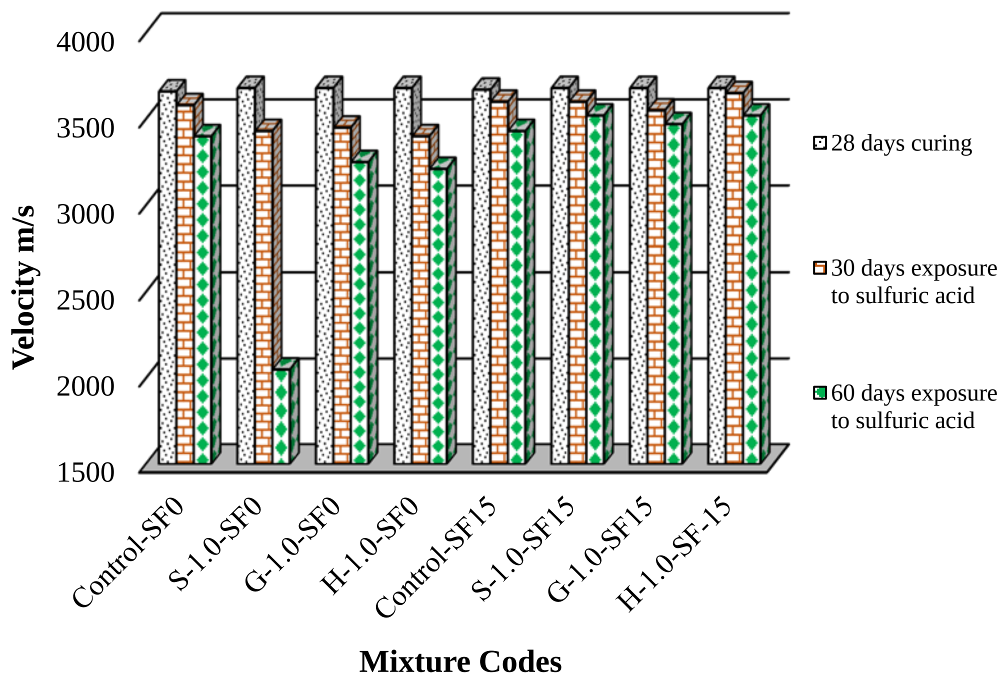


Figure 4.30. Ultrasonic pulse velocity test results

With respect to UPV test results at 28 days curing, there is no significant change in UPV value among mixtures, there is a slight development in UPV results by adding fibers and SF. Researchers have rated UPV values between 3660 - 4570 m/s as a good quality HPCC (Hwang et al., 2012). The average UPV value after 28 days curing was obtained as 3676 m/s in this study.

The results show that the UPV values of the all HPCC mixes decrease after immersing in aggressive sulfuric acid and the loss in UPV value increased with increasing the immersion time as shown in Figure 4.31. The rate of loss was different among mixes, the mix with 1.0% steel fiber and without SF had the lowest UPV value, it was 3430 m/s and 2050 m/s after 30 days and 60 days immersion, respectively. This may due to the reaction between steel and sulfuric acid which results in degradation of HPCC. Meanwhile, the mix with hybrid 1.0% steel-glass FRC and 15% of SF showed better results in UPV values and better resistance to sulfuric acid,The UPV result was 3600 m/s after 30 days immersion and 3520 m/s after 60 days immersion. This is because of presence of the SF in the mix, it is an extremely fine material, which can fill the voids. The pulse of velocity through voids is slower than through solid matter and specimens with SF shows better resistance when exposed to sulfuric acid as discussed before.

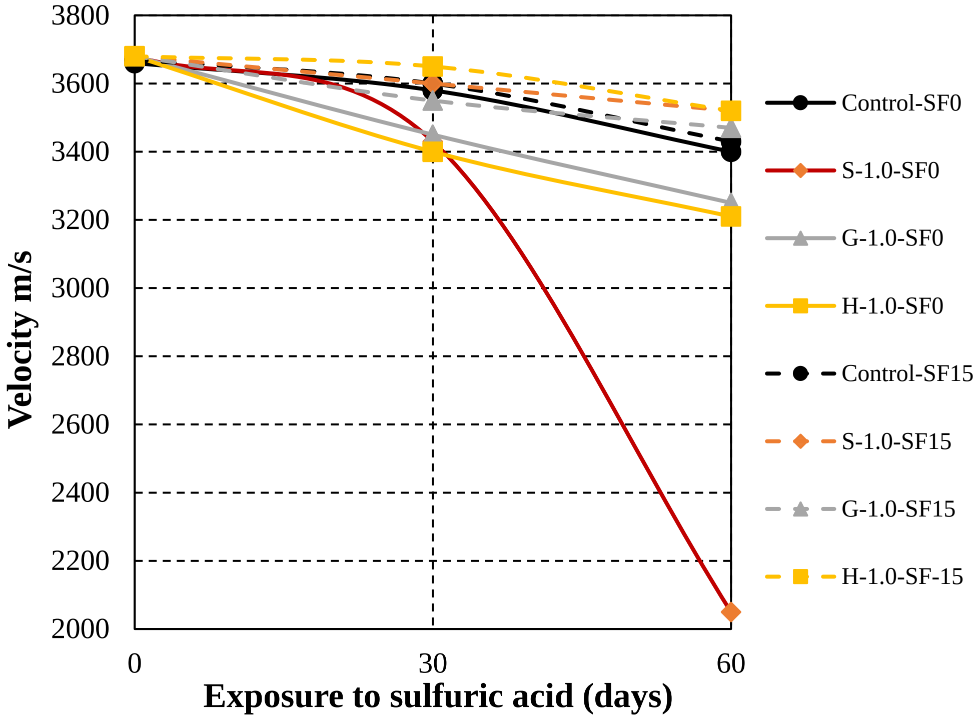


Figure 4.31. The effect of time of sulfuric acid exposure on UPV value of mixtures

4.5.4. Weight loss

Table 4.13. and Figure 4.32. present the results of weight loss (WL) values in this study.

Table 4.13. Weight loss results of specimens due to exposure to sulfuric acid

#	Mix ID	Weight loss % after one-month sulfuric acid exposure	Weight loss % after two months sulfuric acid exposure	#	Mix ID	Weight loss % after one-month sulfuric acid exposure	Weight loss % after two months sulfuric acid exposure
M1	Cont.-SF0	15.35	29.07	M8	Cont.-SF15	11.84	24.93
M2	S-0.5-SF0	14.14	28.72	M9	S-0.5-SF15	11.22	24.28
M3	S-1.0-SF0	12.70	26.91	M10	S-1.0-SF15	11.10	23.58
M4	G-0.5-SF0	15.93	31.10	M11	G-0.5-SF15	12.60	25.43
M5	G-1.0-SF0	15.80	31.40	M12	G-1.0-SF15	13.20	26.76
M6	H-0.5-SF0	14.81	29.77	M13	H-0.5-SF15	12.25	25.57
M7	H-1.0-SF0	13.96	28.70	M14	H-1.0-SF15	12.76	26.67

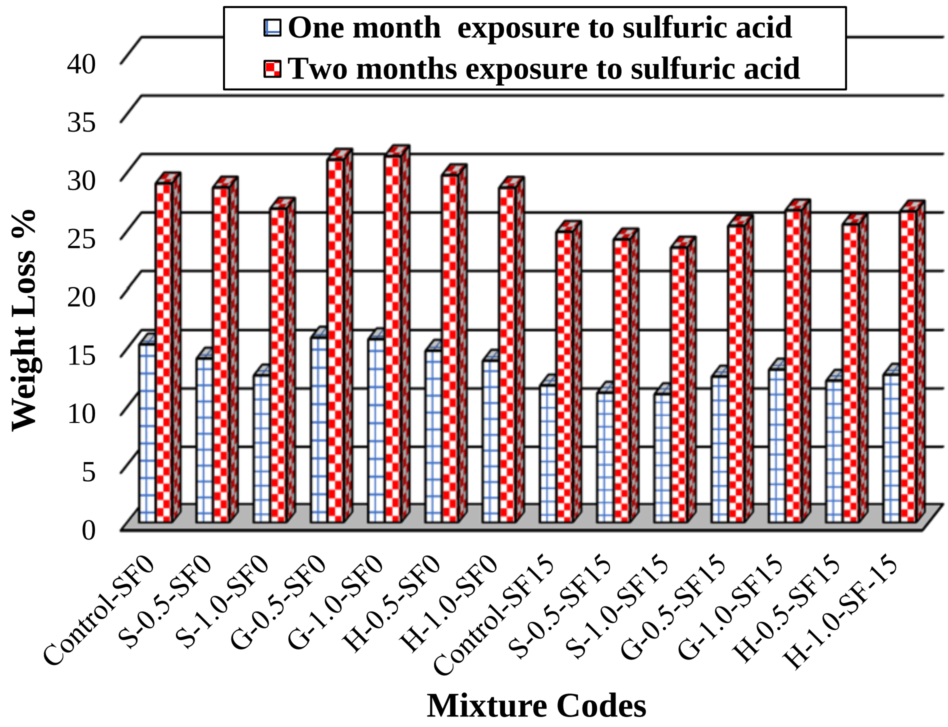


Figure 4.32. Weight loss results of specimens due to exposure to sulfuric acid

The weight changes of the HPCC specimens after two periods of exposure to a 7% sulfuric acid solution were represented in (Table 4.13.) and (Figure 4.32.). While the HPCC specimen with 1.0% steel fiber and 15% SF (M10) had the lowest WL value (11.10%), the specimen with 0.5% glass fiber (M4) had the highest WL (15.93%) after one-month immersion in sulfuric acid. However, after two months immersion in sulfuric acid, the HPCC specimen with 1.0% steel fiber and 15% SF (M10) had the lowest WL value (23.58%) and specimen with 1.0% glass fiber (M5) had the highest WL (31.40%) as shown in Figure 4.34. and 4.35. The results show that the rate of the WL increases with increasing the time of immersion, this is because of increasing chemical reaction between the acid solution and the HPCC which results in losing more HPCC particles as shown in Figure 4.33.

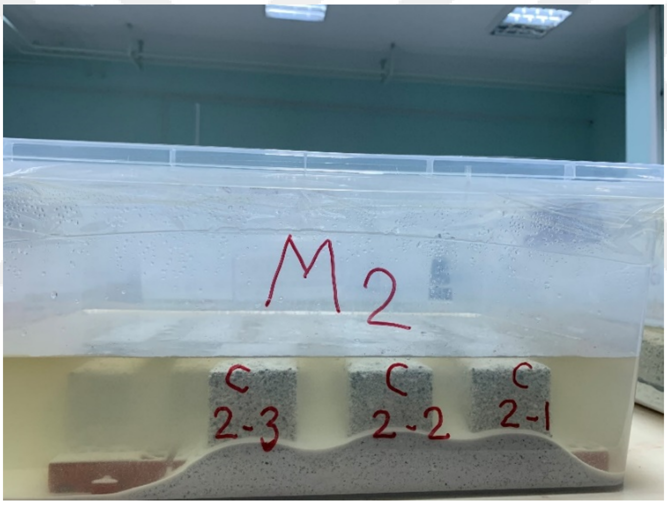


Figure 4.33. Dropping HPCC particles to the bottom of the container resulting in reaction with sulfuric acid solution

The replacement of Portland cement with 15% SF in the mixtures effect positively with decreasing WL results. The reason behind this is the filling effects of silica fume which make the HPCC denser and prevent the ingress of acid into the HPCC. The HPCC containing silica fume was more resistant against acid attack. Additionally, according to studies the adding of steel fiber decreases permeability of HPCC so which result in less aggressive acids penetration and decreases WL.

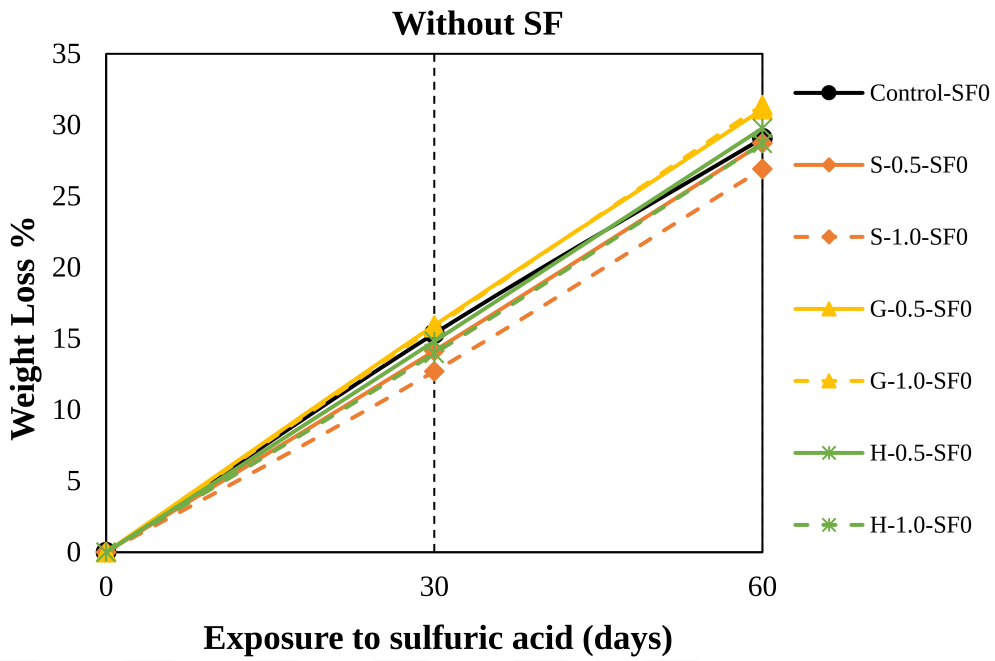


Figure 4.34. Effect of fibers on WL of specimens without SF

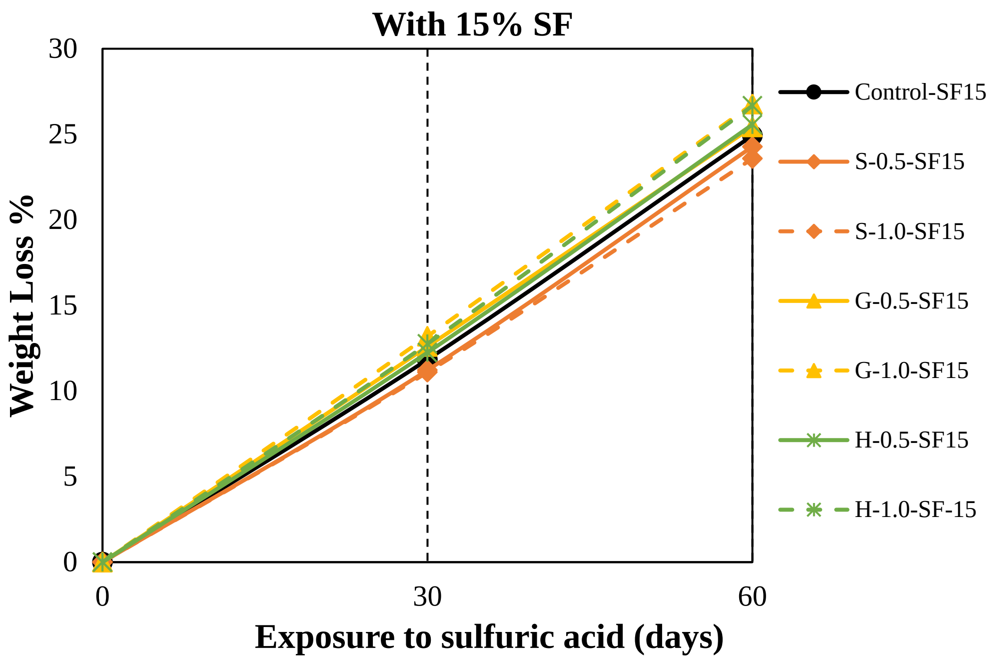


Figure 4.35. Effect of fibers on WL of specimens with 15% SF

4.5.5. Dimension loss

Dimension loss (DL) is the simple non-destructive test method to show the effect of aggressive acids on HPCC. In this investigation the test was carried out on three cubes for each mix, the dimensions in three direction (X,Y,Z) were measured as the initial dimension of samples at the age of 28 days. Then, the specimens were immersed in sulfuric acid solutions. The measurements of dimension change of samples were taken monthly. Table 4.14. and Figure 4.36. illustrate DL results.

Table 4.14. DL results of specimens due to exposure to sulfuric acid

#	Mix ID	DL % after one-month sulfuric acid exposure	DL % after two months sulfuric acid exposure	#	Mix ID	DL % after one-month sulfuric acid exposure	DL % after two months sulfuric acid exposure
M1	Cont.-SF0	2.93	9.11	M8	Cont.-SF15	2.41	7.15
M2	S-0.5-SF0	3.17	9.30	M9	S-0.5-SF15	2.89	7.26
M3	S-1.0-SF0	2.50	8.69	M10	S-1.0-SF15	1.85	6.34
M4	G-0.5-SF0	3.74	11.38	M11	G-0.5-SF15	2.55	7.03
M5	G-1.0-SF0	4.08	11.50	M12	G-1.0-SF15	3.18	9.09
M6	H-0.5-SF0	2.81	10.19	M13	H-0.5-SF15	3.26	8.95
M7	H-1.0-SF0	3.16	10.01	M14	H-1.0-SF15	2.09	9.16

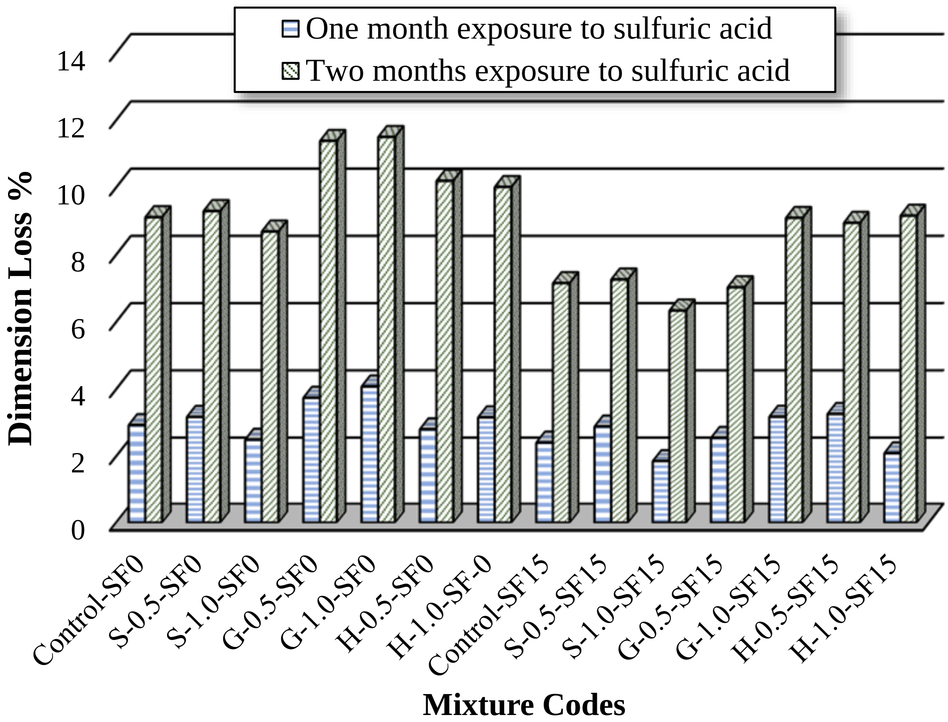


Figure 4.36. DL results of specimens due to exposure to sulfuric acid

These results demonstrate that the mixture with 1.0% steel fiber and 15% SF (M10) had the lowest DL value of 1.85% but the highest DL value was 4.08% for the mix with 1.0% glass fiber (M5) after one-month immersion in sulfuric acid. Also, after two months of immersion in sulfuric acid, the lowest DL value was 6.34% for the mixture containing 1.0% glass fiber and 15% SF (M10) but the highest DL value was 11.50% for the mix with 1.0% glass fiber (M5). The results indicate that DL increases with increasing the immersion time as expected, which was previously stated because of increasing chemical reaction between specimens and surrounding acid solution. Another observation which can be made from (Table 4.14.) and (Figure 4.36.) is that the role of SF. The mixtures containing SF had better sulfuric acid resistance which causes less DL value. This can be attributed to that SF addition causes the reduction of C3A component of Portland cement, which is vulnerable to the sulfate ion attacks and responsible for the secondary ettringite formation. Moreover, the pozzolanic reaction of SF also resulted in decrease of $Ca(OH)_2$ amount. The formation of secondary C-S-H improves the large pores and as a result it enables the protection of HPCC to the harmful chemical attacks (Joorabchian 2010). On the other hand, the addition on 1.0% of glass fiber has A negative effect on DL results, it was observed that the mix with 1.0% glass fiber has more pores and voids. Hence, it faciliates aggressive acids entrance and causes more degradation of HPCC. Additionally, steel fiber has the positive effect on the DL results, it decreases permeability of HPCC and makes the HPCC better resistance to acids.

4.5.6. Visual inspection

In this investigation, the surface photos of the specimens were taken for visual observation before exposing to sulfuric acid at the age of 28 days of normal curing and after exposing to sulfuric acid at the end of each cycles (one-month and two months exposure to sulfuric acid) as shown in Figures 4.37. to 4.39.

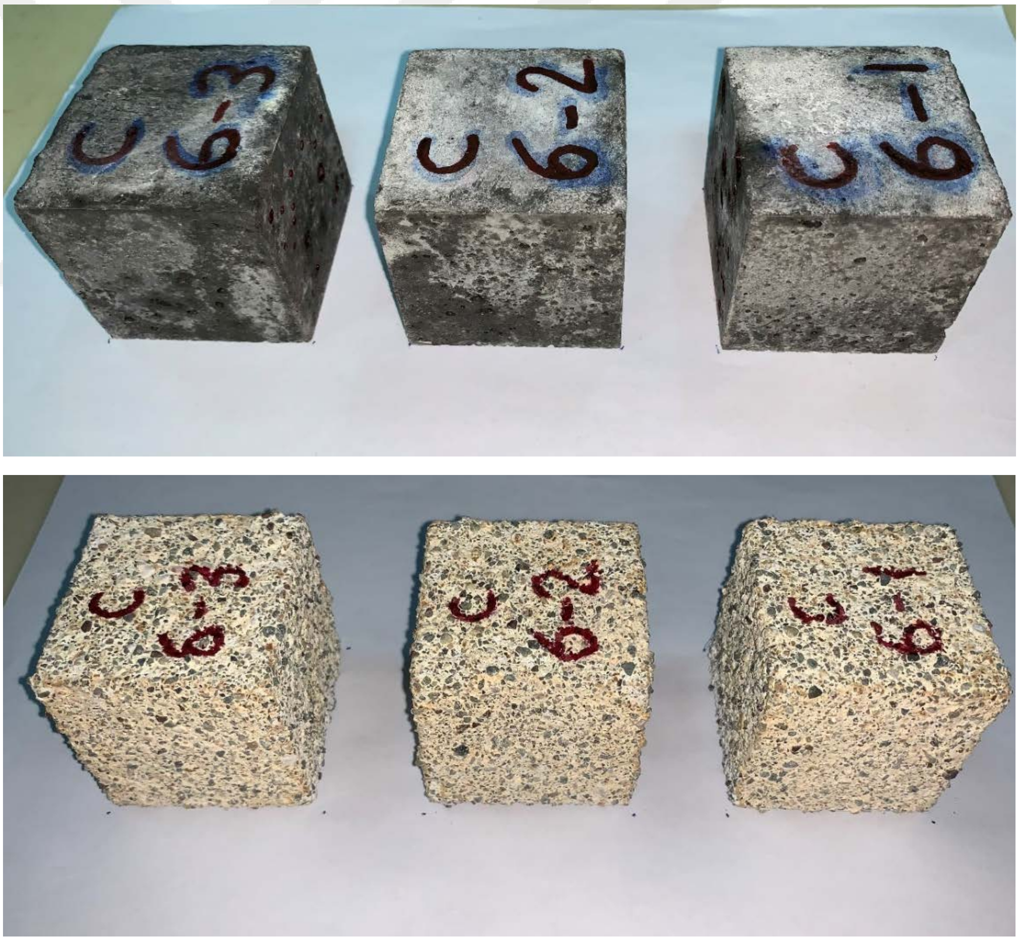


Figure 4.37. Cube specimen after 28 days of normal curing (top) and degradation specimens after one-month (middle) and two months (bottom) of immersion in sulfuric acid solutions with concentrations of 7% side view

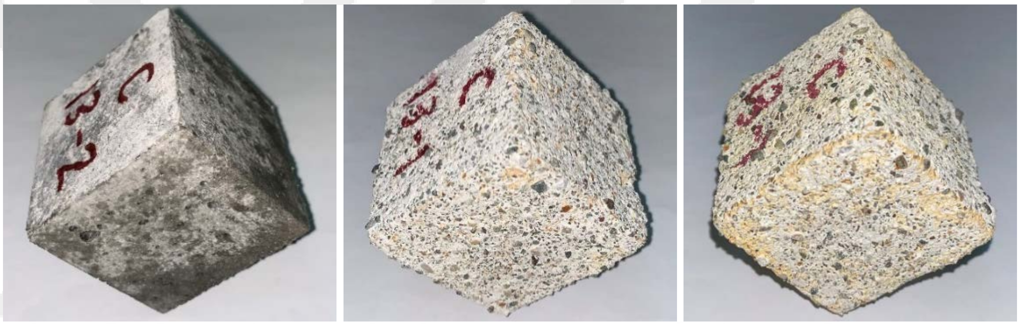


Figure 3.38. Cube specimen after 28 days of normal curing (left) and degradation specimens after one-month (middle) and two months (right) of immersion in sulfuric acid solutions with concentrations of 7% side view

Figure 4.39. Cube specimen after 28 days of normal curing (left) and degradation specimens after one-month (middle) and two months (right) of immersion in sulfuric acid solutions with concentrations of 7% top view

From Figures 4.35. to 4.37., it can be observed that the degradation of specimens increases with increasing the time of immersion in sulfuric acid. Immediately after immersion in the solution, the acid started to react with all the HPCC specimens from all mixtures as indicated by vigorous air bubbles rising up to the surface of the solution as shown in Figure 4.40. Since the first day of exposure, the specimens in a 7% sulfuric acid solution have already lost some of their surface particles and white powdery material (identified as gypsum) deposited progressively on the surface of all specimens. Continual leaching of gypsum led to an off-white residue in the bottom of containers with a consistency similar to fresh cement paste as shown in Figure 4.41.

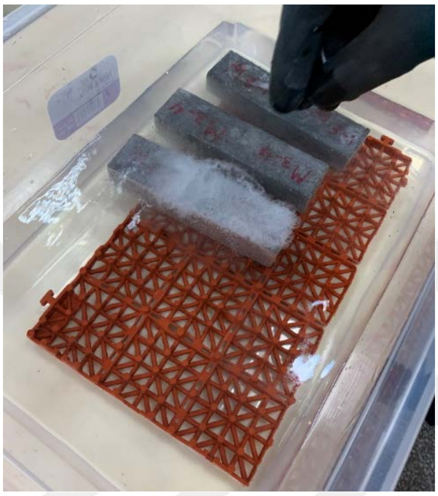


Figure 4.40. Air bubbles rising up to the surface of the solution caused by starting the reaction between the acid and all the HPCC specimens

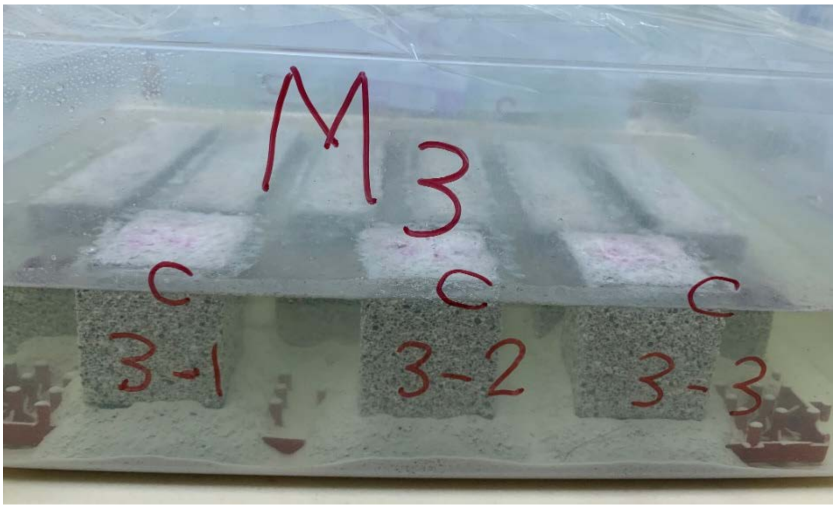


Figure 4.41. Losing particles in the bottom of the container

4.6. Statistical assessment

The general linear model or general multivariate regression model is simply a compact way of simultaneously writing several multiple linear regression models. General linear model ANOVA can be run to determine if more than one numeric or categorial predictor explains variation in a numeric outcome.

The experimental results were graphically and photographically presented and discussed in the previous sections. Here, GLM-ANOVA (general linear model analysis of variance) was used to statistically evaluate the aforementioned results. GLM-ANOVA is a useful statistical tool that is based on the analysis of variance by revealing and comprehending the influence of the independent variables on the dependent variables. The general linear model or general multivariate regression model is simply a compact way of simultaneously writing several multiple linear regression models. General linear model ANOVA can be run to determine if more than one numeric or categorical predictor explains variation in a numeric outcome. The software called Minitab was employed to carry out the statistical evaluation of the experimental results. The statistical tests were conducted at the significance level of 0.05 that is also called the P-value. In this context, Table 4.15 presents the statistical results of flexural and compressive strengths. For this experimental test results, the fiber type and volume fraction, mS content, and curing time were chosen as independent variables whereas the flexural and compressive strength were designated as dependent variables. The results indicated that all independent variables have a meaningful influence on the flexural and compressive strengths when the P-values are considered. However, in order to understand the degree of effectiveness of each independent variable, the percent contribution values should be commentated. The percent contribution values are achieved from the sequential sum of squares and the higher the percent contribution value means the higher the effectiveness of the independent variable. In this regard, it can be stated that the curing time with a contribution of 52.9% is the most effective independent variable on the flexural strength while the most effective independent variable for the compressive strength is fiber type with a contribution of 68.7%. The second impressive independent parameter was fiber volume fraction for both flexural and compressive strength.

Table 4.15. Statistical analysis of the test results on non-exposed specimens

Dependent Variable	Independent variable	Sequential Sum of Squares	Computed F	P-value	Significance	Contribution (%)
Compressive strength	Fiber type	2727.4	249.393	0.000	YES	68.7
	FVF*	876.2	80.29	0.000	YES	22.1
	Silica Fume	596.1	109.25	0.000	YES	15
	Curing Duration	246.9	22.62	0.000	YES	6.2
	Error	185.5	-	-	-	
	Total	3969.0	-	-	-	-
Flexural strength	Fiber type	2.717	10.64	0.000	YES	5.7
	FVF*	14.621	57.29	0.000	YES	30.7
	Silica Fume	2.60	20.38	0.000	YES	5.5
	Curing Duration	25.161	98.59	0.000	YES	52.9
	Error	4.339		-	-	
	Total	47.603		-	-	-

On the other hand, to statistically assess the influence of sulfuric acid exposure on the experimental results, another statistical analysis was performed, in which fiber type and volume fraction and volume fraction, mS content, and sulfuric acid exposure period were considered independent variables, whereas losses in flexural and compressive strengths, UPV, and mass were designated as dependent variables. The results obtained from this analysis are tabulated in Table 4.16.

When the P-values were regarded, it can be seen that fiber type has an ineffective impact on the loss in flexural strength while the impact of fiber volume fraction on the loss in compressive strength and mass is unimportant. However, for the loss in UPV value, not only the fiber type but also its volume fraction have an insignificant influence. In light of these results, the percent contribution results indicated that the sulfuric acid exposure period is the most effective independent parameter on the loss in flexural and compressive strengths and mass. On the other hand, there was no meaningful effect of the independent variables on the loss in UPV values.

Table 4.16. Statistical analysis of the test results on the specimens exposed to sulfuric acid attack

Dependent Variable	Independent variable	Sequential Sum of Squares	Computed F	P-value	Significance	Contribution (%)
Compressive strength loss	Fiber type	230.39	8.49	0.002	YES	11.4
	FVF*	10.93	0.40	0.673	NO	0.5
	Silica Fume	231.21	17.04	0.000	YES	11.5
	Exposure Time	1247,56	91.94	0.000	YES	62
	Error	284,97	-	-	-	-
	Total	2012,86	-	-	-	-
Flexural strength loss	Fiber type	15.81	1.02	0.379	NO	0.5
	FVF*	242.51	15.60	0.000	YES	7.1
	Silica Fume	732.57	94.26	0.000	YES	21.6
	Exposure Time	2230.71	287.02	0.000	YES	65.8
	Error	163.21	-	-	-	-
	Total	3392.47	-	-	-	-
UPV change	Fiber type	223.75	0.96	0.400	NO	5.9
	FVF*	34.78	0.15	0.863	NO	0.9
	Silica Fume	555.72	4.76	0.041	YES	14.5
	Exposure Time	517.89	4.43	0.047	YES	13.5
	Error	2454.10	-	-	-	-
	Total	3824.61	-	-	-	-
Mass loss	Fiber type	24.29	18.42	0.000	YES	1.6
	FVF*	4.18	3.17	0.063	NO	0.3
	Silica Fume	76.10	115.44	0.000	YES	5.2
	Exposure Time	1361.38	2065.14	0.000	YES	92.2
	Error	13.84	-	-	-	-
	Total	1475.86	-	-	-	-

*FVF: fiber volume fraction

5. CONCLUSIONS and SUGGESTIONS

5.1. Summary

The main objective of this investigation program which was to enhance the mechanical properties of high performance cement based composite (HPCC) with desirable fresh and hardened properties by adding hybrid steel-glass fiber reinforcement and the resistance of severe aggressive sulfuric acid was obtained. Through analysis of the results, the fiber content used in the HPCC has played an important role in enhancing the strength properties of HPCC. Hybrid fiber of steel-glass is used to provide improved engineering properties in HPCCs. Also, experimental investigation on using SF as partial replacement of the OPC was carried out in this study. Addition of SF was incorporated to the mixes as a suitable ultra-fine material to fill up the voids of the structure, it showed a positive effect on enhancement of the mechanical properties of the HPCC and better resistance to acidic environments. Another phase of this research was conducted in order to comprehend the behavior of HPCC exposed to sulfuric acid environment.

5.2. Conclusion

Based on the experimental test results, the following conclusions can be drawn:

1. Workability of HPCC decreased with increasing of steel, glass and hybrid steel-glass fibers content due to blockage of the movement of particles by fibers. Addition of glass fiber reduces workability of HPCC in comparison to steel fiber for different volume fraction. Meanwhile, partial replacement of cement with 15% of SF by weight reduced workability of HPCC due to the introduction of large surface area in the HPCC mix by its addition.
2. The unit weight of hybrid steel-glass fiber reinforced HPCC was found approximately similar to that of HPCC without fiber and there is no significant change in unit weight by addition of 15% SF.

3. The 1.0% hybrid of steel-glass fiber reinforced HPCC with 15% of SF clearly shows improvement in terms of flexural strength compared to plain HPCC and records the highest value of flexural strength at ages 28 and 56 days but 1.0% of steel fiber reinforced HPCC with 15% of SF shows the highest value of flexural strength at age of 90 days. The flexural strength of fiber reinforced HPCC was clearly enhanced with the increase of fiber content. In the primary stage of cracking of HPCC, there are numerous steel and glass fibers bridging the micro-cracks and preventing the expansion of the cracks. Also, the brittle mode of failure is changed by the addition of steel and glass fibers into a more ductile one and such fibers were observed to improve the ductility of the HPCC.
4. 1.0% of steel fiber with addition of 15% SF shows the highest value of compressive strength at all ages but the addition of 0.5% glass fiber without SF shows the lowest value of compressive strength at all ages. In this investigation addition of glass fiber decreases the compressive strength of HPCC so it has adverse effect on the compressive strength of hybrid steel-glass fiber reinforced HPCC.
5. The 1.0% hybrid of steel-glass HPCC with 15% SF shows very low capillary absorption property compared to plain HPCC which records the highest capillary absorption in this study. According to previous studies adding fibers reduces the permeability of HPCC and the incorporation of silica fume improves water absorption properties of the Portland cement-based composites owing to a reduction of permeable voids.

6. Conclusions for sulfuric acid exposure can be given as follows;

Considering the high concentration of sulfuric acid solution, period of exposure, the material types as well as proportions used in this thesis, and testing methods the following conclusions are drawn:

- The damage of HPCC was represented by white powdery material deposited progressively on the surface of all specimens. In addition, the cross section of specimens at the end of exposure consisted mostly of a sound core with a very thin reaction zone (0 to 2 mm). However, visual assessment did not show distinctive features of damage among specimens with or without fibers and SF throughout the entire exposure.

- The 1.0% steel fiber sample without SF records the maximum reduction of flexural strength, this is due to reaction of sulfuric acid with steel fibers which causes corrosion and helps entering acids into HPCC samples. Additionally, it was noticed that the specimens containing 15% SF has shown better resistance to aggressive sulfuric acid at the end of each cycles. Also, it was found that the rate of reduction of flexural strength increases by increasing time of exposure.
- Sulfuric acid exposure has a negative effect on strength of HPCC and the compressive strength of HPCC decreases by increasing the time of exposure. It was observed that when a part of cement is replaced with SF, the reduction of strength of HPCC containing the mineral admixture is lower than the reduction of HPCC without SF with the same fiber content, the reason behind this is the filling effects of silica fume which make the HPCC dense and prevent the entry of sulfuric acid into the HPCC. The HPCC containing silica fume was more resistant against sulfuric acid attack.
- From the results of the tests carried out, it could be concluded that the grade of HPCC meets the requirement of good HPCC quality. The average values of UPV in this study after 28 days curing was 3676 m/s. UPV value in influenced by the acid attack, the hybrid 1.0% steel-glass with 15% SF shows highest UPV value and better resistance to acid after each cycles of exposure.
- The WL and DL results of the HPCC specimen that contains 15% SF have shown an improved resistance of these mixtures in comparison to the mixtures without SF with the same fiber content against sulfuric acid invasions. Also, the specimen with 1.0% steel fiber and 15% SF shows the lowest WL and DL reduction. The WL and DL reduction increases with increasing the exposure time.

- It was found that the durability of HPCC is improved by incorporating SF. Adding SF to HPCC, the porosity of the HPCC was reduced. And also, these supplementary materials reduce the leaching of calcium salts from the impermeable surface there by increasing the acid resistance. Meanwhile, fibers acted as porous bridging elements across cracks and permitted the deposition of new hydration products and subsequently arrested the cracks. The combined effect of the supplementary materials makes the HPCC more acid resistance than control HPCC.

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A1. Kasım Mermerdaş, Süleyman İpek, **Ahmed Moatasem Anwer,** Şevin Ekmen, Mustafa Özen (2021) Durability performance of fibrous high-performance cementitious composites under sulphuric acid attack. ***(Under Review)***

B) International Conference, Symposium, Congress Proceedings

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