FIBRE REINFORCED CONCRETE AND HIGH PERFORMANCE FIBRE REINFORCED CEMENTITIOUS COMPOSITES: AN OVERVIEW

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Abstract

This article gives an overview on the recent developments in the area of fibre reinforced concrete (FRC) and high performance fibre reinforced cementitious composites (HPFRCC). It is divided into two main sections. The first section focuses on the definition, fibre classification and applications of FRC, whereas the next section discusses the concepts of HPFRCC, which is a product from the innovations and advancements of research in FRC. The description of two types of HPFRCC, i.e. reactive powder concrete (RPC) and engineered cementitious composites (ECC) are also included. The main objective of this article is to provide an overview on the latest technology in research and applications of FRC and HPFRCC for the benefit of the local construction industry.

Key-words*: Fibre reinforcement; Fibre reinforced concrete (FRC); High performance fibre reinforced cementitious composites (HPFRCC); Reactive powder concrete (RPC); Engineered cementitious composites (ECC).*

1.0 INTRODUCTION

Concrete is undoubtedly the most widely used construction material in the world, and it is expected to be so in the future. Substantial research and development activities have been undertaken in the area of concrete engineering and technology to investigate and innovate the material properties, structural behaviour and applications, and the construction practices of concrete. This has resulted in “new generations” of concrete being constantly improvised and developed in order to meet the ever increasing demand for superior workability, mechanical and durability properties, and they have been utilised successfully in numerous civil and structural engineering applications.

It is also widely understood that plain concrete is a brittle material which possesses low flexural tensile strength, ductility and strain capacity. The tensile strength of concrete, which is generally in the range of 10 % of the compressive strength, causes a number of undesirable consequences in its performance as an effective construction material. This shortcoming has been for the past few decades, and is still one of the main concerns of structural engineers. Furthermore, this scenario is also prevalent in some special application concretes, such as high performance concrete (HPC) and high strength concrete (HSC), which are acknowledged for their enhanced mechanical properties and durability. The superior mechanical properties and durability in HPC and HSC are achieved by modifying the microstructure of these concrete by densifying and reducing the porosity of the matrix. However, this modification of the microstructure leads to a significant increase in the brittleness as well as in the volume changes which occur during the hardening of the material, i.e. in autogenous shrinkage [1]. These negative effects in HPC and HSC results in drawbacks to the beneficial and superior properties demonstrated by them. However, these shortcomings can be reduced to a large extent by incorporating short discontinuous fibres into the concrete mixes, which results in a material known as fibre reinforced concrete (FRC).

2.0 FIBRE REINFORCED CONCRETE

2.1 Introduction

The utilisation of fibres in materials and construction can be traced back to many centuries. During Egyptian times, straws or horsehairs were added into mud bricks, whereas straw mats were discovered as reinforcements in early Chinese and Japanese housing construction [2]. The first use of fibres in cementitious matrices was in 1874 [3], whereas the modern use of fibres in concrete was initiated in the 1960s, and the development in this area proceeded at an accelerated pace in the past four decades. In recent years, FRC has been exploited extensively for both structural and infrastructural engineering applications in view of its superior properties compared to conventional concrete.

ACI 544.1R–82 defines FRC as concrete made with hydraulic cement, containing fine or fine and coarse aggregates, and discontinuous discrete fibres [4]. The principal objective of the fibre addition into the concrete mix is to control the cracking of FRC and then to modify the behaviour of the material once the concrete matrix has cracked [5]. Naaman proposed a composite model to define FRC as a composite with two main components, namely the fibre and the matrix, as indicated in Figure 1. In this model, both the fibre and the matrix are assumed to work together through bond, providing synergism for an effective composite [3]. For the purpose of discussion in this article, the term “concrete” in FRC may be assumed to include any cementitious composites as well.

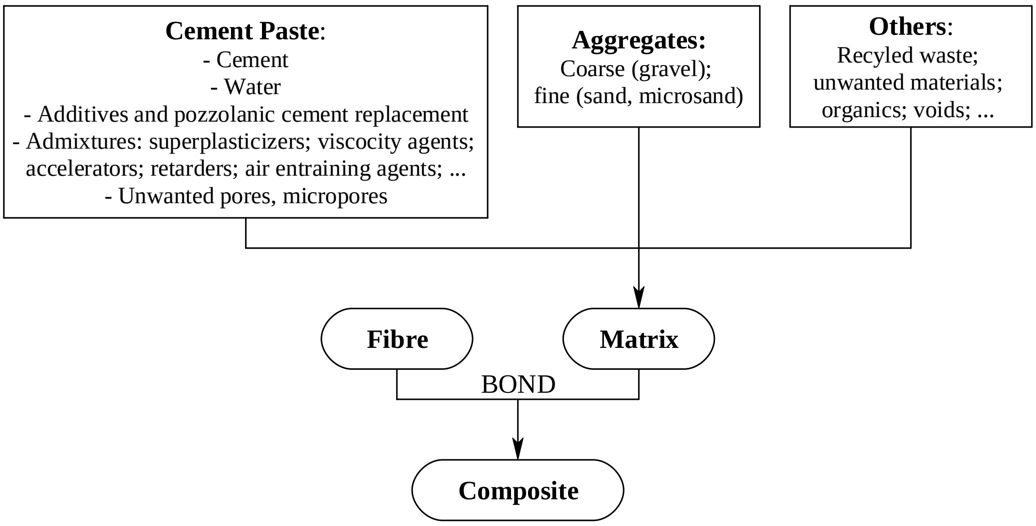

Figure 1: Composite model of FRC with two main components, namely fibre and matrix (from Naaman [3]).

2.2 Fibre Classifications

Fibres which are used in concrete can be in two main forms, either as short-discontinuous components or as thin mesh sheets. These may include natural materials (e.g. palm, jute, bamboo, cellulose, kenaf, etc), natural minerals, manufactured products (e.g. steel, polymer, glass, carbon, etc) or even some waste materials. However, for clarity purposes, the discussions in this article will mainly focus on fibres which are short-discontinuous in nature. A more comprehensive classification “system” of these fibres is given by Naaman (Figure 2). In this system, the characteristics of the fibres are categorised into four, namely the geometrical properties, mechanical properties, physical/chemical properties and material type [3]. For practical utilisation of fibres in FRC applications, properties which are given significant considerations in selection of fibres are material type, tensile strength, elastic modulus and the aspect ratio (the ratio of fibre length to the diameter or equivalent diameter).

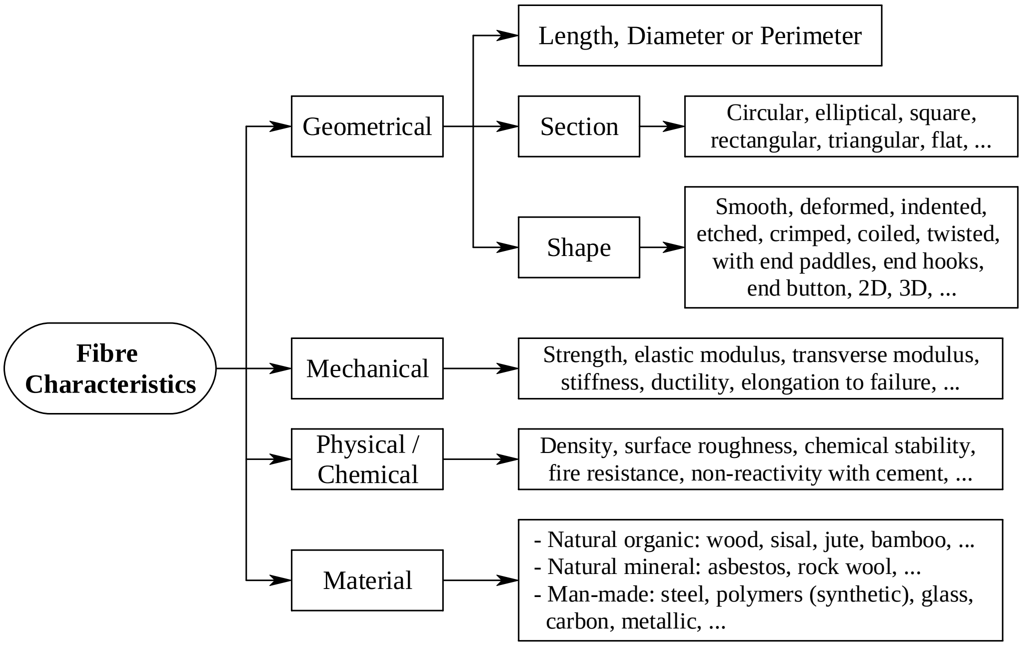

Figure 2: Main characteristics of fibres (from Naaman [3]).

2.3 Applications

Even though the progresses in FRC research and development have been exciting in the past few decades, it should be noted that FRC constitutes only a small fraction of the total amount of concrete used. The use of FRC in practice are increasing steadily with principal applications being for slab on grade (60 %), shotcrete (25 %) and precast members (5 %) [5]. Fibres are also commonly used in controlling plastic and drying shrinkage cracks. More specialised applications for FRC would be in the manufacturing of railway concrete sleepers, construction of highway and airfield concrete pavements, protective structures, hydraulic structures and impact resistant structures. Fibres can also be used to improve the resistance of concrete structures to seismic forces [5], and for structural repair and retrofitting applications [1,3]. Naaman has mentioned that most important applications of FRC are those where other materials cannot compete, specifically in its energy absorption capacity. Therefore, applications in impact and blast resistant structures and seismic structures remain dominant and most competitive [3].

Steel fibres are the most commonly used fibres in FRC but the prospects of polymer based fibres are increasing. The application of short fibres in concrete varies between 0.2 % and 2.0 % but there have been cases where higher percentages were used. Steel fibres are produced either by cutting wire, by shearing sheets, or from a hot-melt extract. They are usually deformed along their end or at their ends to enhance its bond with the cementitious matrix [5]. In the study conducted by Song and Hwang to investigate high-strength steel fibre reinforced concrete, it was observed that the addition of steel fibres at 0.5 %, 1.0 % and 1.5 % resulted in progressively improving compressive strength with concrete containing 1.5 % fibres recording the highest improvement of compressive strength at 15.3 % [6]. But the addition of 2.0 % fibres resulted in a slightly lower 12.9 % increase in the compressive strength compared to the control concrete. Meanwhile, the splitting tensile strength and modulus of rupture of the FRC exhibited marked improvements with an enhancement of 98.3 % and 126.6 % respectively when compared to the control concrete [6]. More recently, steel fibre reinforced high fluidity concrete segments were developed and applied to improve the quality of lining structure of the Metropolitan Expressway Central Circular Shinjuku Route Tunnel in Japan [7].

The use of polymer based fibres has also gained considerable interest, with polypropylene fibre as the most common. Most synthetic fibres exhibit lower modulus of elasticity compared to concrete and they are effective in reducing the plastic shrinkage cracking, and provide additional toughening and impact resistance even at relatively lower fibre volume. Polypropylene FRC is largely used for plastic shrinkage crack reduction, to improve the watertightness of water-retaining structures and to improve the toughness of concrete [5].

On the research front, it should be highlighted that most of the industrial applications of FRC that we see today are the output of extensive research works conducted in the laboratories of universities, research institutions and corporations. However, most of the research works and applications of FRC are focussed in the developed nations such as the USA, Canada, Japan, Australia and the UK. Relevant publications on FRC researches and applications may be obtained from the list of references at the end of this article.

3.0 HIGH PERFORMANCE FIBRE REINFORCED CEMENTITIOUS COMPOSITES

3.1 Introduction

As the term suggests, high performance fibre reinforced cementitious composites (HPFRCC) are products from the innovations and advancements of research in FRC. Some of "them" have their own specific names in line with their customised applications. Naaman stated that to define whether a FRC qualifies as "high performance", is based on the shape of the stress-strain curve in direct tension, i.e. whether it can be described as "strain-hardening" or "strain-softening" behaviour (Figure 3). If the stress-strain curve exhibits strain-hardening behaviour after the first cracking, then the attribute "high performance" is used. Strain-hardening behaviour is generally accompanied by multiple cracking and induces a large energy absorption capacity [3].

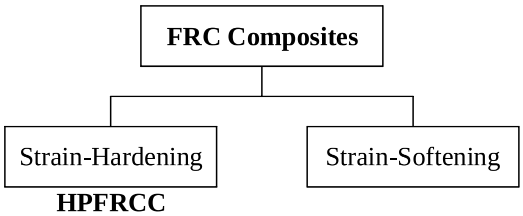

Figure 3: Simplified general classification of FRC composites based on their tensile stress-strain response (from Naaman [3]).

Different varieties of HPFRCC have been and are being developed with different and customised "attributes" in order to meet the ever increasing demand for improved and specialised properties, and applications. In the following sections, the authors would provide an overview on two types of HPFRCC, namely reactive powder concrete and engineering cementitious composites, which have been exploited successfully in both research activities and industrial applications, abroad.

3.2 Reactive Powder Concrete

Reactive powder concrete (RPC) is an ultra-high-strength HPFRCC (usually above 150 MPa), with high cement and mineral admixtures (usually silica fume) content, very low water-binder ratios made possible by the utilisation of new generation hyperplasticizers, and the incorporation of fibre reinforcements (usually steel fibres) in large quantities. Besides its ultra-high-strength properties, RPC also exhibits excellent durability and ductility. The inclusion of large quantities of fibre reinforcement is mainly responsible for the excellent tensile, flexural and ductility properties of RPC, besides eliminating the problem of brittleness which is usually prevalent in concretes. Unlike general understanding on conventional concrete and HPC, RPC contains no coarse aggregates or fine aggregates in its mix. Instead, it comprises of powdery fine sand or quartz sand with particle sizes of 0.600 mm or lower [8].

The first version of this revolutionary material was introduced by French researchers Richard and Cheyrezy [9]. RPC developed by them exhibited compressive strengths ranging between 200 and 800 MPa, and fracture energies ranging from 1200 to 40 000 J/m^2 [9]. Since then, a limited number of researches have been conducted in France, the USA, Japan, Korea, Australia [10,11] and more recently in

New Zealand [12], to research and to develop this material. In the local front, at least one article has appeared in the IEM Journal based on a research undertaken at the University of New South Wales, Australia [11]. In the study conducted by Voo et al., seven RPC prestressed girders without stirrups were tested to study the capacity of RPC beams in shear. It was observed that the quantity of fibres and the type of fibres used in the concrete mixture does not significantly affect the cracking load but has a significant influence on the rate of crack propagation and on their failure loads, and the failure loads were more than twice the cracking loads [10].

RPC has proven itself as an innovative construction material, and not just a "laboratory material", with a few projects to its name mainly in the construction of footbridges and highway bridges. The first application of this material was in the construction of the 60 m span Sherbrooke footbridge in Canada in 1997 [11] and the last known to the authors is the 175 m Papatoetoe footbridge in New Zealand in 2005 [12]. Other examples of projects which utilised RPC include the 120 m Seonyu footbridge in South Korea (2002), the 16 m long Shepherd Gully Creek Highway Bridge in Australia (2004) and the 25 m Futur Bridge in USA (2005) [11]. Structures constructed with RPC offers many supplementary benefits such as increased productivity, reduced reinforcement cost, time savings, higher quality control, enhanced durability, lesser maintenance cost and increased life cycle when compared to conventional reinforced concrete/prestressed concrete (RC/PSC) structures, which will in turn reduce the overall cost and increase the efficiency of the structure in the long run.

3.3 Engineered Cementitious Composites

Engineered cementitious composites (ECC) is a micromechanically "engineered" ultra ductile HPFRCC. This basically means that the mechanical interactions between fibre, matrix and interface in ECC are taken into account by a micromechanical model which relates these constituent properties to composite response [13]. The application of micromechanics allows systematic microstructure tailoring of ECC as well as materials optimization [14]. ECC is developed using similar ingredients as FRC such as cement, water, sand, fibre, and some common chemical admixtures. However, coarse aggregates are not incorporated since they tend to adversely affect the unique ductile behaviour of the composite [15]. The most significant characteristics of ECC is its tensile strain-hardening behaviour with strain capacity in the range of 3 to 7 % with a fibre content which is typically less than 2 % by volume [13]. This basically means that ECC will bend just like a piece of metal under the same stress which will cause conventional concrete to crack and fail

The advantageous attributes of flexible processing in the fresh state and ultra high composite ductility in the hardened state make ECC as an attractive material for a broad range of applications. However, the adoptation and commercial development of ECC technologies must be justified with advantages in cost-benefit ratio [14]. Even though the initial material cost of ECC would be higher than conventional concrete, the long term benefits are sufficient to potentially drive this technology further into its commercialization stage [14]. Several examples of successful industrial applications of ECC are provided in the website of ECC Technology Network [13]. Some of the recent ones include the ECC link slab retrofit for a bridge deck in Michigan, USA; patch repair of a viaduct in Shizuoka, Japan; steel/ECC composite deck for Mihara Bridge in Hokkaido, Japan; and the repair of an earth retaining wall in Gifu, Japan. Besides, readers can also find sufficient amount of literatures and publications on ECC technology on this website [13].

5.0 CONCLUSIONS

FRC and HPRCC have become integral components in modern concrete technology, and in the current construction materials industry. In the local front, efforts are being undertaken at present to research and develop HPFRCC using local materials, and to study the potential of utilising fibres from locally recycled material and local indigenous mineral admixtures, such as rice husk ash in developing FRC and HPFRCC. The vibrant construction industry of Malaysia should always remain open in adopting new emerging technologies relevant to the industry, such as HPFRCC. Concerted efforts are necessary from both the public and private sectors to ensure that the local construction industry remain relevant and competitive in the era of globalisation. As all of us would agree, the construction industry plays a gigantic role in ensuring the developed status of the nation in the near future. As mentioned earlier in this article, the aim of this article is to provide an overview on the research and applications of FRC and HPFRCC for the benefit of the local construction industry. Readers may obtain further information on the topics discussed through the list of references provided in the next section.

REFERENCES

[1] F. A. Farhat, D. Nicolaides, A. Kannellopoulos and B. L. Karihaloo, "High performance fibre-reinforced cement composite (CARDIFRC) – Performance and application to retrofitting", *Engineering Fracture Mechanics*, vol. 74, issues 1-2, pp. 151-167, Jan. 2007.

[2] V. C. Li, "Large volume, high-performance applications of fibers in civil engineering", *Journal of Applied Polymer Science*, vol. 83, issue 3, pp. 660-686, Jan. 2002.

[3] A. E. Naaman, "Fibre reinforced concrete: State of progress at the edge of the new millennium", in *Proc. 9th Int. Conf. on Concrete Engineering and Technology 2006*, pp. 20-48, Subang Jaya, Malaysia, 9-11 May 2006.

[4] A. M. Neville and J. J. Brooks, *Concrete Technology*, Pearson Education Limited, Essex, England, 1990.

[5] S. Mindness, J. F. Young and D. Darwin, *Concrete – 2nd Edition*, Pearson Education Inc., New Jersey, US, 2003.

[6] P. S. Song and S. Hwang, "Mechanical properties of high-strength steel fiber-reinforced concrete", *Construction and Building Materials*, vol. 18, issue 9, pp. 669-673, Nov. 2004.

[7] H. Dobashi, Y. Konishi, M. Nakayama and K. Matsubara, K. (2006). "Development of steel fiber reinforced high fluidity concrete segment and application to construction", *Tunnelling and Underground Space Technology*, vol. 21, issues 3-4, pp. 422, May-July 2006.

[8] Y. L. Voo, "Evolution of concrete technology – The new challenge", *Jurutera – The Monthly Bulletin of The Institution of Engineers, Malaysia*, bil. 2005, no. 3, pp. 20-23, 26, March 2005.

[9] P. Richard and M. H. Cheyrezy, "Reactive powder concretes with high ductility and 200-800 MPa compressive strength", in *Proc. V. Mohan Malhotra Symp., ACI SP-144*, pp. 507-518, San Francisco, USA, 1994.

[10] J. Y. L. Voo, S. J. Foster and R. I. Gilbert, "Shear strength of fibre reinforced reactive powder concrete girders without stirrups", *UNICIV Report No. R-421*, The University of New South Wales, Sydney, Australia, November 2003.

[11] J. Y. L. Voo, "Shear strength of 160 MPa steel fibre reinforced reactive powder concrete bridge girders without stirrups", *Journal of The Institution of Engineers, Malaysia*, vol. 67, no. 2, pp. 41-46, June 2006.

[12] N. P. Lee and D. H. Chisholm, "Reactive powder concrete", *Study Report SR 146*, BRANZ Ltd., Judgeford, New Zealand, 2005.

[13] ECC Technology Network, www.engineeredcomposites.com, The website of ECC Technology Network (Accessed on 8 June 2007).

[14] V. C. Li, "On engineered cementitious composites (ECC) – A review of the material and its applications", *Journal of Advanced Concrete Technology*, vol. 1, no. 3, pp. 215-230, Nov. 2003.

[15] V. C. Li and T. Kanda, "Engineered cementitious composites for structural applications", *Journal of Materials in Civil Engineering*, vol. 10, issue 2, pp. 66-69, May 1998.