MECANICAL BEHAVIOR AND APPLICATIONS OF HPFRCCs: ITU EXPERIENCE

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Abstract

This paper contains the mechanical behavior of some advanced cement based materials such as High Performance Fiber Reinforced Cementitious Composites (HPFRCCs) and their applications as an ITU experience. Normal and Self Compacting Concretes with and without steel fibers were also summarized.

Keywords: Steel fiber, high performance concrete, self compacting concrete, concrete degradation, gully tops, manhole cover.

1. Introduction

There have been incredible advances in concrete technology over the years. Not more than 45 years ago, the maximum compressive strength obtained at the construction site was about 40 MPa [1], such a concrete considered quite low strength when compared to the modern very-high strength concretes with cube compressive strengths between 200 MPa and 800 MPa, tensile strengths between 25 MPa and 150 MPa, and fracture energies of about 30000J/m^2 [2-4]. In recent years, a number of specific developments have occurred in parallel to the leading to the evolution of what is commonly described as high performance concretes. Such concretes have high strength combined with highly enhanced durability. The brittleness of concrete, however, increases with an increase in its strength. In other words, the higher the strength of concrete, the lower is its ductility. The inverse relation between strength and ductility is a serious drawback and limits the use of high strength concrete [5]. Their potential use is yet to be established and more work is required, in particular, to evaluate their long-term performance. These materials have already been successfully laboratory tested for strengthening structures and their potential use in areas subjected to earthquakes needs to be investigated [6]. The fracture energies of Reactive Powder Concretes (RPCs), are about 300 times that of normal strength concrete or even 1350 times in case of Slurry Infiltrated Fiber Reinforced Concrete (SIFCON) [7]. The low porosity of RPCs gives them important durability and low transport properties and makes them potentially suitable for some structures exposed to harsh environmental conditions [8,9].

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The interface between cement paste and aggregate particles is the weakest zone in concrete, and the use of ultra-fine particles, such as silica fume, is important for densification and for the improvement of the stability of fresh concrete, thus, enhancing the overall durability and strength. Micro-silica or silica fume is a by product of silicon and ferrosilicon industries; it has been used since 1950s to improve the properties of concrete. To gain benefits from these particles, good dispersion within the concrete system is necessary and can be provided by means of a superplasticizer [10,11]. The internal structure of RPC is optimized by precise gradation of all particles in the mix, to add short steel fibers for improved ductility and to allow the resulting concrete to harden under pressure and increased temperatures [12].

The aim this work is to review some advanced cement based materials studied at ITU such as High Performance Fiber Reinforced Cementitious Composites (HPFRCCs) and their applications.

2. Classification of Cementitious Composites

From the strength point of view, the classification of high strength concretes can be made as: i) normal strength concrete (NSC) up to grade 60 MPa, ii) high strength concrete (HSC), grades 60-90 MPa, iii) very high strength concrete (VHSC), grades 90-130 MPa, iv) reactive powder concrete (RPC), grades 200-800 MPa, and v) high performance lightweight concrete (HPLC) greater than 55 MPa [13].

From the mechanical behavior point of view, SFRCs can be divided into two categories based on their performances: i) conventional SFRCs, and ii) HPFRCCs such as RPCs. The conventional SFRCs exhibit ductile behavior compared to the brittle matrix, but their flexural and tensile strengths are not very high, and especially the compressive strengths of these materials do not practically change with the fiber volume fraction. The HPFRCCs, however, exhibit large strain hardening before peak stress, and their tensile and compressive strengths are very high compared to those of conventional SFRCs [14]. Ductile Fiber Reinforced Cementitious Composites (DFRCCs) or Strain Hardening Cementitious Composites (SHCCs) show hardening deflection and multiple cracking in bending with significant ductility in tension and compression. DFRCC (or SHCC) 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. DFRCC is a broader class of materials than HPFRCC. FRCC includes the entire class of FRCCs, where DFRCC as well as other composites such as fiber reinforced concrete (FRC) and fiber reinforced mortar (FRM) are sub-sets [15]. 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% [16]. HPFRCC also includes SIFCON and SIMCON (Slurry-Infiltrated Mat Concrete).

3. Effects of Curing on the Mechanical Behavior of HPFRCCs

In the work of Ozalp et al. [17], effects of fiber strength and curing conditions on the mechanical behaviour and fracture properties of high performance cement based composites with hybrid steel fibers were investigated. Depending on the temperature curing condition, concretes with hybrid steel fiber showed behaviour of enhanced toughness and ductility. Fracture energy of plain concrete increased up to 94 times owing to concretes with normal strength steel fiber, while in concretes with high strength steel fibers the increase in fracture energy due to steel fibers was 166 times. In their work, partial replacement of aggregate by steel fiber was based on one to one volume basis.

The test results of Ozalp et al.[17] have shown that the most significant effects of both the fiber addition and curing condition are observed on the fracture energy of composites. It was seen that the use of high strength steel fibers improves the mechanical performance and increases the fracture energy of the composite. Especially after the first crack, the formation of strain hardening in the ascending branch of the curve is a typical indication of high performance cementitious composites. The high temperature curing regimes activate pozzolanic reactions in the composites investigated; as a result, fracture energies of the composites increase significantly. The composites with normal strength hooked-end steel fibers have lower peak load and steeper gradients of the softening branch compared to the composites with high strength hooked end steel fibers and the highest fracture energies were obtained from these composites.

4. Mechanical Behaviour of HPC with HS Short Steel Fibers

Some experimental results obtained by Guvensoy et al.[18] are shown in Table 1. As seen in the table, 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 1 shows the mechanical behavior of a conventional mortar, 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.

Table 1.Mechanical properties of HPFRCCs [18]

Mechanical properties		M1	M2	M3	M4	M5
Compressive strength, f_c	MPa	162	156	117	146	220
Net bending strength, f_{net}	MPa	54	49	30	22	37
Splitting tensile strength, f_{st}	MPa	30	24	20	21	38
Fracture energy, G_F	J/m^2	23500	18740	9840	8560	17220

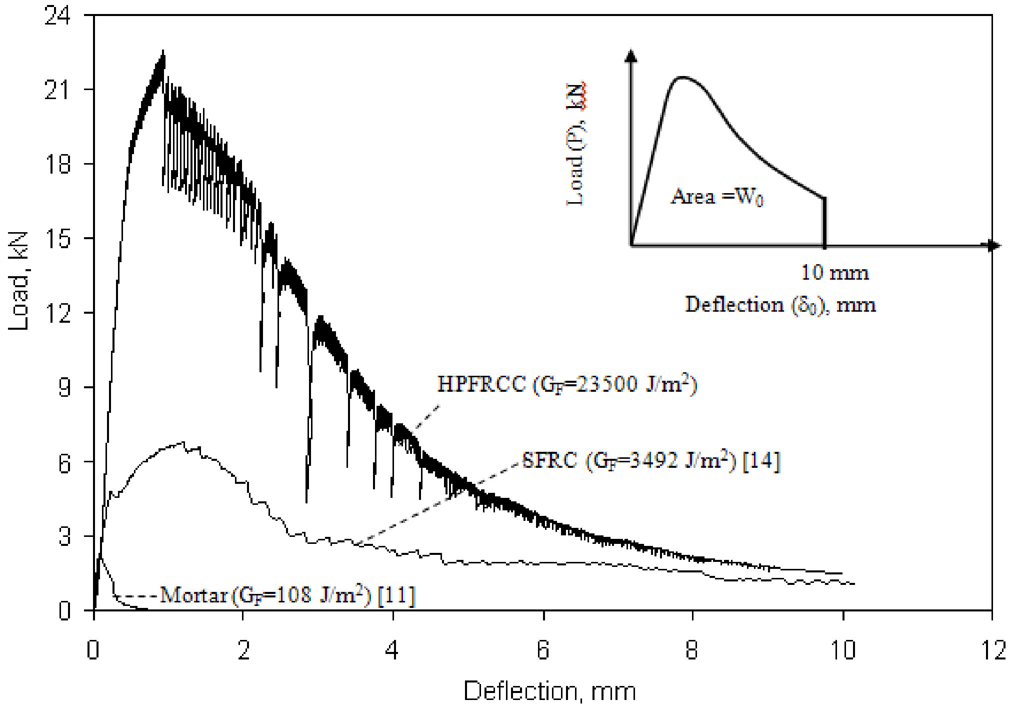


Fig.1. Comparison of the load-mid span deflection curves of HPFRCC (for mixture M1), SFRC and conventional mortar [18]

5. Degradation Properties of HPFRCCs

The determination of a unique focal point of stiffness degradation in concrete has been defined by Lee et al.[19] for compression, and used by Tasdemir et al.[11] for three point bending, as shown in Figure 2. In the later one, the first three unloading-reloading cycles has been used to locate the focal point; when the postpeak load dropped to about 40 percent of the maximum value, further cycles proved to be inappropriate to use. The normalized stiffness as a measure of degradation of stiffness and the focal point had been determined by Tasdemir et al.[11] using unloading-reloading cycles in both the load-Crack Mouth Opening Displacement (CMOD) and the load-deflection curves. The normalized stiffness had been correlated to the normalized local fracture energy, to the normalized permanent CMOD and δ, and to the normalized load (strength degradation). Thus, the focal point has been employed as a measure of concrete brittleness.

Figure 3 shows load-mid span deflection curves obtained from the bending tests under cyclic loading on HPFRCC beams. As seen in the figure, there is no significant loss in the initial compliance of HPFRCCs, the slopes of the unloading-reloading loops are almost same as the slope of the initial ascending part of the load-deflection curve. This is an evidence of the ductility of HPFRCCs. Although, the residual strength decreases after the peak stress, stiffness degradation in HPFRCCs is not significant. Under cyclic actions, steel fibers efficiently bridge the cracks and no significant loss of stiffness is observed even when high levels of deflections are reached. As schematically seen in the inset of Figure 2, similar results were obtained in conventional steel fiber reinforced concretes depending on the steel fiber volume fraction (V_f) and the aspect ratio (L/d) by Bayramov et al. [20], and also in steel fiber reinforced lightweight concretes depending on aggregate type by Campione et al. [21].

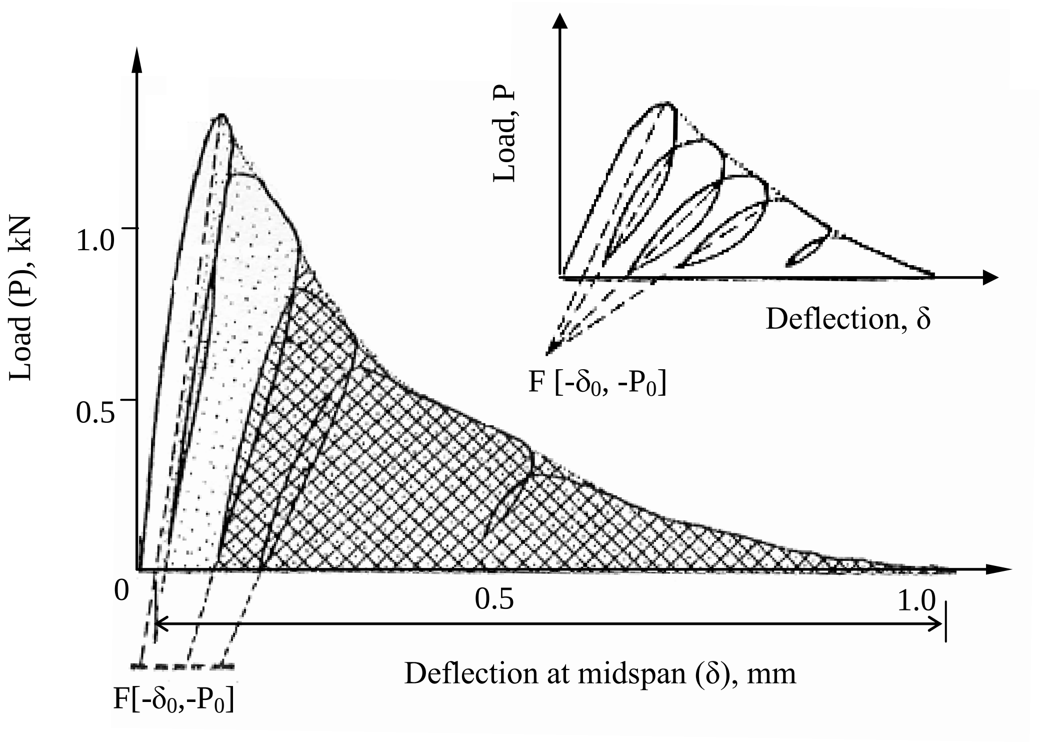


Fig 2. Typical results of unloading-reloading cycles for a plain concrete beam[11].

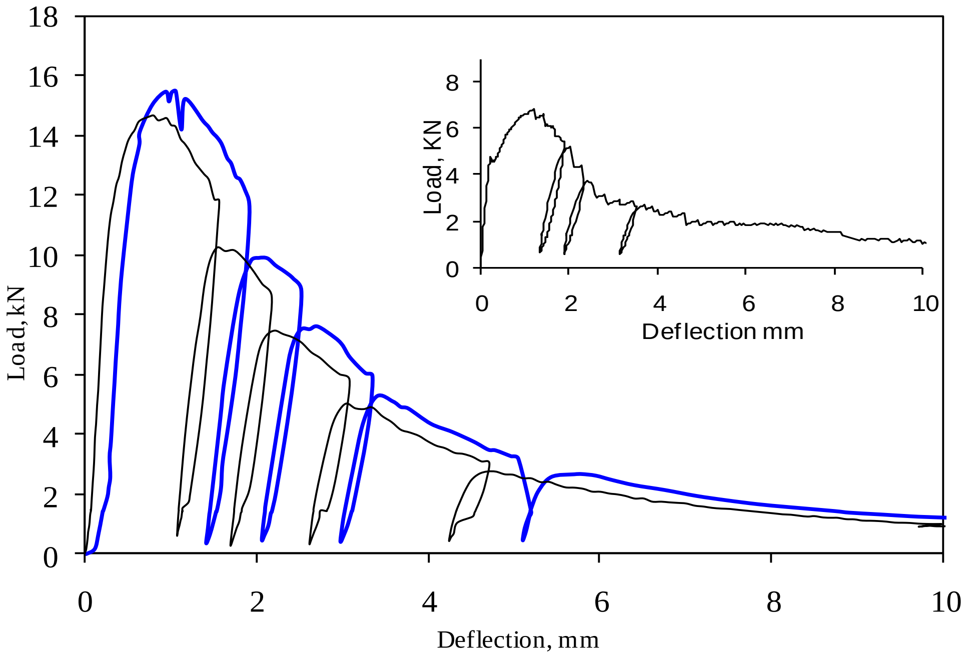


Fig.3. Typical load-mid span deflection curves of HPFRCCs [18].

6. SCCs with and without Steel Fibers

In a recent study, conducted at ITU, the mixture design, workability, mechanical properties and fracture behavior of Self Compacting Hybrid Steel Fiber Reinforced Concretes were investigated (SCHSFRC). Three different types of steel fibers with and/or without hooked-ends were added to the mixtures to examine the effect of hybrid steel fibers and their strengths on the mechanical and fracture properties of these concretes. Two different volume fractions of fibers, 1.5 and 0.75% of the total volume of concrete, were used. The results have shown that increasing the fiber content of the concretes slightly reduced the workability of HSFRSCC. It has been shown that the effects of strength and the volume of the steel fibers on the mechanical behavior of the concretes. It is seen that the use of hybrid steel fibers improves the mechanical performance and increases the fracture energy of the concretes. Especially after the formation of the first crack, the progress of strain hardening in the ascending branch of the curve is a typical indication of high performance cementitious concretes. The increase in the fiber content significantly increased the fracture energy of concretes. The short fibers had a limited effect on the post-peak response of load versus displacement at midspan of the beam, while there was a substantial effect of long fibers on the post peak response part of curve, which resulted in a high value of fracture energy. The concretes with normal strength hooked-end steel fibers had lower peak loads and steeper gradients of the softening branch compared to the concretes with high strength hooked-end steel fibers and the highest fracture energies were obtained from the latter concretes [22].

The mixture design, fresh and hardened properties of self-compacting concretes with and without steel fibers were studied by Yilmaz et al.[23]. In these mixtures, water/powder ratio was kept constant at the value of 0.52 by volume and, part of cement was replaced with silicious powder by volume. Steel fiber volume fraction in self-compacting fiber reinforced concretes (SCFRCs) were kept constant at 1%. It was observed that both compressive strength and modulus of elasticity of SCCs and SCFRCs were not affected adversely although water to cement ratio was increased from 0.24 to 0.38 (i.e. cement to powder ratio decreased from 0.73 to 0.48), while the cement content was decreased from 850 kg/m^3 to 310 kg/m^3. The energy absorption capacity was increased by 13 to 68 times with the addition of fibers. It was also observed that the fiber reinforced concrete with water/cement ratio of 0.63 (i.e. cement/powder ratio of 0.30) did not show self-compacting ability.

7. SCCs with Normal or Lightweight Aggregates

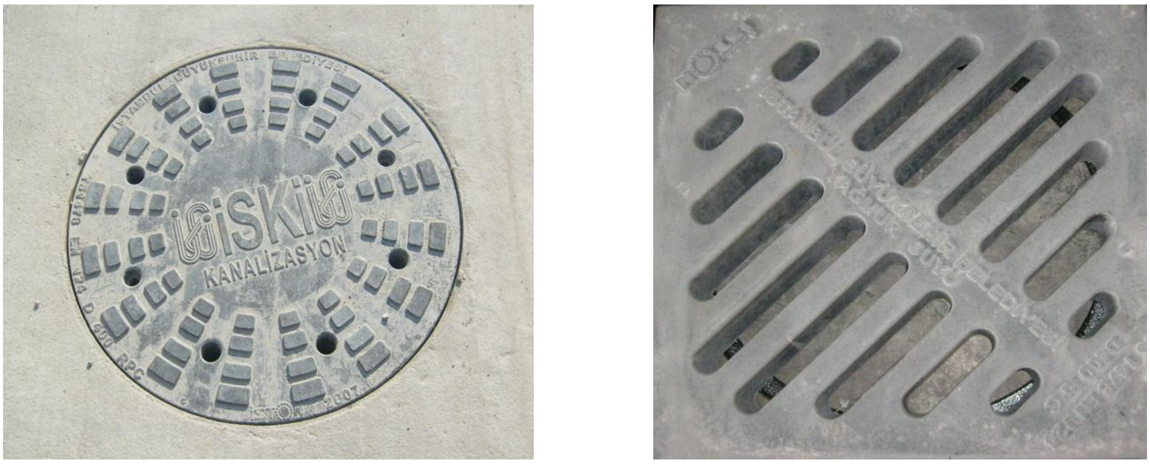
In the work of Tasdemir et al.[13] the mixture design, workability, mechanical properties and fracture behavior of normal and lightweight self compacting concretes with and without steel fibers were studied. The compressive strengths, elastic moduli, net bending strengths and fracture energies of self compacting concretes with different steel fiber contents were compared to those of plain concretes. The net bending strength, fracture energy and the ductility of the self compacting concrete mixtures were significantly enhanced compared to those of plain normal and lightweight concretes. Fracture energy of plain concrete increased 39 times, owing to the addition of steel fibers; while in lightweight concretes the increase in fracture energy due to steel fibers were 96 times. Thus, the steel fiber reinforced concretes show a behavior of enhanced toughness and ductility when compared to plain concretes.

8. Some Applications of HPSFRCCs

Ilki et. al.[6] have investigated the behavior of non-ductile column confining zones without adequate lap splices using High Performance Fiber Reinforced Cementitious Composites (HPFRCC) panels. Their 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. Higher energy absorption and more stable hysteresis loops were recorded, despite of the insufficient transverse reinforcement in the confinement zone. It was shown that the investigated retrofitting technique significantly improved for both the strength and particularly the ductility. The details of the testing program, the retrofitting technique and the test results can be found in the work of Ilki et al.[6].

Gully tops and manhole covers produced in Iston, which is a company of Istanbul Metropolitan Municipality, can be used in roads and urban environment for rain water drainage. In these structural elements containing classical reinforcing bars, ultra high performance steel fiber reinforced composites are used as the matrix. The strength of these matrices reaches up to the compressive strength of 350 MPa. The average load carrying capacity of gully tops and manhole covers produced was 460 kN. This means that these productions can be used as a class of D400 which is a load carrying ability indicated in

EN 124. They are available in different sizes and with special design such as square gully tops and circular manhole covers. Typical examples are shown in Figure 4 [17].



(a) Circular manhole

(b) Gully tops

Fig. 4. The city infrastructures examples produced with reactive powder concrete [17].

9. Conclusions

Based on the experimental studies at ITU, summarized in this paper, following conclusions can be drawn as follows:

It can be concluded that short fibers function as a bridge to eliminate the micro-cracks, as a result the tensile strength of composite increases, and they pulled out after the macrocracks are formed. Thus, the short fibers have a little effect on the post-peak response of load versus displacement at the mid span of the beam. The large fibers have no significant effect on preventing micro-cracking, however, there is a substantial effect of large fibers on the post-peak response part of load versus displacement curve of the beams, resulting in high value of fracture energy. Curing regimes enhance the microstructure of the composite, as a result, the compressive strength, specific fracture energy, toughness and flexural strength can be greatly improved.

There is no significant loss in the initial compliance of HPFRCCs, the slopes of the unloading-reloading loops are almost the same as the slope of the initial ascending part of the load-deflection curve. In HSCs without steel fibers, the focal point defined can be taken as a measure of concrete brittleness. In HPFRCCs, however, this point is far from the origin or does not exist, in contrast to that of HSCs without steel fibers. Although, the residual strength decreases gradually after the peak stress in HPFRCCs, the stiffness degradation is not significant under cyclic loading condition.

In the production of gully tops and circular manhole covers, specially designed HPFRCC was used as the matrix. Compressive strength of this matrix was about 350 MPa. The load carrying capacity of these productions was 460 kN, which corresponds to a class D400 indicated in EN 134.

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