CONTRIBUTION OF FIBRES TO THE SUSTAINABILITY OF CONCRETE

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Abstract

To improve the sustainability of concrete, it is necessary to consider not only its material properties, but also its durability. As is already well known, for plain concrete, the durability and sustainability can be increased by maintaining a low w/c ratio, replacing as much cement as possible with supplementary cementing materials, limiting autogenous shrinkage, and providing a very compact "skin" to inhibit the ingress of aggressive ions. However, in severe environments, even these steps may not be enough to guarantee durability. In this paper, the role of fibres in increasing the durability will be explored. In particular, it will be shown that fibres can reduce the permeability of concrete, and inhibit the transport of chloride ions through the concrete. This will help delay the onset of corrosion in the reinforcing bars in reinforced concrete structures, thereby increasing their service life. As well, cellulose fibres can induce pore refinement in concrete, leading also to reduced permeability. For high volume fly ash concrete containing high PVA fibre contents, self-healing of microcracks is also enhanced.

Keywords: Fibres; sustainability; permeability; self-healing; microcracks; durability

1. Introduction

We live in a world of finite natural resources and sources of energy. The *greenhouse gas emissions* (mostly CO_2, CH_4 and N_2O) resulting from our exploitation of these resources contribute to global climate change (global warming). Unfortunately, the cement and concrete industries have a considerable effect on these emissions, mostly through their production of CO_2. Today, concrete is by far the most widely used construction material worldwide. Indeed, next to water, it is the most widely used material in the world, with about 20 billion tonnes produced annually (as of 2011). This requires the production of about 3.6 billion tonnes of Portland cement. (To put this into perspective, the annual world production of steel is about 1.5 billion tonnes; that of coal is about 6.5 billion tonnes; the total production of gold *throughout human history* is 171,300 tonnes! The volume of concrete produced annually is about 3350 times the volume of the Pyramid of Cheops).

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Thus, the cement and concrete industries use large volumes of raw materials, and their production requires the energy equivalent of about 26 days of world crude oil production (Aitcin and Mindess, 2011). As well, the manufacture of Portland cement is responsible for about 6-7% of the world's CO_2 emissions, since about 0.8 tonnes of CO_2 are liberated per tonne of cement produced, about half from the chemistry of the reactions, the rest from the manufacturing processes.

The use of concrete will continue to grow significantly over at least the next few decades, as many of the less developed countries in Asia and South America begin to industrialize on a large scale. Concrete will continue to be the material of choice to build (or rebuild) our infrastructure. It is thus important to decrease the environmental impact of concrete construction, both for economic reasons, and to make concrete structures more sustainable.

2. How can we make concrete more sustainable?

There are many different ways to decrease the carbon footprint of concrete construction, but the three most significant ones by far are:

- Replacing as much Portland cement as possible with supplementary cementing materials and fillers
- Using high strength concrete in order to decrease the amount of concrete required to carry the structural loads
- Increasing the durability of concrete

The focus here will be on increasing concrete durability, in particular the role that fibres can play in this regard. Most commonly, fibres are added to concrete to improve its post-cracking ductility and load-bearing capacity; at the fibre addition rates generally used in practice (< 1% by volume) they have relatively little effect on strength. However, the proper use of fibres can lead to enhanced structural properties, such as efficiencies in the use of reinforcing bars and in structural design. More importantly, as is discussed in detail below, fibres can also be used to decrease the permeability of concrete, thus inhibiting the ingress of deleterious ions, and hence improving the durability in potentially damaging environments. Fibres can also enhance the self-healing of microcracks.

3. Effects of Fibres on Permeability and Durability

The permeability of concrete is the most important parameter governing its long-term durability. The permeability, in turn, is controlled primarily by the interconnected porosity in the cement paste, and microcracking in the concrete. The porosity in the cement paste, and the degree of connectivity, are determined by the water: cement ratio, the degree of hydration, the amount of air entrainment, and the exact nature of the cementitious binder. On the other hand, the density and location of the microcracks are determined by the level of applied stress or deformation. The stress or deformation may be external, as a result of the applied loads, or it may be internally induced as a result of drying shrinkage, thermal gradients, or abrupt changes in the hygro-thermal environment.

Concrete is an inherently permeable material. However, the degree to which we can make the concrete impermeable determines the rate at which aggressive ions, either in liquids or in gases, can penetrate into the concrete. While there is generally little that we can do about the porosity, it is possible to control the degree of microcracking, and hence the permeability, by the judicious use of fibre additions to the concrete. For instance, Banthia and Bhargava (2007) showed that the addition of collated cellulose fibres could significantly reduce the permeability of the concrete, as shown in Figure 1. They originally attributed the effects of the fibres to two mechanisms:

1. Fibre additions stiffen the fresh concrete mixture, thereby reducing aggregate settlement and bleeding. This reduces the formation of bleed channels, thus decreasing the ease with which water can flow through the material.
2. Hydrophillic fibres, such as the cellulose fibres used in their study, better engage the water in the mixture, reducing the overall early–age shrinkage, thus producing a material with less internal cracking.

However, later a much more detailed microstructural examination of this fibre system was carried out by Banthia, Sappakittipakorn and Jiang (2012), using mercury intrusion porosimetry and cryoporometry. They found that the cellulose fibre additions also led to pore refinement and reduced porosity, leading to a more durable material. Moreover, while the permeability of plain concrete increased markedly when the concrete was stressed, that of the fibre reinforced concrete increased only to a much smaller degree. In subsequent work, Bhargava and Banthia (2008) went on to show that such fibre additions could lengthen the useful service life of the concrete. Figure 2 shows the increase in durability of stressed FRC compared to plain concrete.

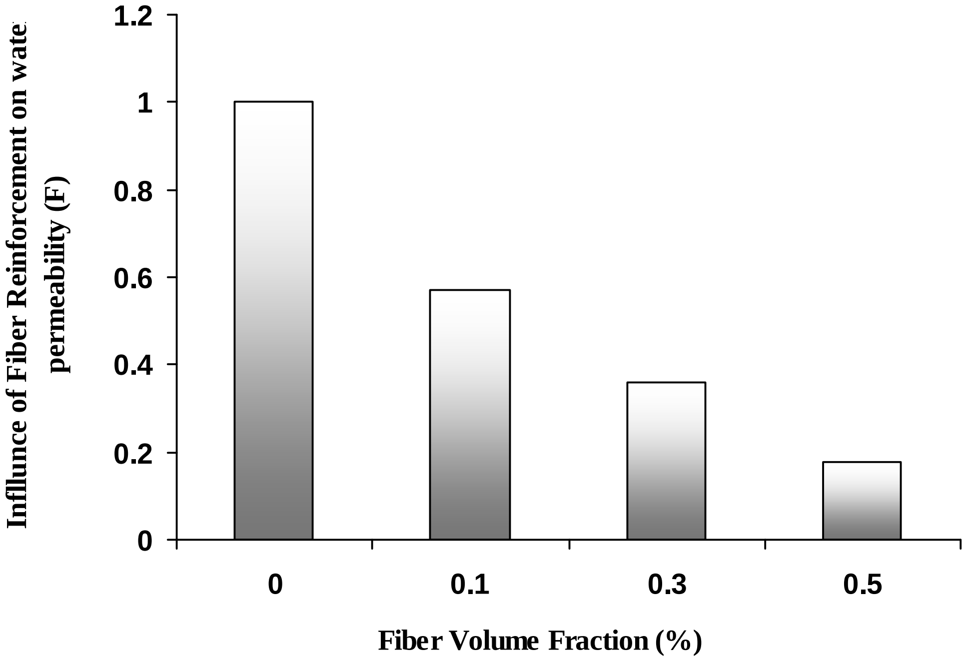

Fig.1: Relative permeability values for fibre-reinforced concrete and plain concrete, from Banthia and Bhargava (2007).

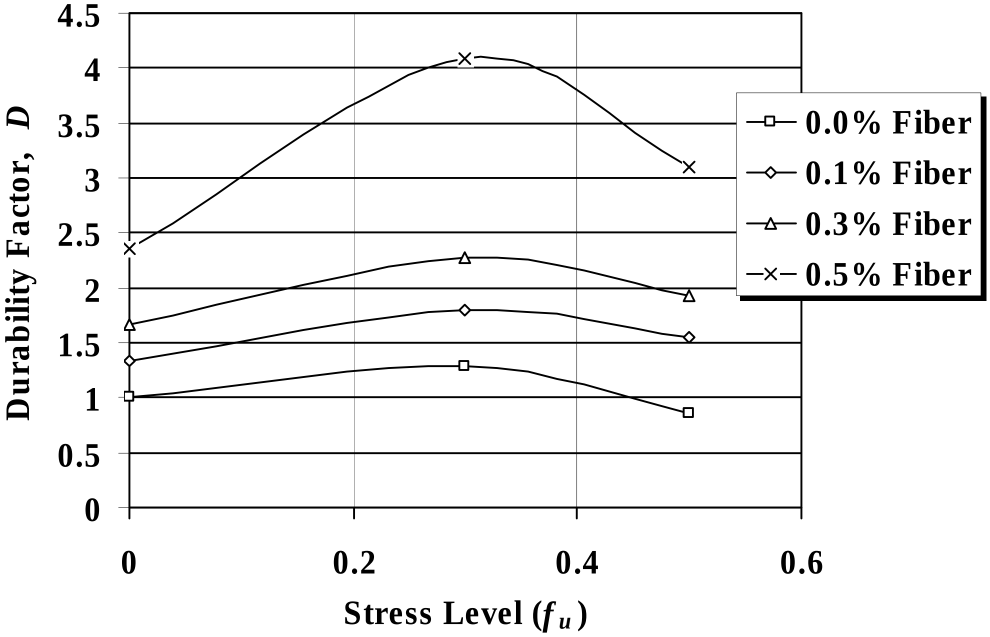

Fig. 2: Influence of stress and fibre volume fraction on durability (Bhargava and Banthia, 2008).

Synthetic fibres also seem to be able to delay the onset of corrosion in conventionally reinforced concrete. Bulk diffusion tests (Sappakittipakorn and Banthia, 2012) indicated that while the presence of fibres (cellulose and polypropylene) increased the total amount of chlorides that diffused into the fibre reinforced concrete (FRC), the fibres chemically combined with some of the diffusing chlorides such that only a limited quantity of the chlorides was available for steel corrosion. It was found that the presence of fibres measurably delayed the onset of steel corrosion. Fibres seemed to be particularly effective in delaying the onset of corrosion in concrete members under load (Sappakittipakorn and Banthia, 2010 and 2012).

There is also some evidence that fibre reinforcement can improve the freeze-thaw resistance of concrete. For instance, Yun *et al.* (2012) found that damaged conventionally reinforced concrete structures could be repaired in aggressive freeze-thaw environments with as layer of concrete reinforced with synthetic fibres.

4. Autogenous Healing (“Self-Healing”)

Fine cracks in concrete can “heal” more or less completely if they are allowed to close in the presence of moisture. This is due to the hydration of still unhydrated cement that which becomes exposed to water at the crack surfaces. In plain concrete, cracks up to perhaps 0.2 mm can be healed in this way. There is considerable recent evidence that fibre reinforced concrete enhanced the ability of concrete to undergo this autogenous healing. Fibres help to keep cracks from widening under load, and thinner cracks are more susceptible to self-healing. For instance, Homma, Mihashi and Nishiwaki (2009) found that very fine polyethylene fibres promoted self-healing, not only by keeping the cracks thinner, but also by providing a substrate onto which the new reaction products (calcium carbonate) could precipitate. This did, however, require the presence of moisture (Mihashi and Nishiwaki, 2012). Even under cyclic tensile loading, Desmettre and Charron (2013) found that at equivalent stress levels in the reinforcement, the water permeability was significantly lower in the FRC than in plain concrete.

Ahn, Kim and Kang (2012) investigated the behaviour of cracked High Performance Fiber Reinforced Cementitious Composites (HPFRCC) submerged in water. They found that most of the cracks below 0.5 mm were soon fully filled by newly formed hydration products; after that, the self-healing capacity was largely dependent on the crack width. Their conclusion was that HPFRCC had a high potential for self-healing in underwater structures. Yang *et al.* (2009) showed that in their Engineered Cementitious Composites (EEC), self-healing also occurred under wet-dry cycling, in terms of both mechanical and transport properties. Even for specimens pre-loaded to a tensile strain of 3%, the tensile strain capacity after self-healing was close to 100% of virgin specimens. However, they found that the crack widths had to be below 1.5 mm, and preferably below 0.5 mm, in order for significant self-healing to occur.

5. Natural Fibres

There is now increasing interest in the use of natural fibres, such as sugar cane bagasse, sisal, jute, elephant grass, and so on. In general, such fibres are not as good as the more common steel, polypropylene and carbon fibres in terms of the mechanical properties of their respective FRC's. However, the natural fibres are widely available, cheap, and capable of helping in the production of relatively low-cost, locally available building materials.

6. Structural Applications

As stated above, FRC has mostly been used because the fibres impart some post-cracking ductility and load bearing capacity. Most of the research that has been carried out over the last fifty years has focussed on improving the *material* properties of the fibres (fibre geometry, fibre type) or of the FRC (toughness, flexural or tensile strength, behaviour under dynamic loading, and so on). Unfortunately, all too little research has been carried out on the *structural* properties of FRC. At least in North America, FRC cannot be used for structural applications, except in a few special circumstances. Thus, the benefits that FRC can bring in terms of sustainability cannot be fully utilized at this time. FRC can be particularly effective when used in conjunction with conventional steel reinforcement. It is also very beneficial in the seismic design of structures, or in structures which may be subjected to blast or impact loading (Bentur and Mindess, 2007). It is to be hoped that proper design guidelines for the structural use of FRC will soon become a common feature of building codes.

There are, as well, much more innovative ways in which the special properties of FRC can be utilized. For instance, using fabric formwork, it is possible to cast architecturally interesting, optimised structures that use up to 40% less concrete than an equivalent strength prismatic section, offering potentially significant embodied energy savings in new concrete structures (Orr *et al.*, 2012). One major structural challenge is how to provide transverse reinforcement in slender, non-prismatic beam elements. This study showed that the use of ultra-high performance fibre reinforced concrete could eliminate entirely the need for transverse steel, leading to efficiencies in construction as well.

7. Concluding Remarks

It is, of course, very difficult to *quantify* the environmental benefits of using FRC. However, Achilleos *et al.* (2011) did make an attempt to do so, in terms of pavement construction in Cyprus. They estimated that steel fibre reinforced concrete (SFRC) used for pavements, compared to roller compacted concrete (RCC), would result in 30% lower air emissions and 29% less energy consumption. Comparing fibre reinforced RCC to plain RCC, the fiber reinforced RCC had 18% less air emissions and 16% less energy consumption. While these (approximate) numbers may be applicable to the particular pavement considered in this study, any savings would have to be estimated for each particular project. As another example, it is well known that in some types of structural elements, it is possible to eliminate completely the use of conventional steel reinforcement by properly designed steel fibre reinforced concrete. For instance, Destrée and Silfwerbrand (2012) described the use of steel fibre reinforced concrete to construct suspended slabs resting on pile grids for the Swedborg Arena in Stockholm. Their design led to a saving of about 100 kg/m^3 of steel reinforcing bars, approximately equivalent to a saving of about 1.33 kg of CO_2 emissions per m^3 of concrete. While the energy and CO_2 emissions saved by the use of FRC will of course vary for each particular project, it is clear that the proper use of FRC can lead to considerable savings, leading to more sustainable concrete construction. Konstad *et al.* (2012) have also found that a significant amount of conventional rebar can be replaced by steel FRC.

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