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Conventional and HPSFRCCs as Repair and Strengthening Materials

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ABSTRACT: High Performance Steel Fiber Reinforced Cementitious Composites (HPSFRCCs) have been receiving increasing attention due to their superior mechanical and durability characteristics. These high performance materials exhibit remarkable flexural strength and very high ductility. As a result, they have high potential for use in repair and strengthening of concrete structures. In this paper, properties of these cementitious composites are compared to those of conventional steel fiber reinforced concrete mixtures. The performance based optimum design and performance classes of the conventional cementitious materials are summarized. Available test results that show the potential of the new high performance class of materials for strengthening of reinforced concrete elements are presented.

1 INTRODUCTION

Within 30 years, a major earthquake is expected in the Istanbul metropolitan area and studies indicate that retrofitting of many structures is urgently needed (Bal et al. 2008). Currently, schools, hospitals, bridges and some other public buildings are being retrofitted. Of the several retrofitting methods and materials that may be used for a structure in question, high performance steel fiber reinforced cementitious composites (HPSFRCCs) may be used as an alternative retrofitting material. The microstructure of HPSFRCCs have a more compact particle arrangement and is enhanced by the presence of the strongest cementitious hydrates compared to high performance concrete (HPC). HPSFRCCs are produced by using very fine sand, cement, silica fume, superplasticizers, and short cut steel fibers. Their very low porosity gives them important durability and transport properties and makes them potentially suitable materials for storage of industrial wastes. These features are achieved by i) precise gradation of all particles in the mixture to yield a matrix with optimum density, ii) reducing the maximum size of the particles for improved homogeneity of the concrete, iii) reducing the amount of water in the concrete, iv) extensive use of the pozzolanic properties of highly refined silica fume, v) optimum composition of all components, vi) the use of short cut steel fibers for ductility, vii) hardening behavior under pressure and increased temperature, resulting in very high strengths (Richard & Cheyrezy 1994; Walraven 1999). Since HPSFRCCs have excellent impact resistance properties, they can be employed for; i) military structures, ii) seismic protection of strategic structures, and iii) retrofitting of reinforced concrete structures. They are also used for small or medium size prefabricated elements (Tasdemir 2010).

The main objective of this work is to compare the properties of HPSFRCCs to conventional steel fiber reinforced concretes (SFRCs). The performance based optimum design and performance classes of the conventional ones are discussed. Available test results that show the potential of the new high performance class of materials for strengthening of reinforced concrete elements are presented.

2 CLASSIFICATION OF CEMENTITIOUS COMPOSITES

From the mechanical behavior point of view, SFRCs can be divided into two categories based on their performance: i) conventional SFRCs, and ii) HPSFRCCs such as reactive powder concretes. The conventional SFRCs exhibit ductile behavior compared to the brittle matrix, but their flexural and tensile strengths are not very high, and in particular the compressive strengths of these materials practically do not change with the fiber volume fraction. The HPSFRCCs, however, exhibit considerable strain hardening before peak stress, and their tensile and compressive strengths are very high compared to those of conventional SFRCs (Alaee 2002). Ductile Fiber Reinforced Cementitious Composites (DFRCCs) show deflection hardening and multiple cracking in bending with significant ductility in tension and compression. DFRCC is a class of Fiber Reinforced Cementitious Composite (FRCC) that exhibits multiple cracking. Multiple cracking leads to improvement in properties such as ductility, toughness, fracture energy, and strain capacity under tension, compression, and bending. As seen in Figure 1, DFRCC is a broader class of materials than HPFRCC (High Performance Fiber Reinforced Concrete Composite). FRCC includes the entire class of fiber reinforced cementitious composites, where DFRCC as well as other composites such as fiber reinforced concrete (FRC) and fiber reinforced mortar (FRM) are sub-sets. Engineered Cementitious Composites (ECCs), make up a particular type of HPFRCC, whose composition is optimized in a cost-effective way on the basis of micromechanics. ECC typically has a tensile strain capacity of greater than 3%. Microstructure optimization limits the fiber content of ECC to be less than 2-3% (JCI-DFRCC, 2003). HPFRCC also includes SIFCON (Slurry-Infiltrated Fiber Concrete) and SIMCON (Slurry-Infiltrated Mat Concrete).

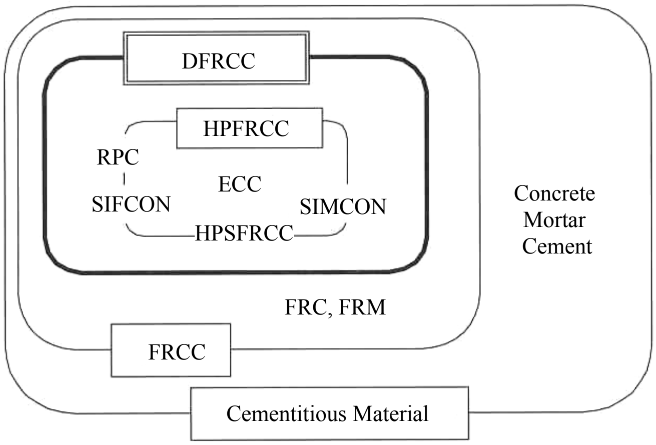


Figure 1. Classification of cementitious composites (JCI-DFRCC, 2003).

3 DISPERSION AND ORIENTATION OF FIBERS IN HPSFRCC

Homogenous dispersion and orientation of fibers influence both fresh and hardened concrete properties especially for high fiber volume fractions as in HPSFRCCs. The number of fibers in cross-section is one of the key factors affecting the mechanical properties of such mixtures. Fiber dispersion and orientation in HPSFRCCs were investigated in a recent study (Akcay & Tasdemir 2012) in which the dispersions were evaluated based on the fiber density obtained using image analysis. It was observed that the fibers in all mixtures were dispersed homogenously and no local disintegration or fiber clumping occurred, owing mainly to the use of a proper superplasticizer.

The orientation of fibers in the fracture plane of beams was also determined in the same study. For this purpose, the geometrical properties of each fiber whose coordinates in binary images were already known were verified. The orientation angle between 0-90º to the loading direction was determined by taking into account the projectile of the fibers on the plane. Figure 2 shows the average values of orientation angles of long fibers. The radius of each nested circle interval represents ratio of number of the orientated fibers to the total number of fibers in percentage. If the orientation angle is about 90º, fibers can work efficiently in the fracture plane. The results indicated that the orientation of fibers was almost in the desirable condition meaning that effective mixing with superplasticizers and self compaction had taken place. As a result, mechanical properties can be improved. Flexural strength and fracture energy of the mixtures can be enhanced with fibers dispersed homogenously and orientated to function effectively.

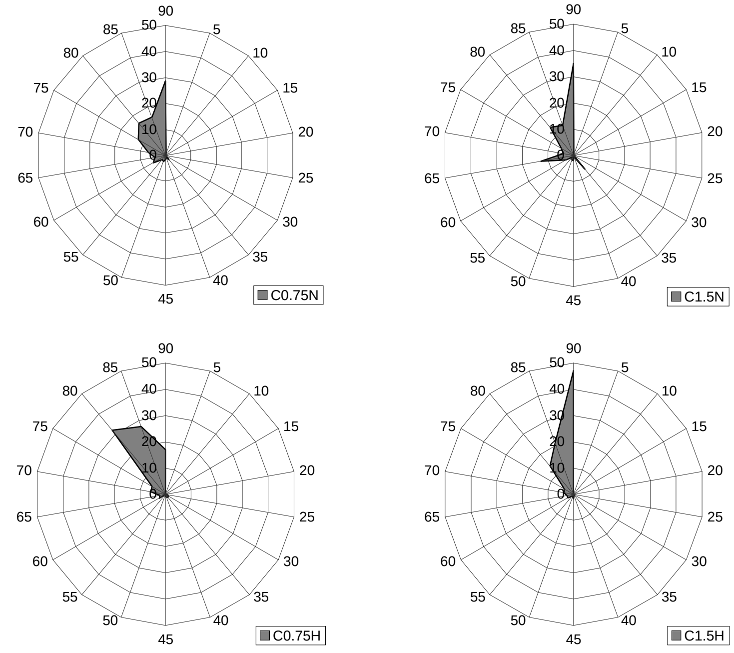


Figure 2. The distribution of orientation angle (in percent) of long fibers in concrete (Akcay & Tasdemir 2012).

4 BEHAVIOR UNDER BENDING

One of the main roles of fibers in cementitious composites is to improve the mechanical behavior under bending. The use of fibers greatly increases energy absorption and ductility in flexure. The main contribution of steel fibers to concrete can be seen after matrix cracking. If a proper mixture is designed, after the matrix cracking, randomly distributed fibers in the matrix act as crack arresters by bridging mechanism, undergo a pull-out process, delay crack formation and limit crack propagation (Brandt 1995). Debonding and pulling out of fibers from the matrix require more energy; therefore, a substantial increase occurs in toughness. Several factors such as fiber type, aspect ratio, volume fraction, orientation of fibers in the matrix and pull-out resistance of fibers as well as matrix properties influence the performance.

Load deflection curves obtained from four-point bending tests are shown in Figure 3 for mixtures containing different amounts of fibers with an aspect ratio of 80. The area under each curve is a measure of the fracture energy of the material. It is clear from the figure that the fracture energy increases as the fiber volume fraction of steel fiber increases. As seen in the figure, each curve is linear until cracking takes place. The strain hardening behavior that follows the formation of the first crack, except for the mixture with low steel fiber volume fraction (0.32%), is a typical characteristic of high performance cement based composites. Similar results were obtained for the mixtures with the other aspect ratios. The load-deflection curves in Figure 3 are given up to a specified deflection. It is seen from these curves that the energy at this deflection is still not totally dissipated.

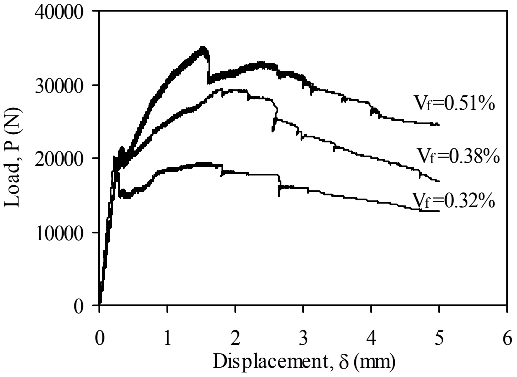


Figure 3. Load - midspan deflection curves for mixtures containing fibers with the aspect ratio of 80 (Yalcin 2009).

The mechanical model of high performance cement based composites containing high amounts of steel fibers can be shown schematically as in Figure 4. In such a model, the stress – strain relationship consists of a first ascending branch for linear elastic behavior and a second ascending branch for the linear strain hardening behavior. As a result, a bi-linear stress-strain behavior is obtained until the peak stress.

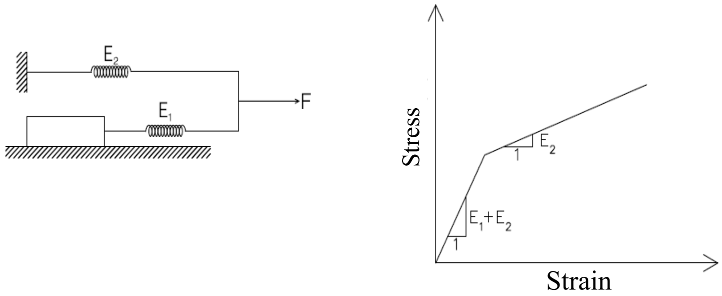


Figure 4. Linear elastic – linear strain hardening material model.

Some experimental results obtained by Guvensoy et al. (2004) show that the addition of steel fibers results in net bending strengths ranging from 22 to 54 MPa, splitting tensile strengths from 21 to 38 MPa, compressive strengths from 117 to 220 MPa, and fracture energies from 8560 J/m^2 to 23500 J/m^2. Figure 5 shows the mechanical behavior of a plain concrete, conventional SFRC, and HPFRCC under three point monotonic bending test. The measured average fracture energy was 23500 J/m^2 for HPFRCC and 108 J/m^2 for the conventional mortar. It can be concluded that the fracture energy of HPFRCC is almost 220 times that of the conventional mortar.

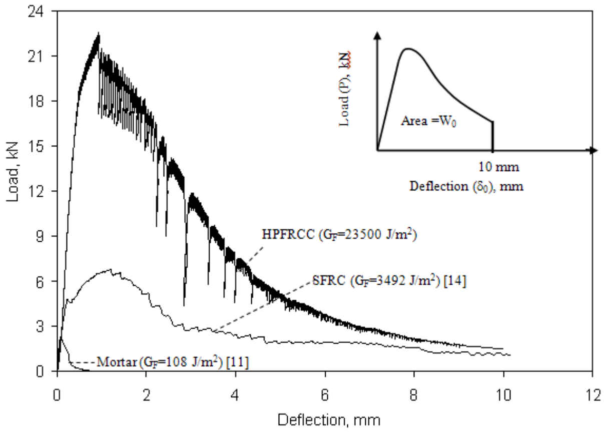
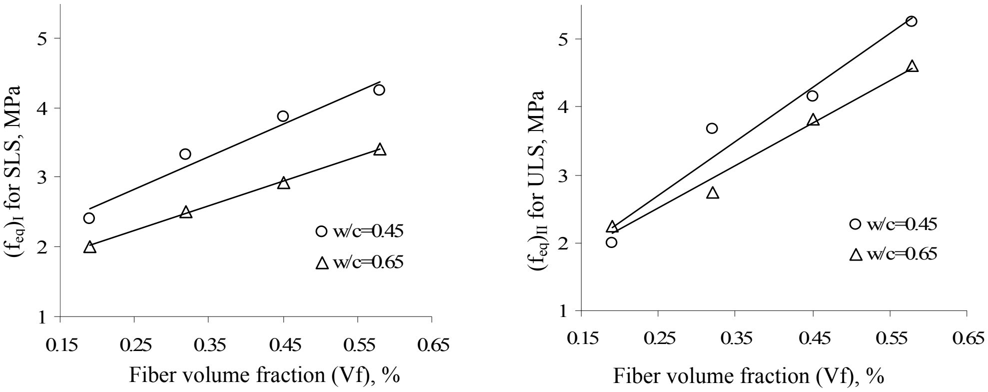


Figure 5. Comparison of the load-mid span deflection curves of HPSFRCC, SFRC and plain concrete, i.e. mortar (Guvensoy et al. 2004).

5 EQUIVALENT FLEXURAL STRENGTHS FOR PERFORMANCE BASED DESIGN

The load displacement curves given in Figure 3 can be used for evaluating the equivalent flexural strengths for both Serviceability Limit State (SLS) and Ultimate Limit State (ULS). The specified deflections for SLS and ULS are $\delta_0 + 0.65$ and $\delta_0 + 3.15$ mm, respectively. Figure 6 shows effects of concrete strength and fiber content on the equivalent stresses for the serviceability and ultimate limit states. For a certain volume fraction of hooked end steel fibers, the equivalent stress $(f_{eq})_I$ increases significantly as the water-cement ratio of SFRC decreases. It should be noted that these experimental results are valid for a given matrix strength and fiber properties. It can be concluded that the ability of the beam to absorb energy is substantial, even if the cut-off point is taken at the specified deflections of $\delta_0 + 0.65$ and $\delta_0 + 3.15$ mm. Hence, it can be concluded that the results obtained give a clear picture of how a quasi-brittle concrete transforms into a ductile composite with the addition of steel fibers (Bayramov et al. 2004).

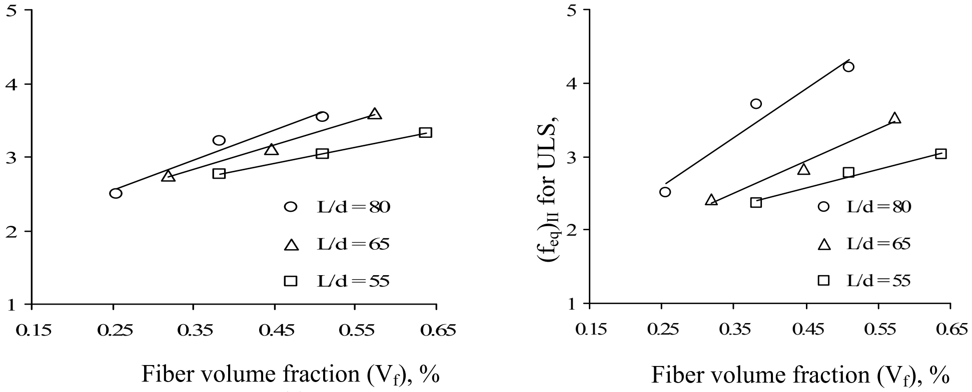


(a) (b)

Figure 6. Equivalent flexural stress versus fiber volume fraction curves for (a) SLS and (b) ULS (Yalcin et al. 2007).

Based on the test results obtained by Yalcin et al (2007), the performance classes of SFRCs for both small and large deformations (i.e. SLS and ULS), can be given. For example, the performance class of SFRC with water-cement ratio of 0.45 and fiber volume fraction of 0.19% can be shown as, C 40/50 F 2.39/2.00. Similarly, for the mixture of SFRC with water/cement ratio 0.65 and V_f = 0.19%, its performance class becomes C 30/37 F 2.01/2.25 (Yalcin et al. 2007).

Figure 7 shows the effects of fiber content on the equivalent flexural tensile strengths for both SLS and ULS for three different aspect ratios. As seen in these figures, for a certain volume fraction of hooked end steel fibers, equivalent flexural tensile strength ($f_{eq\text{-}I}$ or $f_{eq\text{-}II}$) increases significantly as the aspect ratio of steel fiber increases. For a certain concrete class, it is seen that the fiber content and aspect ratio are the main variables in determining the performance classes of fiber reinforced cementitious composites (Bayramov et al. 2002). Based on the test results obtained by Yalcin (2009), the performance classes of SFRCs for both small and large deformations (i.e. SLS and ULS) can be given. For example, the performance class of the mixture (L/d=65, V_f = 0.45% and w/c = 0.55) can be said to be C35/45 F 3.11/2.82.



(a) (b)

Figure 7. Equivalent flexural strength versus fiber volume fraction curves for (a) SLS and (b) ULS (Yalcin et al. 2010).

6 OPTIMIZATION

Optimization usually involves considering several responses simultaneously. A multi-objective optimization problem is solved by using the single composite response (D), which is the geometric mean of the individual desirability function (Myers & Montgomery 1995). The desirability approach involves transforming each estimated response, d_i, into a dimensionless utility bounded by $0<d_i<1$. After building the regression models, all independent variables are varied simultaneously and independently in order to optimize the objective functions (Bayramov et al. 2004). For the results given above, the composite desirability (D) for this multi objective optimization is shown in Figure 8. However, this approach can be extended to other mixtures containing fibers.

7 HPSFRCC FOR SEISMIC RETROFITTING

The behavior of non-ductile column confining zones with and without adequate lap splices using HPSFRCC panels were investigated in an experimental study (Ilki et al. 2009). The specimens were composed of the upper half of a column of the lower story, the beam-column connection and the lower half of a column of the upper story.

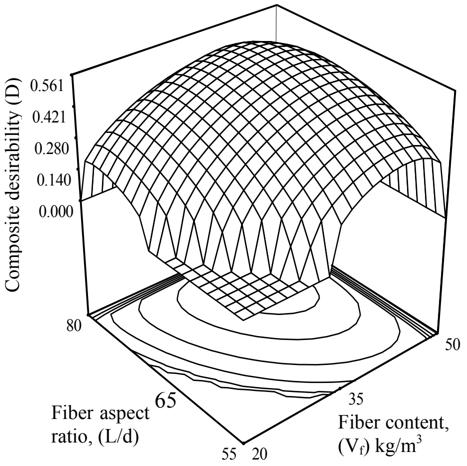


Figure 8. Response surface plot of the composite desirability (D) when $f_{eq\text{-}I}$, $f_{eq\text{-}II}$, f_{sp} and G_f are maximized and fiber content (V_c), L/d and cost of mixture are minimized simultaneously (Yalcin et al. 2010).

Longitudinal reinforcing bars of the 2 of the specimens were continuous, while the other 2 specimens had lap-splices of 40 times the diameter of longitudinal bars, not satisfying the requirement that the lap-splice lengths should have been around 90 times the diameter of longitudinal bars considering the yield strength of plain bars and concrete quality. As seen in Figure 9, higher energy absorption and more stable hysteresis loops were recorded, despite the insufficient transverse reinforcement in the confinement zone. It can be concluded that the investigated retrofitting technique significantly improved the load capacity and particularly the ductility (Ilki et al. 2009).

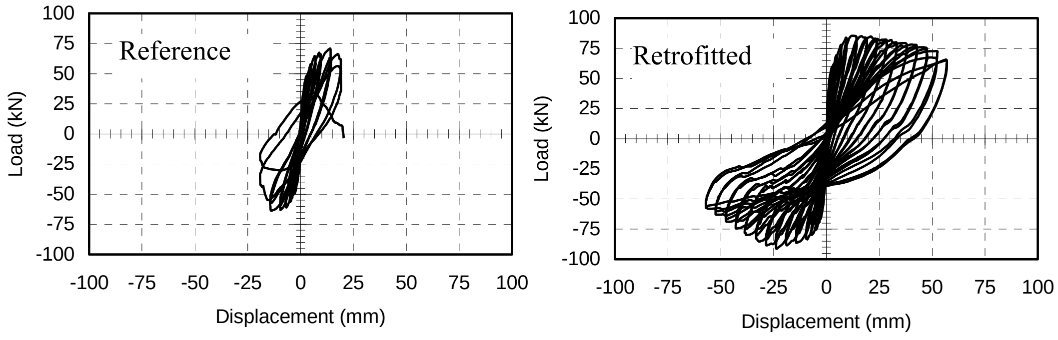


Figure 9. Hysteresis loops of column-beam sub-assemblages under cyclic loading conditions: (a) Reference, and (b) Retrofitted (Ilki et al. 2009).

8 CONCLUSION

Based on the available data on HPSFRCCs, the following conclusions can be drawn in relation to their potential suitability for diverse applications in Civil Engineering.

1. The fracture energy of HPSFRCC is almost 220 times that of the plain concrete and the compressive strength of these cementitious composites reach up to 220 MPa.
2. Performance classification of conventional steel fiber reinforced concretes can be made according to the parameters of strength class, the volume fraction and aspect ratio of steel fibers.
3. Although high amounts of fibers are used in HPSFRCCs, through proper mixture proportioning and suitable plasticizers, fibers can be dispersed homogenously in the mixture without clumping.
4. The new generation of cement based materials show great potential for use in retrofitting of concrete structures damaged by earthquakes or by unexpected loads. Promising laboratory findings are likely to accelerate the transfer of their use into engineering practice.

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