Strategies for High Performance Fiber Reinforced Cementitious Composites Development

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ABSTRACT: In this article, the strategies for development of High Performance Fiber Reinforced Cementitious Composites (HPFRCC) are briefly discussed. Focus is placed on HPFRCC materials intended for practical applications. With this as a premise, we discuss three essential requirements for successful adoption of HPFRCC in the real world: high performance, low cost, and easy execution. If any of these three aspects were violated, it would be difficult for the HPFRCC material in question to be accepted. This article is a summary of an invited presentation given at the International Workshop on Advanced Fiber Reinforced Concrete at Bergamo, Italy during Sept. 24-25, 2004.

1 INTRODUCTION

In recent years, the definition of an HPFRCC – a fiber reinforced cement based matrix material that exhibits tensile strain-hardening behavior under uniaxial tension (Naaman and Reinhardt, 1996), has generally been accepted. Advances of HPFRCC have proceeded to a point where some versions of this class of materials have been put into full scale, albeit limited, structural use. A number of professional societies, including the American Concrete Institute, the Japan Concrete Institute, and RILEM, have organized technical committees to work towards code implementation for HPFRCC to serve as structural load-carrying materials. It may be expected that the practical acceptance of HPFRCC will continue to grow with time as experience in their use and data on long-term performance accumulates. This paper outlines the strategies for the development of HPFRCC, taking into account common expectations and constraints from the practicing community. In the following, we discuss considerations of performance, cost and execution, three essential ingredients for any HPFRCC to be accepted by practitioners. Some current applications of a specialized version of HPFRCC – Engineered Cementitious Composites (ECC) – are highlighted.

2 HIGH PERFORMANCE

As high performance concrete illustrates, the meaning of high performance can be quite different in different countries. In Japan, the words "high performance" pertain to self-consolidation (or self-compaction), whereas they often mean high durability in Europe and high strength in the US. It is fair to say that a truly high performance concrete material must have attributes in the fresh and hardened states which are not achievable in normal concrete.

As an alternative view, one might ask what demands are not met by current concrete material. This leads to considerations of lacking durability of many R/C structures, and poor resistance to severe loading such as seismic events. For durability, it is important that the material has good crack width control. For seismic resistance, it would be desirable that the material can deliver structural ductility for safety during the event, and minimize repair needs subsequent to the event. HPFRCC materials that overcome these deficiencies of normal concrete may lay claim to the adjective of "high performance."

In addition to the above, special functionalities, such as light-weight, and fresh property attributes which lend themselves to enhancing construction speed or reduction in labor cost, adds to the value of this material.

Finally, sustainability performance should be elevated to a prime level, regarded as important as structural performance. Development of HPFRCC must integrate infrastructure sustainability as an intrinsic characteristic of the material. Although the development of HPFRCC with regard to sustainability is still in its infancy, there are reasons to believe that this is not only a desirable goal, but also a feasible one (Li et al, 2004).

3 LOW ECONOMIC COST

The requirement of low cost of HPFRCC for practical adoption is obvious in a very highly cost-sensitive construction industry. For successful development of HPFRCC, it is necessary to minimize material cost, place emphasis on installed cost, educate on service life cost, and promote sustainability as a combination of economical, environmental and social costs.

A major cost component of HPFRCC is the fiber, typically many times more than the cost of cement, water, and sand. For this reason, it is necessary to minimize the amount of fibers in HPFRCC, and move away from the pervasive but impractical concept of equating high performance to high fiber content. To achieve high performance while minimizing fiber content, it is necessary to optimize the HPFRCC so that synergistic interactions occur at the fiber, matrix and interface level. This requires analytic tools that embody the mechanics of interaction between these three phases, generally referred to as micromechanics. Although micromechanics has played an important role in understanding the mechanical behavior of HPFRCC at the microstructural level for some time now, it is only in recent years that strategies have been systematically developed to use micromechanics in a reverse manner – that is, to use micromechanics as guidelines to systematically tailor the ingredients in order to achieve desired composite properties. Such a strategy has been demonstrated in the development of Engineered Cementitious Composites, or ECC, based on the premise of maximizing the composite ductility while minimizing the amount of fibers (Li, 1993, 2003; Kanda and Li, 1999; Li et al, 2001, 2002). ECC currently employs 2% volume content of random short fibers.

Often what is most important to potential users of HPFRCC is not the cost of the material per cubic meter. Rather it is the initial or first cost that decides the adoption of the material in a given application. Installed cost generally includes the material cost, labor cost, and transportation cost. For example, by taking advantage of the tensile and shear properties of HPFRCC, the use of this material may lead to elimination of shear reinforcing bars resulting in a reduction in total material and labor cost. The possibility of thinner structures thus reducing material volume and dead load, may lead to a drastic cut in the installed cost. If special functionalities of the HPFRCC are present, such as ease of execution (e.g., self-consolidating casting) or light-weightedness, they may induce reduction in labor and transportation costs. In fact, by reducing damage during transport of HPFRCC precast elements due to the higher fracture resistance, cost savings can be realized via repair expenses even before installation. The justification of adoption of fiber reinforced concrete (although not HPFRCC) based on installed cost has been explicitly mentioned by Failla and Magnetti (2004) in recounting their experience in the adoption of SFRC in Italy.

When the above considerations are taken into account, it should be clear that the cost of HPFRCC material itself, while important, is only a part of the initial cost. From an economics viewpoint, the installed cost often dictates the decision of the adoption of an HPFRCC or not.

4 EASE OF EXECUTION

Once economically feasible, the need for ease of execution at a construction site becomes paramount. The ease of execution often implies the use of normal construction equipment. Naturally, it would be preferred if the material can self-consolidate. This indeed has been demonstrated in ECC material (Kong et al, 2003). A crucial means of achieving self-consolidation effectiveness has been minimizing fiber content. Thus the use of micromechanics to minimize the fiber content leads to advantages economically as well as ease of execution. Other rheological characteristics of ECC have been devised so that this material can be processed by spraying like shotcreting (Kim et al, 2003), or by extrusion (Stang and Li, 1999; Takashima et al, 2003).

5 EXAMPLES OF ECC APPLICATIONS

To illustrate the versatility of HPFRCC in the real world, a number of recent/on-going projects involving the use of ECC are briefly highlighted below.

Figure 1 shows the repair of the Mitaka Dam in the Hiroshima-Prefecture in 2003 (Kojima et al, 2004). This dam is over 60 years old, with a severely damaged concrete surface. Cracks, spalling and water leakage were concerns that prompted the use of ECC as a cover layer. This 20 mm layer was applied by the spraying technique onto approximately 600 m^2 of the upstream dam surface.

Figure 2 shows the repair of an earth retaining wall in Gifu, Japan. This wall had been damaged by alkali-silicate reaction, in the form of macrocracking. The use of a regular concrete for repair was beyond consideration due to expected reflective cracking. ECC was adopted to control the cracking of the surface layer. One year after installation, only microcracks less than 50 µm in width could be observed (Rokugo, 2004).

Figure 3 shows extruded ECC pillars (Takashima et al, 2003). ECC pipe elements with capabilities of withstanding large imposed deformation have also been developed (Stang and Li, 1999).

Figure 4 shows a schematic of a bridge deck link-slab retrofit, to be conducted in the summer of 2005 in the state of Michigan in the US. This demonstration project involves the replacement of a conventional expansion joint by a ECC link-slab designed to absorb all deformation imposed by shrinkage, temperature and live (traffic) loads. The concept (Kim et al, 2004) involves exploiting the tensile ductility of ECC so that the material is used into the tensile strain-hardening state during normal service conditions. The tight crack width and fatigue resistant features of ECC are employed to ensure durability.

Figure 5 shows the use of ECC for patch repair of a bridge deck in Michigan, US (Li and Lepech, 2004). While the average daily traffic count is relatively low, a large number of 11-axle gravel trucks use this structure, greatly adding to the load magnitude. Over two years of service life, including two winters of Michigan weather conditions with many freeze-thaw cycles, the ECC patch remains in good condition, with microcracks limited to 30 µm. In contrast, the surrounding concrete placed one day earlier, is exhibiting cracking with crack width in the mm range. This is likely one of the very few HPFRCC applications that have been exposed to real weather and service loads and continuously monitored (for over 700 days) for performance.

Figure 6 shows the Mihara Bridge newly constructed in Hokkaido, Japan <<http://nissei-kensetsu.co.jp/bihara.html>>. This cable-stayed bridge, expected to open to traffic in May, 2005, has a thin composite ECC/steel deck. The tensile ductility and tight crack width control are features that contribute to a 40% reduction in weight and an expected service life of 100 years.

6 CONCLUSIONS

This article suggests a micromechanics based design strategy of HPFRCC, aimed at meeting stringent practical demands of high tensile ductility performance, cost-sensitivity, and ease of execution at construction sites. This strategy has resulted in ECC materials that are being adopted in repair and retrofit applications, in pre-cast and cast-on-site structural applications, and in full-scale demonstration and commercial projects. In the application examples cited, tensile ductility and tight crack width are common performance characteristics exploited. These characteristics are not available in normal concrete or common fiber reinforced concrete.

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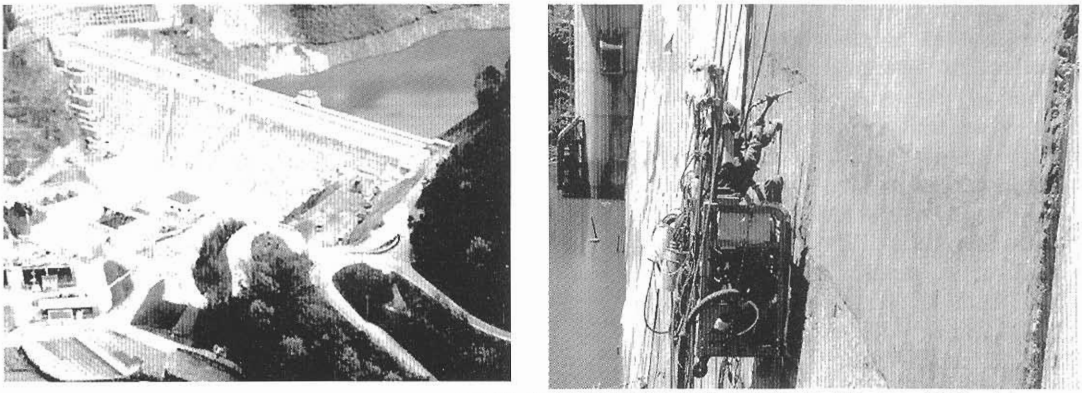


Figure 1: Repair of the Mitaka Dam (Japan) with a 20 mm thick ECC cover using a spray technique (Courtesy, T. Kanda).

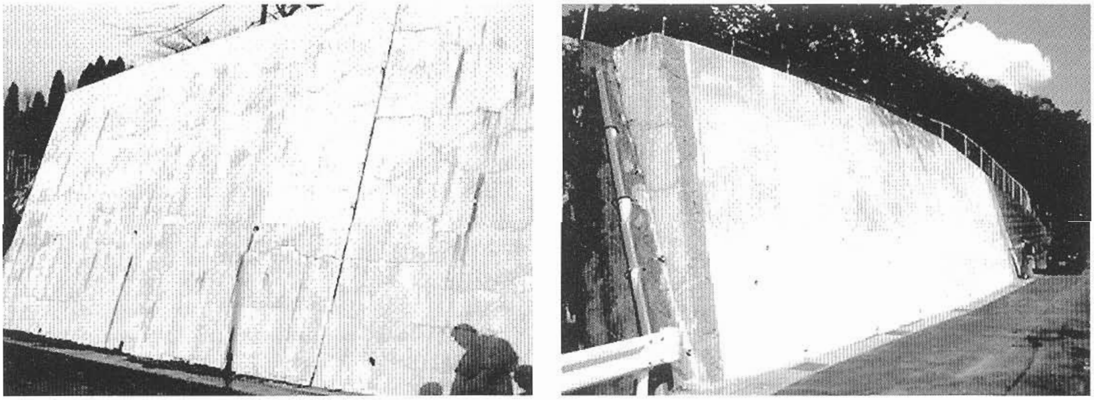


Figure 2: Repair of an ASR damaged earth-retaining wall with a sprayed ECC, Gifu, Japan (Courtesy: K. Rokugo).

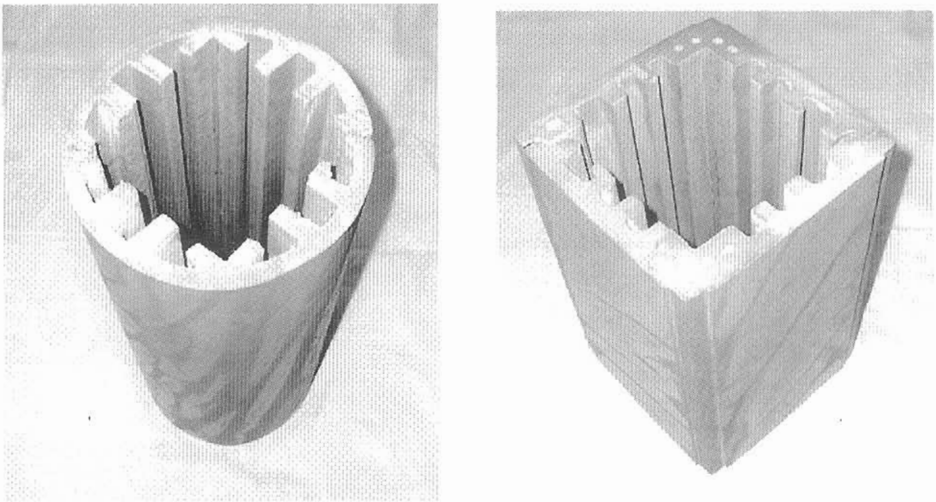


Figure 3: Extruded ECC Pillars (Courtesy: H. Takashima).

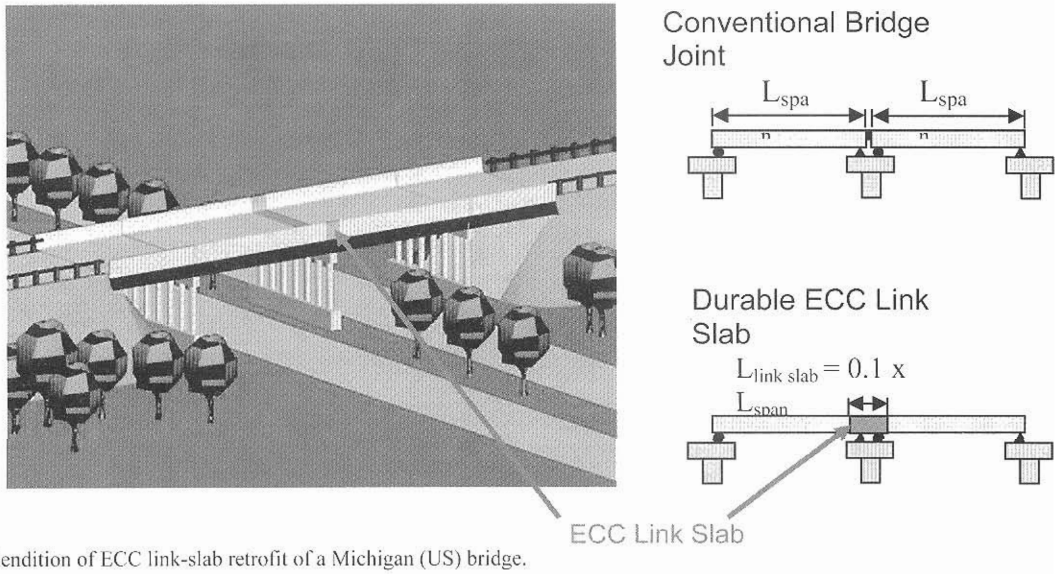
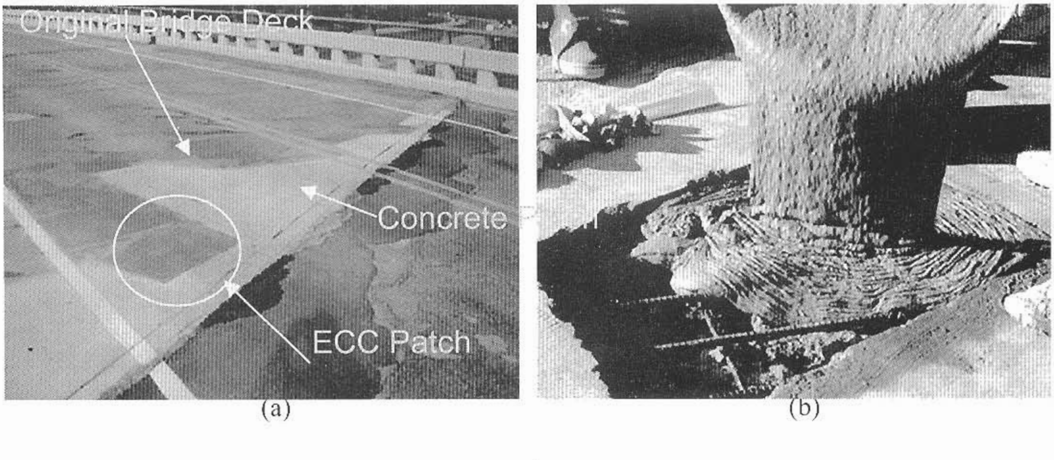


Figure 4: Rendition of ECC link-slab retrofit of a Michigan (US) bridge.



(a) (b)

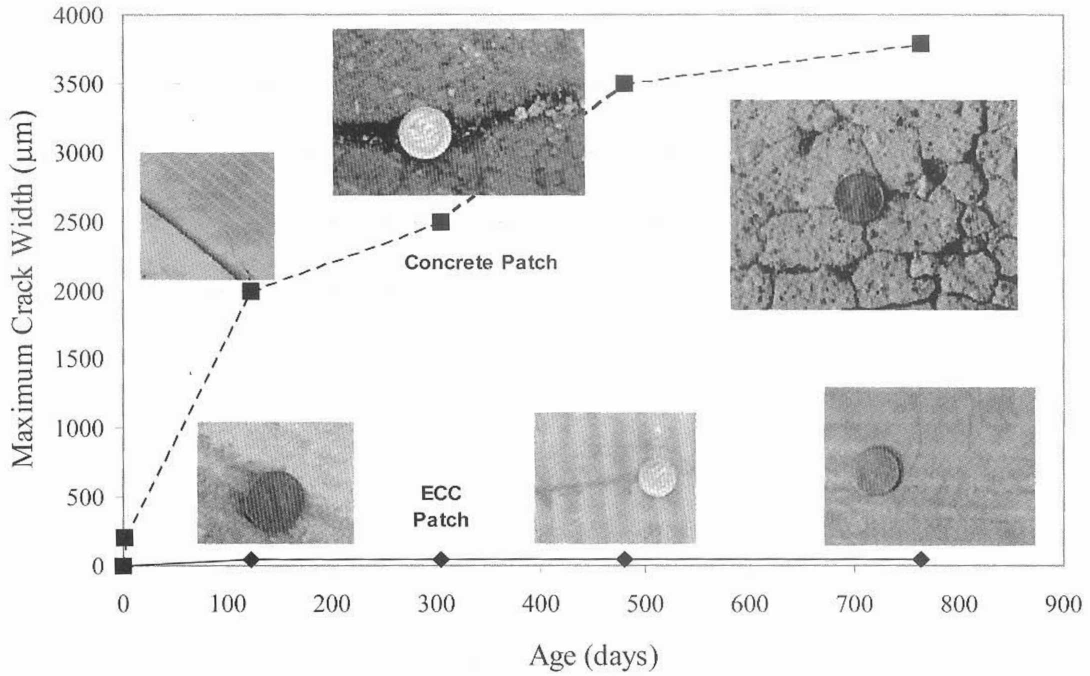


Figure 5: ECC for patch repair of a bridge deck in Michigan, US, showing (a) the concrete and ECC repair areas, (b) self-consolidating casting, and (c) maximum crack width development over time.

Figure 6: The Mihara bridge (Hokkaido, Japan) uses a steel/ECC composite deck (Courtesy, T. Kanda).