ACHIEVING “GREEN” CONCRETE THROUGH THE USE OF HIGH PERFORMANCE FIBER REINFORCED CONCRETE

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ABSTRACT

Concrete is one of the most widely used materials for infrastructure all over the world. The process of producing portland cement, however, contributes considerable emission of CO₂, a greenhouse gas that leads to negative impact on the environment. In addition, the sustainability of concrete can be substantially reduced due to its brittle nature. Concrete cracks easily due to corrosion-induced damage in a bridge system or soil expansion in a pavement system. The consequent repeated maintenance activities during the service life leads to significant CO₂ release, energy usage, and consumption of natural resources. Indeed the diminished amount of limestone in some regions, as indicated by recent study, sends a warning sign to the entire construction industry that concrete will not be a cost-effective material in the near future if its sustainability could not be enhanced.

This paper presents a “green” concrete which exhibits high durability and damage tolerance ability, low maintenance requirement, and low energy costs. This is achieved through the use of high performance fiber reinforced concrete (HPFRC). HPFRC is essentially crack-free under service loading and shows ductile behavior when subjected to extreme loading, such as seismic force. Recent studies also demonstrate the superior corrosion resistance of this material. The excellent damage tolerance properties of HPFRC ultimately extend the service life of infrastructure systems and reduce the impact on the environment.

INTRODUCTION

A sustainable (or green) concrete structure is one that is constructed so that the total societal impact during its entire life-cycle is minimal (Naik, 2008). This calls for a design considering not only the aspects of mechanical properties and initial cost, but also the durability characteristics. Recent statistic data shows that, in industrially developed countries, about 40 percent of the total construction costs are related to repair and maintenance of existing structures which are deteriorated or damaged under environmental, loading, or other effects (Metha and Monteiro, 2006). The durability issues of structures can lead to a significantly higher life-cycle cost compared to initial construction cost.

Among a variety of materials used for construction, concrete is one of the most widely used materials for infrastructure all over the world. According to ACI Committee 201, durable concrete will retain its original form, quality, and serviceability when

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exposed to its environment (ACI Committee 201, 2001). However, the porous and brittle nature of concrete, when interacting with environmental actions such as weathering action, chemical attack, or external loadings, generally reduces its usable service life due to increased permeability, cracking and subsequent damage. Deterioration of concrete from commonly encountered environmental effects is illustrated in Figure 1, and Figure 2 shows some typical results due to those effects.

**Figure 1.** Deterioration of concrete from commonly encountered environmental and loading effects (Metha, 1997, with minor modifications by the author)
(a) Concrete spalling of bridge girders due to corrosion of reinforcing steel

(b) Severe cracking of concrete pavement due to soil expansion

(c) Concrete spalling and buckling of reinforcing bar of beam-column connection due to seismic loading

**Figure 2.** Example of concrete deterioration from environmental effects
The consequence of concrete deterioration and short service life is the requirement of repair and replacement, and this in turn consumes more natural resources. It is well recognized that the process of producing portland cement contributes considerable emission of CO₂, a greenhouse gas that leads to negative impact on the environment. Production of one ton of Portland cement produces about one ton CO₂ and other greenhouse gases. In addition, recent study indicates that the diminishing amount of limestone in some geographical regions can be a threat to development of cement concrete industry (Naik, 2008). Note that limestone is used to manufacture portland cement as well as aggregate in concrete. Further consumption of energy and release of CO₂ due to construction machines and traffic jam during repair and replacement work is another consequence of deterioration of concrete structures.

The deficiencies of conventional concrete and subsequent impact to the environment calls for a more durable material that will last longer under environmental actions, hence contributes to the conservation of natural resources and protection of ecology.

**FIBER REINFORCED CONCRETE (FRC)**

Many solutions have been proposed for enhancing the sustainability of concrete, and the use of *fiber reinforced concrete* (FRC, see example in Figure 3) is a promising one. Fiber is known to be an effective reinforcement to limit initiation and propagation cracks in concrete, as well as to enhance the performance of post-cracking response (ACI Committee 544, 2001). Previous investigations have shown that, by adding fiber into concrete and using proper mix compositions, the ability of concrete to resist various environment effects can be greatly enhanced. Some of the research results are briefly summarized as follows:

![Figure 3. Steel fiber reinforced concrete used in concrete structural members](image)

1. Permeability of concrete: Bhargave and Banthia conducted compression tests on plain and fiber reinforced concrete cylinders to investigate the change in permeability due to increased microcracking under compression (Bhargave and Banthia, 2008). It is
observed that while a rapid increase in the permeability occurred for plain concrete beyond a certain threshold of compressive stress, the magnitude of the increase in the permeability remained small for the FRC. They also concluded that fibers will enhance the durability of concrete and lengthen its useful service life.

2. Corrosion of steel reinforcing bars: based on experimental observation, Grubb et al. (2007) reported that steel rebar imbedded in steel fiber reinforced concrete is more resistant to corrosion than the rebar in the conventional plain concrete. The reason can be that fibers close to the rebar surface provide a source of passive confinement, which hinders the development of expansive corrosion products. One the other hand, Kosa (2003) proposed another corrosion-resistant mechanism of steel fiber reinforced concrete, in which the oxygen required for cathode reaction coming outside the concrete is first consumed by the corrosion of steel fibers placed near the concrete surface and only limited oxygen can reach the rebar. This slows the progress of a cathode reaction, which in turn delay the corrosion process. The other reason that FRC can prolong the corrosion propagation period is due to the fact that smaller crack widths in FRC impede the conductive chloride ions to come into direct contact with the steel rebar (Sahmaran et al., 2008).

3. Alkali-silica reaction (ASR): Research carried out by Bektas et al. (2006) shows that using steel fibers in concrete can effectively control and minimize cracking associated with the volumetric expansion of the AS gel. By limiting the formation of microcracking, the AS gel is unable to leave the reactive aggregates and hence confined to the reaction site.

4. Plastic shrinkage cracking: plastic shrinkage cracking on concrete members can be critical weak points for aggressive substances to penetrate into concrete. Studies conducted by Naaman et al. (2005) indicate that, for all practical purposes, addition of any fibers used in their experimental program at a volume fraction of 0.4 percent will totally eliminate plastic shrinkage cracking.

5. Creep: Tests on steel fiber reinforced concrete beams under long-term loading shows that addition of fibers to conventional reinforced concrete beams reduces the amount of creep thus decreases the deflection (Purkiss and Blagojevic, 1993).

6. Fatigue (cyclic loading): Paskova and Meyer (1997) reported that steel fibers have a considerable beneficial effect on the fatigue behavior of concrete. Compared with plain concrete, 1.0 percent steel fiber increases the fatigue life of concrete by 8.75. Jun and Stang (1998) also claimed that the fatigue strength of plain concrete for 2 million cycles has 1.5 times increase if 1.0% steel fibers by volume is introduced.

7. High temperature: experimental studies have shown that fragmentation and spalling of concrete can be effectively limited by adding steel fibers, which are mostly undamaged up to 500-600°C, and provide confining action to the concrete (Gambarova, 2004). Kosa (2003) also indicated that addition of organic fibers to concrete can effectively improve the fire resistance of concrete members. This is because that organic fibers in the concrete begin to melt when exposed to high temperature and leave voids inside the concrete, which provide the effect of blast control.
HIGH PERFORMANCE FIBER REINFORCED CONCRETE (HPFRC)

While FRC is able to enhance the structural performance under commonly encountered environmental effects, it can still suffer severe damage under extreme loading, such as seismic forces. This is due to the fact that great ductility beyond elastic limit is required to prevent collapse for structures subjected major earthquakes.

During the past few years, major breakthroughs have taken place in the field of fiber reinforced concrete. With traditional FRC materials, only a modest improvement in post-cracking response can be obtained with a tensile softening response after first cracking. In contrast, high performance fiber reinforced concrete (HPFRC) have the ability to exhibit a tensile strain-hardening response up to strains greater than 1.0 percent (Figures 4 and 5), accompanied by a multiple cracking process. Thus, large deformations are needed to cause visible damage in HPFRC members.

HPFRCs have been experimentally shown as a viable alternative for achieving highly damage tolerant structures with reduced amounts of reinforcement detailing. It is worth mentioning that, HPFRCs can be easily premixed in ready mix trucks with a range of volume fraction about 1.0 percent to 2.0 percent fiber, thereby making it readily accessible to various applications in the field. Conventional concrete is brittle in tension, which in turn is vulnerable to spalling, bond failure, shear failure, etc. With the tensile stain-hardening characteristics, HPFRCs will benefit enormously applications such as: earthquake resistant structures; blast and impact resistant structures; reduction in congestion of reinforcement such as in seismic beam-column connections and ends of prestressed beams.

![Figure 4. Typical responses of conventional FRC and HPFRC (Naaman, 2003)](image-url)
Large-scale cyclic tests on HPFRC beam-column connections (Parra-Montesinos et al., 2005; Chao, 2005) demonstrated the excellent damage tolerance properties of HPFRC, even under severe earthquake. As shown in Figure 6, the heavy transverse confinement in the joint region and beam plastic hinging zones were almost completely replaced by HPFRC, which also increase the constructability. Figures 7 and 8 show the cracks occurred in the beam plastic hinging zone and joint region when pushed to 2% and 6% drift, respectively. It is noted that 2% is generally the largest drift allowed when subjected to design earthquake according to current code. The cracks observed during 2% drift were limited and with very small widths, signifying that no repair work is needed after earthquake. No spalling or fracture of concrete was seen in HPFRC specimen even under extreme large drift (6%).

Figure 5. Crack development in plain concrete, FRC, and HPFRC
Figure 6. HPFRC beam-column connection specimen (Chao, 2005)
Figure 7. Cracks in the beam plastic hinging zone (Chao, 2005)
Figure 8. Cracks in the joint region (Chao, 2005)

CONCLUSIONS

There is a universal consensus that our global infrastructure faces a pressing need in the 21st century for both greater sustainability and better protection from natural and man-made hazards. This calls for an advanced material which can be used to delay or prevent the decay of infrastructure and buildings when subjected to commonly encountered environmental actions as well as severe loadings such as earthquake and
impact. The major problem of concrete, the most common material used in infrastructure all over the world, is the considerable deterioration and repair works needed due to its brittleness and limited durability. By using high performance fiber reinforced concrete, an environmentally friendly material, significant enhancement in the sustainability of concrete structures can be expected due to its high damage-tolerance characteristics. These characteristics can enhance security and protection properties as well as reduce significant amount of repair-rehabilitation-maintenance work and give infrastructure and buildings longer service life, all of which will eventually lower the environmental impact due to greenhouse effect by reducing the production of cement (thus reducing pollution due to the emissions of CO₂ and other particulates).

REFERENCE

ACI Committee 201, “Guide to Durable Concrete,” ACI 201.2R-01, American Concrete Institute, 2001.


