ENGINEERING AND DURABILITY PROPERTIES OF FIBROUS CEMENTITIOUS COMPOSITES CONTAINING HYBRID, KENAF AND BARCHIP

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by

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LIST OF ABBREVIATIONS

PFA	Pulverised Fuel Ash
GGBS	Ground Granulated Blast-Furnace Slag
MIA	Mortar Industry Association
SF	Steel Fibre
PP	Polypropylene Fibre
PE	Polyethylene Fibre
PVA	Polyvinyl Alcohol Fibre
SEM	Scanning Electron Microscopy
EDX	Energy Dispersion X-Ray
FRC	Fibre Reinforced Concrete
FRCC	Fibre Reinforced Cementitious Composites
HPFRCC	High Performance Fibre Reinforced Cementitious Composites
ECC	Engineered Cementitious Composites
POFA	Palm Oil Fuel Ash
RHA	Rice Husk Ash
SCM	Supplementary Cementitious Materials
BSI	British Standard Institution
ASTM	American Society for Testing and Materials
ITZ	Interfacial Transition Zone
MARDI	Malaysian Agricultural Research and Development Institute

CIRI-CIRI KEJURUTERAAN DAN KETAHANAN KOMPOSIT SIMEN BERSERAT YANG MENGANDUNGI HIBRID, KENAF DAN BARCIP

ABSTRAK

Ciri-ciri kejuruteraan dan ketahanan komposit simen berserat yang mengandungi hibrid, kenaf dan barcip adalah gabungan bahan-bahan simen tambahan sebagai pengganti simen seperti Debu bahan api terhancur (PFA) dan Sanga relau bagas yang digiling (GGBS) dengan tambahan kandungan serat seperti serat barcip dan kenaf. Masalah yang berlaku pada umumnya adalah apabila kandungan simen lebih tinggi akan meningkatkan gas karbon dioksida, suhu persekitaran dan pengecutan yang tinggi. Tambahan lagi, kombinasi serat diaplikasikan untuk memperbaiki tingkah laku lenturan mortar berbanding dengan mortar konvensional. Penyelidikan eksperimen dilakukan untuk mencirikan sifat-sifat PFA, GGBS, serat Barchip dan Kenaf; untuk menyiasat ciri-ciri rheologi dan kejuruteraan; untuk menilai prestasi ketahanan mortar; dan untuk mengkaji tingkah laku lenturan komposit simen berserat yang mengandung hibrid, kenaf dan barcip dari segi kekuatan mampatan, kekuatan lenturan, indeks ketangguhan, halaju nadi ultrasonik, modulus keanjalan dinamik, rintangan beban kesan, pengecutan pengeringan, penyerapan air, kebolehtelapan intrinsik gas, penembusan klorida, jumlah keliangan, pembangunan mikrostruktur, tindak balas pesongan beban, tindak balas tekanan mampatan beban, kapasiti impak beban, mod kegagalan dan perkembangan keretakan pada panel dan papak. Sebanyak tujuh campuran mortar direka bentuk dengan PFA dan GGBS yang digunakan pada penggantian simen malar sebanyak 10% dan 40% yang digabungkan dengan serat mono (2.5% serat barcip atau 2.5% serat kenaf) dan serat hibrid (gabungan di antara serat barcip dan kenaf dengan peningkatan sehingga 2.0%) dengan jumlah berat isipadu yang dirawat di dalam keadaan pengawetan air dan tempoh pendedahan kitaran. Kemasukan serat barcip pada 2.5% telah di dapati lebih tinggi kekuatan mampatan di antara 4.0% - 9.8% di dalam pengawetan air dan di antara 1.3% - 14.9% di dalam pendedahan kitaran yang lebih tinggi berbanding dengan mortar kawalan. Walau bagaimanapun, kekuatan lenturan komposit simen berserat mengandungi hibrid, kenaf dan barcip yang dimasukkan ke dalam serat mono (2.5% barchip) dan serat hibrid, HBK 1 (0.5% serat kenaf + 2.0% serat barcip) dan HBK 2 (1.0% serat kenaf + 1.5% serat barcip) diperhatikan lebih tinggi daripada mortar kawalan dengan peratusan, B (15.3% - 65.5%), HBK 1 (5.8% - 55.4%) dan HBK 2 (4.2% - 62.1%) di dalam tempoh pengawetan air dan pendedahan kitaran dari 7 hingga 364 hari. Oleh itu, panel dan papak komposit simen berserat yang mengandungi hibrid, kenaf dan barcip didapati lebih tinggi tindak balas beban pesongan beban, tindak balas beban tekanan mampatan dan juga pembangunan ciri-ciri retakan yang bagus untuk spesimen B, HBK 1 dan HBK 2 berbanding dengan panel dan papak kawalan.

ENGINEERING AND DURABILITY PROPERTIES OF FIBROUS CEMENTITIOUS COMPOSITES CONTAINING HYBRID, KENAF AND BARCHIP

ABSTRACT

Engineering and durability properties of fibrous cementitious composites containing hybrid, kenaf and barchip was the combination of the supplementary cementitious materials as cement replacement such as Pulverised Fuel Ash (PFA) and Ground Granulated Blast-Furnace Slag (GGBS) with additional of fibres content like Barchip and Kenaf fibre. Due to the problems that generally happen when cement content was higher will increase the carbon dioxide gases, environmental temperature, and high shrinkage. In addition, the combination of fibre was applied to improving the flexural behaviour of mortar as compared to the conventional mortar. The experimental research was conducted to characterise the attributes of PFA, GGBS, Barchip and Kenaf fibres; to investigate the rheological and engineering properties; to assess the durability performances of hardened mortar; and to study the flexural behaviour of fibrous cementitious composites containing hybrid, kenaf and barchip in term of compressive strength, flexural strength, toughness indices, ultrasonic pulse velocity, dynamic modulus of elasticity, impact load resistance, drying shrinkage, water absorption, intrinsic gas permeability, chloride penetration, total porosity, microstructure development, load-deflection response, load compressive strain response, impact load capacity, failure mode and crack development of panels and slabs. A total of seven mortar mixes were fabricated with PFA and GGBS used at constant cement replacement of 10% and 40% in combination with mono (2.5% of barchip or 2.5% kenaf fibre) and hybrid fibre (combination between barchip and kenaf

fibre level up to 2.0%) by total volume weight cured in water and cyclic exposure condition. The inclusion of barchip fibre at 2.5% was found to have the higher compressive strength between 4.0% – 9.8% cured in water curing and 1.3% - 14.9% cured in cyclic exposure higher as compared to the control mortar. However, the flexural strength of fibrous cementitious composites containing hybrid, kenaf and barchip which the inclusion of mono fibre (2.5% barchip) and hybrid fibre, HBK 1 (0.5% kenaf fibre + 2.0% barchip fibre) and HBK 2 (1.0% kenaf fibre + 1.5% barchip fibre) was observed higher than the control mortar with the percentages, B (15.3% - 65.5%), HBK 1 (5.8% – 55.4%) and HBK 2 (4.2% – 62.1%) cured in water and cyclic exposure durations from 7 to 364 days. Therefore, the fibrous cementitious composites containing hybrid, kenaf and barchip panels and slabs were found to have the higher load-deflection response, load compressive strains response and also better crack development characteristics for specimens B, HBK 1 and HBK 2 as compared to the control panel and slab.

CHAPTER ONE

INTRODUCTION

1.1 Background

Engineering and durability properties of fibrous cementitious composites containing hybrid, kenaf and barchip was the combination of two major part which is supplementary cementitious materials and fibres. There were two supplementary cementitious materials has been used in this research were Pulverised Fuel Ash (PFA) and Ground Granulated Blast-Furnace Slag (GGBS). This both materials are known as by-product material or wastage materials that needed to be disposed of. However, due to the large quantity of this wastage materials, it will cause harm to the environmental issues such as gas emission greenhouse, global warming, and others. Therefore, the inclusion of by-product materials or wastage materials can replace and reduce the cement used in the mortar or concrete that can help to reduce the environmental issues.

The characteristics of PFA and GGBS were suitable to be used as supplementary cementitious materials. Based on mortar industry association (MIA), these materials not only impart technical benefits to both the fresh and hardened properties of mortar they are also environmentally friendly. In addition, both materials are products resulting from industrial processes and their use. GGBS is a by-product from the blast-furnaces that was used to make an iron. Mixtures of iron-ore, coke and limestone are fed into blast-furnaces which operate at a temperature of about 1500°C. Two products such as molten iron and molten slag are produced when iron-ore, coke and limestone melt in the blast furnace, and the lighter molten slag floats on the top of the molten iron. The molten slag comprises mostly silicates and alumina. The process of granulating the slag involves cooling of molten slag through high-pressure water jets. This rapidly quenches the slag and granular particles are formed which are generally less than 5 mm. The granulated slag is further processed by drying and then grinding in a rotating ball mill to a very fine powder, which is called GGBS. GGBS can be used as a direct replacement for ordinary cement on a one-to-one basis by weight. Replacement rates for GGBS vary from 30% to up to 85% (Siddique & Bennacer, 2012).

Besides that, it can reduce the quantity of primary raw materials that have to be extracted from the ground. GGBS is classified as a latent hydraulic material. This means that it has inherent cementitious properties, but these have to be activated. The normal means of achieving this is to combine the material with Portland cement. In addition, PFA is classified as a pozzolans material. Pozzolans are a broad class of siliceous or siliceous and aluminous materials which, in themselves, possess little or no cementitious value but which will, in finely divided form and in the presence of water, react chemically with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties (Apparao & Naik 2016). The quantification of the capacity of a pozzolan to react with calcium hydroxide and water is given by measuring its pozzolanic activity (Snellings et al. 2012). The pozzolanic activity is a measure for the degree of reaction over time or the reaction rate between a pozzolan and Ca^{2+} or $Ca(OH)_2$ in the presence of water.

The rate of the pozzolanic reaction is dependent on the intrinsic characteristics of the pozzolan such as the specific surface area, the chemical composition, and the active phase content. Physical surface adsorption is not considered as being part of the pozzolanic activity, because no irreversible molecular bonds are formed in the process (G. Papadakis et al. 1992). The chemical composition of PFA like a high percentage of silica (60 – 65%), alumina (25 – 30%) and magnetite, Fe_2O_3 (6 – 15%) enables it to be used for the synthesis of zeolite, alum and precipitated silica. The other important physicochemical characteristics of PFA, such as bulk density, particle size, porosity, water holding capacity, and surface area makes it suitable to be used as an adsorbent (Ahmaruzzaman, 2010). This type of material does not generally have inherent cementitious properties, but if it is combined with a highly alkaline material it forms a cementitious product (MIA 2012). In this study, the combination of PFA and GGBS has been used about 50 % as cement replacement from the total of binder materials or cementitious composites.

However, the supplementary cementitious materials for this research was remained constant due to the percentages of PFA is 10 % and GGBS is 40 % as cement replacement. In addition, to improve the flexural behaviour of fibrous cementitious composites, the hybrid fibres have been used in this study in order to enhance the flexural behaviour characteristics and ductility of fibrous cementitious composites. Fibres such as steel (SF) fibre, polypropylene (PP) fibre, polyethylene (PE) fibre, polyvinyl alcohol (PVA) fibre and Barchip fibre have been used in cementitious composite mixes. Thus, for this study, there are two types of fibre that have been used such as Barchip fibre and Kenaf fibre. The application of the fibre improves strength and strain capacity as well as energy absorption of the concrete (Soe et al., 2013), thus reduces the damage that a concrete structural member may suffer upon being subjected to impact load. High modulus fibre such as glass fibre and carbon fibre increases the bulk strength and toughness of the material, but their intrinsic brittle behaviour does not allow for ductility or strain hardening behaviour. Low modulus fibres such as polyvinyl alcohol fibre, polypropylene fibre and polyethylene fibre have been found to be able to improve the ductility of the concrete mixture significantly as well as reduce the cracking and impact (Soe et al., 2013). Particularly, the characteristics of fibre affect the mechanical properties of the materials significantly. High ductility is a result of the interactions between fibre, matrix and fibre matrix interfacial zone in the cementitious composites material and local failure is delayed by developing multi-cracks (Li, 2008).

There has been a growing interest in the use of natural fibres in composite applications such as Kenaf fibre that has been used over the past few years. This type of fibre presents many advantages compared to synthetic fibres likes lower in cost, lower in fibre density, easy to find and biodegradability. Biodegradability can be measured in a number of ways. Respirometer tests can be used for aerobic microbes. First one places a solid waste sample in a container with microorganisms and soil, and then aerates the mixture. Over the course of several days, microorganisms digest the sample bit by bit and produce carbon dioxide that resulting amount of CO_2 serves as an indicator of degradation. The most common natural plant used in this application is bast fibre such as bamboo, jute, flax, kenaf, coconut, palm oil and sisal. One of the reasons for this growing interest is that natural fibres have a higher specific strength than glass fibre with a similar specific modulus. Then, natural fibres can offered desirable specific strengths and modulus at a lower cost with their properties and cheaper sources (Akil et al. 2011). Therefore, the engineering performance of fibrous cementitious composites containing hybrid fibres was studied about the supplementary cementitious materials (PFA and GGBS) and fibres (barchip fibre and kenaf fibre) that were implemented for enhancing the mechanical strength, durability properties, and structural application, respectively.

1.2 Problem Statement

The engineering and durability properties of fibrous cementitious composites containing hybrid, kenaf and barchip were investigated such as mechanical properties, durability performances and flexural behaviour of concrete. However, there are several problems statement has been considered that will fill the gap of knowledge in this study. The problems statement was described as below:

1. Binary and ternary blended concrete was introduced to improve the strength and durability properties of concrete. However, most of the binary or ternary blended concrete has a lower strength of flexural behaviour such as load-deflection relationship, load compressive strains relationship and crack development of concrete.

2. The inclusion of kenaf and barchip fibre with the ternary blended concrete or mortar containing Portland cement, Pulverised Fuel Ash and Ground Granulated Blast-furnace Slag were exhibited less research has been done in this area.

3. Kenaf fibre is the one of natural fibre that can be explored to be used in the construction and building materials. However, there is less research done using

this fibre in the mortar especially for the ternary blended mortar that containing more than three binder materials.

4. The use of synthetic fibre such as polypropylene fibre, glass fibre, and others has been exposure widely in past decades. However, the hybridization of synthetic fibre and natural fibre was less contributed in the ternary blended cementitious composites mortar especially for barchip and kenaf fibre.

Therefore, based on literature review the gap of knowledge a reasonable solution for these problems is via the substitution of larger portions of the cement with industrial wastes or by-products as supplementary cementitious materials without sacrificing its mechanical properties in general, particularly its ductility. In addition, the inclusion of fibres into concrete not only provides considerably more ductile structure but also improves structural properties such as tensile strength, static flexural strength, impact strength, flexural toughness and the energy absorption capacity of the concrete.

1.3 Research Aims and Objectives

This study is designed to investigate the suitability of constant supplementary cementitious materials, barchip, kenaf and hybrid fibres content that will be used as replacement materials of binder content (PFA and GGBS) and additional material for implementation in engineering and durability properties of fibrous cementitious composites. Therefore, this research has involved with barchip fibre and kenaf fibre that will admixture inside of cementitious composites as mono and hybrid fibre.

The present investigation also aims to study the flexural behaviour of the engineering and durability properties of fibrous cementitious composites containing hybrid, kenaf and barchip fibres test panels and slabs under flexure static load condition. The effect of varying level of hybrid fibres using barchip and kenaf fibre on the mechanical properties of flexural behaviour has been studied and exhibited in the form of load-deflection characteristics, load-compressive strain response, toughness indices, impact load resistance and crack development.

The objectives and overall aims of the research are summarized as follows:

- To characterise the chemical and physical compositions, mineralogy, a specific gravity of PFA, GGBS, Barchip and Kenaf fibre.

- To investigate the rheological properties and engineering performance of fibrous cementitious composites containing hybrid fibres in term of compressive strength, flexural strength, toughness indices, ultrasonic pulse velocity, dynamic modulus of elasticity, impact load resistance and drying shrinkage behaviour.

- To assess the effect of the inclusion of PFA-GGBS as partial replacement and Barchip and Kenaf fibres as additional materials on durability properties of hardened mortar namely water absorption, intrinsic air permeability, chloride permeability, total porosity and microstructure development.

- To study the flexural behaviour in term of load-deflection characteristics, load compressive strain response, impact load capacity, failure mode and crack development of panels and slabs containing hybrid fibres.

1.4 Significance of research

This research is designed to derive experimental data on engineering and durability properties of fibrous cementitious composites containing hybrid, kenaf and barchip. The most important benefit being the elimination of pulverised fuel ash and ground granulated blast-furnace slag also known as coal ash (produce during the combustion of coal) and industrial by-product from the production of steel waste disposal problem by recycling of PFA and GGBS as supplementary binder in concrete and mortar that can be used in structural application. Therefore, in this study, the inclusion of PFA and GGBS is 50 % of total binder weight that can improve the strength and durability of hardened mortar.

This research is also aimed to investigate the use of fibres as a material additive for enhancing the durability performance and mechanical strength of cementitious composites mortar. Based on the flexural behaviour of experimental data derived from the laboratory testing of engineering and durability properties of fibrous cementitious composites containing hybrid, kenaf and barchip panels and slabs will contribute towards a better understanding on the toughness indices, impact load resistance, load-deflection behaviour, load compressive strain behaviour, and others.

The detail of experimental work has been explained as below:

1. The assessment of chemical properties includes evaluation on the mineral phase, loss on ignition (LOI) and chemical compositions of the binder materials by using the X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD) analysis. The physical properties of fibres were given by the supplier.

2. The assessment on rheological properties of the engineering performance of fibrous cementitious composites containing hybrid fibres mortars covers the slump value of the mixes that it's will be determined in fresh state before the inclusion of fibres. Besides that, the assessment on mechanical strength properties of the hardened mortar for engineering performance of fibrous cementitious composites containing hybrid fibres includes the determination of compressive strength and flexural strength at the duration of hydration. For purpose of stiffness assessment, dynamic modulus of elasticity, ultrasonic pulse velocity, toughness indices and impact load resistance of the hardened mortar was also investigated.

3. The assessment of durability properties of the engineering performance of fibrous cementitious composites containing hybrid, kenaf and barchip fibres mortars cover the water absorption, porosity, intrinsic air permeability, chloride permeability and drying shrinkage. In addition, the scanning electron microscopy and energy dispersion x-ray analysis were observed to investigate the characteristics of mortar matrix and fibre interfacial transition zone.

4. Investigate flexural behaviour of engineering performance of fibrous cementitious composites panels and slabs containing hybrid fibres. The investigation on structure behaviour is carried out a total of 4 mixing of slabs that have better strength and durability strength were fabricated (900 × 600 × 30 mm) with various barchip fibre content up to a maximum of 2.0 % coupling with various kenaf fibre between 0.5 % and 2.0 %. The monitoring parameters include the load-deflection behaviour, stress-strain compressive response, crack behaviour and crack pattern.

1.5 Scope and Limitation of the studies

In this study, there are limitations that cannot be done due to the time limit and the cost of the testing. For the engineering performance of fibrous cementitious composite, only two types of the hybrid fibres were proposed for optimum strength properties. Therefore, in this study, only barchip fibre and kenaf fibre have been chosen because of the strength characteristics and durability behaviour of these fibres compared to the other fibres. Besides that, the chloride permeability and scanning electron microscopy/ energy dispersive x-ray were observed for the selected ages only because of the time limitation. Chloride permeability was considered one of the testing that involve the many steps to be followed until getting the final results of chloride content same as SEM/EDX testing. In this study, there were many types of testing have been measured and observed. Therefore, it’s cannot only focus on the chloride permeability and SEM/EDX testing to define the performance of fibrous cementitious composites containing hybrid, kenaf and barchip fibre. Other than that, the research has followed the method was proposed as mention in this study in the next chapter.

1.6 Layout of the thesis

In this thesis, there are seven chapters to cover the major aspects of the engineering properties and behaviour of the performance fibrous cementitious composites containing hybrid fibres mortar. In Chapter One, the background to this research investigation has been briefly discussed on contemporary problems encountered in the production sector, the significance of this research study and also the limitation of work covered in this study.

In Chapter Two, a critical review of literature related to the use of binder materials in cementitious composites. The characteristics of the FRC, HPFRCC, and ECC is presented. The effect of the inclusion of supplementary cementitious material and additional of fibres on mechanical strength namely compression and flexural strength properties are reviewed and discussed. The critical of the summary also included in this chapter to define the gap of knowledge of the research.

The detail of relevant test methodology and experimental programme are described in Chapter Three. Other than, the characteristics of materials used and important parameters of investigation in the experimental programme are also discussed in this chapter.

Chapter Four discusses on the non-destructive and destructive assessment aspects namely dynamic modulus of elasticity, ultrasonic pulse velocity, compressive strength and modulus of rupture (or flexural strength), impact load resistance and drying shrinkage of hardened mortar.

In Chapter Five, a detailed in durability assessment analysis on intrinsic air permeability, the total porosity, and water absorption are presented for the durability performance evaluation. In addition, chloride permeability and microscopy of structures such as scanning electron microscopy and energy dispersion X-ray will be included in the engineering performance of fibrous cementitious composites containing hybrid fibres mortar.

Chapter Six will investigate in the structural or flexural behaviour of fibrous cementitious composites containing hybrid, kenaf and barchip fibres panels and slabs such as load-deflection response, load compressive strains response, crack development characteristics and crack pattern at failure mode is also described in details.

Finally, in Chapter Seven, the overall conclusion from the experimental works are summarized. Recommendations for implementation and further research are also suggested in this chapter.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The review of past literature is one of the most important part in research work. This chapter highlighted the high level of interest on normal concrete and mortar, fibre reinforced concrete/mortar and hybrid fibre reinforcement. In this chapter, the criteria of these concrete will be included to review the different for each other. The characteristics of two types of fibres which are kenaf and barchip fibre also will be discussing as these fibres were adopted as independent variables in this experimental programme.

In addition, the others by-product(wastage product) or known as supplementary cementitious materials such as Palm oil fuel ash (POFA), Ground granulated blast-furnace slag (GGBS), Rice Husk Ash (RHA) and Pulverised Fuel Ash (PFA) that have been used in cementitious composites also will be discuss in this chapter. However, the discussion about the hybrid fibres on normal concrete and cementitious composites also has been reviewing more details in this chapter.

The critical summary of literature will be the last part of this chapter. It highlighted the large gap of knowledge in the application of supplementary cementitious materials (SCM) and fibres inclusion in those described environment and formulates the framework of this research.

2.2 Fibre Reinforced Concrete

Fibre reinforced concrete (FRC) is a new structural material which is gaining increasing importance. Addition of fibre reinforcement in discrete form improves many engineering properties of concrete. There were many different types of fibres and the application of FRC in different areas. Concrete is weak in tension and has a brittle character. The concept of using fibres to improve the characteristics of construction materials was about 100 decades ago. Early applications include the addition of straw to mud bricks, horse hair to reinforce plaster and asbestos to reinforce pottery. Use of continuous reinforcement in concrete (reinforced concrete) increases strength and ductility but requires careful placement and labour skill. Alternatively, the introduction of fibres in discrete form in plain or reinforced concrete may provide a better solution. Addition of fibres to concrete makes it a homogeneous and isotropic material. When concrete cracks, the randomly oriented fibres start functioning, arrest crack formation and propagation, and thus improve strength and ductility (Nemati, 2015).

Table 2.1 Type of fibre reinforcement.

Years	Type of fibre reinforcement
Below 1900	Horsehair
1900	Asbestos fibres, Hatscheck process
1920	Griffith, theoretical vs. apparent strength
1950	Composite materials
1960	Fibre reinforced concrete (FRC)
1970	New initiative for asbestos cement replacement Steel fibre reinforced concrete (SFRC) Glass fibre reinforced concrete (GFRC) Polypropylene fibre reinforced concrete (PPFRC) Shotcrete
1990	Micromechanics, hybrid systems, wood based fibre systems manufacturing Techniques, secondary reinforcement, HSC ductility issues, shrinkage crack control.
2000 +	Structural applications, Code integration, New products. Hybrid fibre (synthetic and synthetic/ synthetic and natural)

Source : (Nemati, 2015)

The failure modes of FRC are either bond failure between fibre and mortar matrix or material failure. In addition, for many applications, it is becoming increasingly popular to reinforce the concrete with small, randomly distributed fibres.

Their main purpose is to increase the energy absorption capacity and toughness of the material, but also increase the tensile and flexural strength of concrete. Typical load-deflection curves for plain concrete and fibre-reinforced concrete are shown in Figure 2.1. Plain concrete fails suddenly once the deflection corresponding to the ultimate flexural strength is exceeded. On the other hand, fibre-reinforced concrete continues to sustain considerable loads even at deflections considerably in excess of the fracture deflection of the plain concrete. Examination of fractured specimens of fibre reinforced concrete shows that failure takes place primarily due to fibre pull-out or de-bonding. Besides plain concrete, a fibre-reinforced concrete specimen does not break immediately after initiation of the first crack. This has the effect of increasing the work of fracture, which is referred to as toughness and is represented by the area under the load-deflection curve. The failure mechanism is by pull-out and never exceed the tensile strength of the fibre. The addition of any type of fibres to plain concrete reduces the workability. Concrete mixtures containing fibres possess very low consistencies. However, the place ability and compact ability of concrete are much better than reflected by the low consistency. In FRC crack density is increased, but the crack size is decreased (Nemati, 2015).

Furthermore, it may also contain pozzolans and other admixtures commonly used in conventional concrete. However, fibres of various shapes and sizes produced from steel, plastic, glass, and natural materials are being used for most structural and non-structural purposes, steel fibre is the most commonly used of all the fibres. There is considerable improvement in the post-cracking behaviour of concretes containing fibres. Although in the fibre reinforced concrete the ultimate tensile strengths do not increase appreciably, the tensile strains at rupture do. Compared to plain concrete, fibre reinforced concrete is much tougher and more resistant to impact (Nemati, 2015).

There are many types of fibre that has been used in fibre reinforced concrete such as steel fibre (different type likes straight, crimped, twisted, hooked, ringed, and paddled ends), glass fibre, natural organic and mineral fibres (wood, asbestos, cotton, bamboo, rock wool, oil palm, coconut, jute, sisal, kenaf and others), polypropylene fibre (plain, twisted, fibrillated, and with buttoned ends) and others synthetic fibre likes Kevlar, nylon, polyester, polyvinyl alcohol (PVA), barchip and others.

Concrete is a quasi-brittle material with a low strain capacity which reinforcement of concrete with short randomly distributed fibres can approach some of the concerns related to concrete brittleness and low resistance to crack growth. Fibres are used as reinforcement that can be able in capturing cracks at both micro- and macro-levels. At the micro-level, fibres inhibit the initiation and growth of cracks, and after the micro-cracks coalesce into macro-cracks, fibres provide mechanisms that abate their unstable propagation, provide effective bridging, and impart sources of strength gain, toughness and ductility (Zhang et al. 2014). Nowadays, the development has continued with expansion to a variety of other fibres, such as glass, carbon, synthetics (polyethylene, polypropylene and barchip), natural fibres (coconut and oil palm) and in current years, hybrids that combine either different fibre types or fibre lengths.

Furthermore, the term of fibre reinforced concrete (FRC) is defined by ACI 116R, Cement and Concrete Terminology, as a concrete containing dispersed randomly oriented fibres. Inherently concrete is brittle under tensile loading and mechanical properties of concrete may be improved by randomly oriented short discrete fibres which prevent or control initiation, propagation, or coalescence of cracks (Hannant, 1987). The character and performance of FRC changes depending on the properties of concrete and the fibres. The properties of fibres that are usually of interest are fibre concentration, fibre geometry, fibre orientation, and fibre distribution. Using a single type of fibre may improve the properties of FRC to a limited level. However, the concept of hybridization, adding two or more types of fibre into concrete, can offer more attractive engineering properties as the presence of one fibre enables more efficient utilization of the potential properties of other fibre (Banthia & Gupta, 2004).

Apart from the gradually expanded use of the tension-softening branch of FRC in structural property enhancements, fibres in small dosage have been successfully used in controlling restrained drying shrinkage cracks. Early years of the 1980's, interest in creating a fibre reinforced concrete material with tensile ductility has been gaining ground. Within FRC, the toughness of the material is increased, but no change in ductility is achieved. Ductility is a measure of tensile deformation (strain) capacity typically such as ductile steel but not with concrete material.

The modern day version of continuous fibre reinforcement is represented by textile reinforced concrete materials that may be prestressed. Developed in parallel, the use of discontinuous fibres at high dosage (4-20%) such as in cement laminates and in SIFCON (Slurry Infiltrated Fibre CONcrete) has resulted in concrete composite materials that attain higher tensile strength than normal concrete and which are not as brittle, but with much less ductility than their continuous fibre and textile reinforced counterparts. These materials may be considered a class of materials separate from FRC in that different degree of tensile ductility is achieved, often accompanied by a strain hardening response distinct from the tension-softening response of FRC. Meanwhile, Figure 2.1 indicates the differences between the tensile response of normal concrete, FRC, and HPFRCC, such as obtained from a uniaxial tension test. This figure emphasizes the transition from brittle concrete to quasi-brittle FRC (tension softening) to ductile HPFRCC (strain hardening) (Fischer & Li 2003).

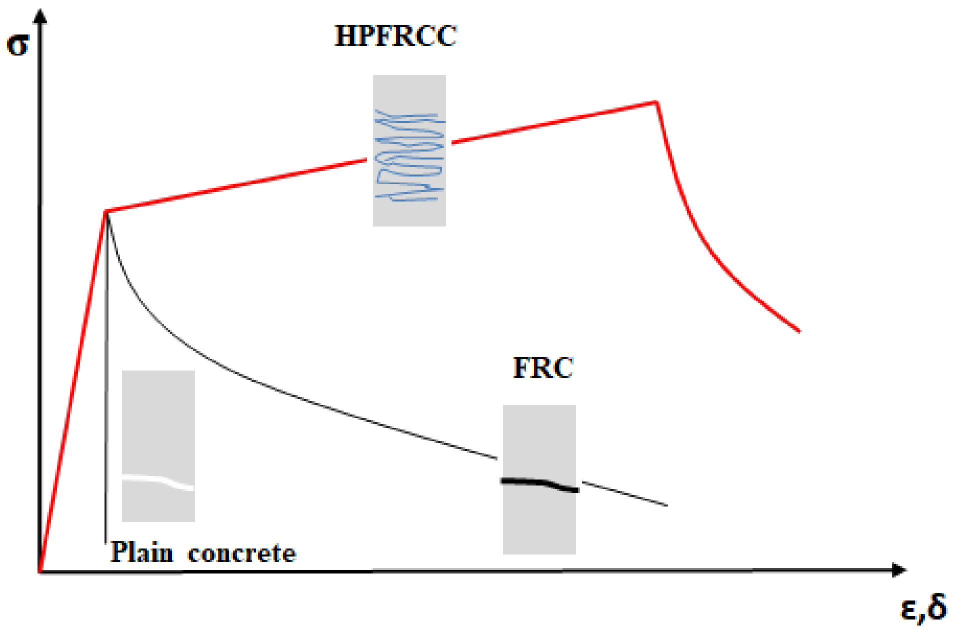

Figure 2.1: Uniaxial tensile stress–deformation relation of plain concrete, FRC, and HPFRCC. (Adoption from Fischer and Li, 2003).

A large proportion of reinforced concrete structures present durability problems (steel corrosion, chemical attacks by chlorides and sulphates, freeze-thaw damage, carbonation, etc.) before reaching their design life. Most of these deteriorations are due to the ingress of water and aggressive agents into the concrete. Three transport modes can occur in structures: diffusion (due to a concentration gradient), permeability (due to a pressure gradient) and capillarity suction (due to capillarity effects). Transport by diffusion occurs typically in structures exposed to the severe environment (chloride, sulphate ions, etc.) for which the ions concentration is higher outside than inside the concrete. Transport by permeability is predominant for structures submitted to high pressure (dams, liquid containment, nuclear power plant containment, etc.), but may also occur under smaller pressure gradients in other exposed structural elements (beams, slabs, walls, etc.). Transport by capillarity suction occurs for example when a structure is subjected to wet-dry cyclic. Depending on the kind of structures, the three transport modes can occur simultaneously. Nevertheless, one of these modes is often predominant (Desmettre & Charron, 2012).

2.3 Development of Fibre Reinforced Cementitious Composites

Fibre reinforced cementitious composites (FRCC) exhibiting strain hardening and multiple cracking behaviour have been developed. Past research works indicate that strain hardening was mostly achieved in FRCC with high cement content in the matrix such as cement paste and cement mortar (Şahmaran & Li, 2008). The inherent requirement of high cement content in these composites is not only cost prohibitive but also inconsistent with recent trends in environmental awareness calling for limited cement contents in cementitious materials. Therefore, it is important to develop strain hardening FRCC incorporating cement-replacing materials such as PFA (FA), palm oil fuel ash (POFA) and ground granulated blast-furnace slag (GGBS).

The review paper by Owaid et al., (2012) clearly explains the role of supplementary cementitious materials in reducing greenhouse gas emissions (Owaid et al. 2012). Hybrid fibre FRCC exhibiting strain hardening and multiple cracking behaviour have also been developed recently (Ahmed & Maalej, 2009; Ahmed et al., 2007).In hybrid fibre composites, two or more different types of fibres are suitably combined to exploit their unique properties. The hybridization of fibres in FRCC can be done in different ways, such as by combining different lengths, modulus and tensile strengths of fibres. Large macro fibres bridge the big cracks and provide toughness, while small micro fibres enhance the response prior to or just after the cracking.

Microfibres also improve the pull out the response of macro fibres, thus produce composites with high strength and toughness (Banthia & Nandakumar, 2003). Mono fibre composites containing high modulus fibres normally show high ultimate strength, low strain capacity and small crack width properties (Li & Maalej, 1996), while those containing low modulus fibres show low ultimate strength, high strain capacity and large crack width properties. A hybrid composite, with a proper volume ratio of high and low modulus fibres, can be expected to show simultaneous improvement in ultimate strength, strain capacity and crack width properties (Ahmed et al., 2007; Ahmed & Maalej, 2009).

Nowadays, there are several numbers of articles have dealt with the topic of hybrid fibre reinforced cementitious composites. The improvement of mechanical properties such as compressive strength, flexural strength, flexural toughness, tensile strength and impact strength of hybrid fibre reinforced cementitious composites over mono fibre composites and plain concrete has been reported by several researchers (Bank et al., 2010; Kawamata et al., 2003; Maalej et al., 2005; Lawler et al., 2005). The use of PFA as partial replacement of cement on the development of FRCC has been documented in a number of studies (Sahmaran & Yaman, 2007; Faiz & Ahmed, 2007; Atis & Karahan, 2009). The uses of PFA in FRCC not only reduce the amount of cement but also help to evenly disperse fibres during mixing (Qian & Stroeven, 2000a; Qian & Stroeven, 2000b). Experimental results also indicate that interfacial bond strength of fibre and matrix fracture toughness reduce due to the use of PFA in FRCC The low matrix fracture toughness has the low first crack strength are in favour of strain hardening behaviour and low interfacial bond strength of fibre improves the ductility of the composites (Ahmed & Maalej, 2009).

The strain hardening and the multiple cracking behaviour of hybrid fibre FRCC containing high volume PFA (FA) have been documented in a limited number of studies. Other studies by Zhu et al. tested the ECC with 70% combination mineral admixtures of FA and ground granulated blast furnace slag (SL) investigated the mechanical properties and drying shrinkage. The results show that ECC with combination mineral admixtures can achieve strain hardening behaviour, tensile capacity of ECC can be more than 2.5 % at 90 days. This incorporation SL into the matrix can effectively increase compressive strength at all ages, especially at an early age, which is convenient to apply the ECC for the field which demands strong strength at an early age. (Zhu, Yang et al., 2012).

The study by Ahmad & Maalej, (2009) concluded that the hybrid steel-PE fibre composites showed lower ultimate strength but higher deflection capacity at the peak load than that of hybrid steel-PVA fibre composites. Strain-hardening behaviour accompanied by multiple cracking was achieved in all hybrid steel-PE fibre composites. In addition, a hybrid combination of 1.5 vol% steel and 1.0 vol% PVA exhibited the best performance in terms of highest flexural strength, 0.5 vol% steel and 2.0 vol% PE exhibited highest deflection and energy absorption capacities. A rate of strength loss after peak load in hybrid steel-PE composites was found to be lower than that of steel-PVA hybrid composites. The 50% replacement of cement by PFA is found to be an optimum PFA content in hybrid fibre composites (Ahmed & Maalej, 2009).

On the durability side, Lawler et al., (2005) tested permeability characteristics of cracked hybrid composites under tensile loading condition and demonstrated that fibre hybridization significantly increases the resistance to water ingress. The microfibers delayed the development of micro-cracks and so the composite demonstrated greater strength and crack resistance than a similar matrix reinforced with macro-fibres only. This influence was less pronounced than was observed with a mortar matrix that has been explained by differences in the failure mechanism of the fibres. A stronger fibre-matrix bond resulting from a lower water-to-binder ratio caused the microfibers to break instead of pull out. The macro fibres were also more likely to break in the hybrid fibre reinforced concrete than in the same matrix containing macro fibres alone since the microfibers reinforced the matrix, increasing the macro fibre pull out resistance (Lawler et al., 2005). More recently, Banthia and Soleimani, (2005) tested several types of hybrids in normal strength concrete and showed that hybrids based on polypropylene and mesosphere carbon fibre produced the highest level of fracture energy synergy. Likewise, a hybrid combination of two types of carbon fibres low modulus, isotropic pitch-based carbon fibre and high modulus, mesosphere pitch-based carbon fibre showed significant promise. These authors also investigated three fibre hybrids with carbon and polypropylene micro-fibres added to macro-steel fibres and showed that steel macro-fibres with highly deformed geometry produce better three-fibre hybrids than those with a less deformed geometry (Banthia & Soleimani, 2005). Also, composites with a lower volume fraction (Vf) of fibre reinforcement were seen as having a better prospect for hybridization than composites with a high volume fraction (Vf) of fibres. In other words, FRCs with low toughness are better candidates for hybridization than composites with a higher toughness.

Finally, Banthia and Gupta, (2004) showed that the strength of the matrix plays a major role in the optimization of hybrid composites. The use of two or more types of fibres in a suitable combination may potentially not only improve the overall properties of concrete but may also result in performance synergy. The combining of fibres, often called hybridization, is investigated in this paper for a very high strength matrix of an average compressive strength of 85 MPa. Control, single, two-fibre and three- fibre hybrid composites were cast using different fibre types such as macro and micro-fibres of steel, polypropylene and carbon (Banthia & Gupta, 2004). However, large diameter crimped fibres are specified as these fibres are inexpensive, disperse in concrete easily, do not reduce the workability excessively and finish without difficulty. Unfortunately, such fibres also provide a low toughness. A test program was conducted here to investigate if the flexural toughness could be enhanced by replacing a part of the large diameter fibres with smaller diameter fibres while maintaining fibre dispensability and workability.

2.4 High Performance Fibre Reinforced Cementitious Composites

High performance fibre reinforced cementitious composites (HPFRCCs) are a group of fibre-reinforced cement-based composites which possess the unique ability to flex and self-strengthen before fracturing. This particular class of concrete was developed with the goal of solving the structural problems inherent with today's typical concrete, such as its tendency to fail in a brittle manner under excessive loading and its lack of long-term durability. Because of their design and composition, HPFRCCs possess the remarkable ability to strain harden under excessive loading. In layman's terms, this means they have the ability to flex or deform before fracturing, a behaviour similar to that exhibited by most metals under tensile or bending stresses. Because of this capability, HPFRCCs are more resistant to cracking and last considerably longer than normal concrete. Another extremely desirable property of HPFRCCs is their low density. A less dense, and hence lighter material means that HPFRCCs could eventually require much less energy to produce and handle, deeming them a more economical building material. Because of HPFRCCs' lightweight composition and ability to strain harden, it has been proposed that they could eventually become a more durable and efficient alternative to typical concrete. HPFRCCs are simply a subcategory of ductile fibre-reinforced cementitious composites (DFRCCs) that possess the ability to strain harden under both bending and tensile loads, not to be confused with other DFRCCs that only strain harden under bending loads (Sirijaroonchai et al., 2009; José et al., 2013; Kuder & Shah, 2010; Fakharifar et al., 2014)

The general tensile behaviour of cementitious composites is demonstrated in Figure 2.2. Plain unreinforced cementitious materials exhibit a strain-softening response with low tensile strength and ductility. Conventional fibre-reinforced composites (FRC) are reinforced with a low volume of fibres, typically 0.5–2%, and also have a strain-softening response, but demonstrate an increase in post-peak ductility. With HPFRCC, there is an increase in the elastic limit (defined as the point at which the first macro crack is formed; prior to this, microcracking dictates performance), followed by a strain- hardening response as multiple cracks form but do not widen. Lastly, strain softening is seen as cracks widen.

The studies by Farnam et al, (2010) was investigated the behaviour of HPFRC panel under impact loading and perform parametric based on simulation. Predicted crack and failure patterns on both sides of the HPFRC panel based on finite element simulation are in good agreement with their corresponding experimental results. The results obtained from the finite element analysis such as the number of strikes for the failure initiation, midpoint deflection, diameters of upper and lower circular damage patterns of the generated truncated cone, and the shape of failure patterns are in good agreement with corresponding experimental results (Farnam et al., 2010). However,