///VSP///
Composite Interfaces 18 (2011) 169–184
COMPOSITE INTERFACES
brill.nl/ci

Workability and Mechanical Performance of Steel Fiber-Reinforced Self-Compacting Concrete with Fly Ash

Osman Gencel [a,b], **Witold Brostow** [b,*], **Tea Datashvili** [b] **and Michael Thedford** [b]

[a] Civil Engineering Department, Faculty of Engineering, Bartin University, 74100 Bartin, Turkey
[b] Laboratory of Advanced Polymers and Optimized Materials (LAPOM), Department of Materials Science and Engineering and Center for Advanced Research and Technology (CART), University of North Texas, 1150 Union Circle # 305310, Denton, TX 76203-5017, USA

Received 28 October 2010; accepted 11 February 2011

Abstract
Steel fibers change the properties of hardened concrete significantly. However, addition of fibers to fresh concrete results in a loss of workability. Self-compacting concrete (SCC) is an innovative concrete that is able to flow under its own weight, completely filling formwork and achieving full compaction without vibration. We have studied composites of SCC with steel fibers for further property enhancement. Water/cement ratio and cement, fly ash and superplasticizer contents were kept constant at 0.40, 400, 120 and 6 kg/m^3, respectively. The fiber amounts were 15, 30, 45 and 60 kg/m^3. Slump flow, J-ring and V-funnel tests were conducted for evaluating the fluidity, filling ability and segregation risk of the fresh concretes. There were no problems with mixing or workability while the fiber distribution was uniform. Steel fibers can significantly enhance toughness of SCC and inhibit the initiation and growth of cracks.

Keywords
Fiber-reinforced cement, concrete rheology, self-compacting concrete, fly ash

1. Introduction

Self-compacting concrete (SCC) has little resistance to flow so that it can be placed and compacted under its own weight with little or no vibration effort. SCC has viscosity such that segregation and bleeding do not occur. SCC was developed in Japan in the late 1980s as a solution to achieve durable concrete structures independent of the quality of construction work [1]. SCC usage is also reported to lower the noise

* To whom correspondence should be addressed. E-mail: wbrostow@yahoo.com

 DOI:10.1163/092764411X567567

level on the construction site and diminish the effect on the environment [2]. Consequently, the use of SCC as a construction material has gradually increased over the last few years [3]. Generally, SCC is produced using new generation superplasticizers to reduce the water–binder ratio. In addition, supplementary cementitious or inert materials such as limestone powder, natural pozzolans, and fly ash are used to increase the viscosity and fresh concrete workability and reduce the cost of SCC.

The use of fly ash reduces the demand for cement, fine fillers and sand that are required in SCC [4, 5]. Fly ash, a by-product of coal power plants, has been reported to improve mechanical properties such as freeze–thaw resistance, sulphate resistance, alkali–silica reaction, durability and abrasion resistance when it has been used as a cement replacement material in mortar and concrete. Also shrinkage and permeability of hardened concrete are decreased due to filling of micropores [6]. Utilization of fly ash (FA) in concrete technology is becoming more common — also because FA reduces the chloride penetration and steel corrosion in concrete [7]. Two common causes of corrosion in concrete are related to localized breakdown of passive films on steel by chloride ions and by reaction with atmospheric carbon dioxide. Usually chlorides penetrate into concrete by diffusion along water paths or open pores. Some of these chlorides can react with the cement compounds, mainly tricalcium aluminates, forming stable chloro complexes. The presence of fly ash leads to an increase in the amount of tricalcium aluminates present and also an increase in the content of calcium silica hydrate formed in pozzolanic reactions. Consequently, there are less free chlorides available to initiate corrosion [4].

At the same time, unsalvaged FA causes environmental pollution and the cost of storage of FA is very high [6]. The usage of industrial waste materials in concrete, in regards to both environmental pollution and the positive effect on a country's economy, is beyond dispute.

The term 'fiber-reinforced concrete' is defined by ACI (American Concrete Institute) 116R document, Cement and Concrete Terminology, as a concrete containing dispersed randomly oriented fibers. Inherently concrete is brittle under tensile loading and mechanical properties of concrete may be improved by randomly oriented short discrete fibers which prevent or control ignition, propagation, or coalescence of cracks [9]. Also other experimental study showed that fibers used in concrete in various application areas improve the mechanical properties of concrete such as flexural strength, compressive strength, tensile strength, creep behavior, impact resistance and toughness [9].

It is well known that fibers reduce the workability of concrete and this seems a handicap for on-site applications. There is not enough study carried out on fiber-reinforced concrete produced with FA and combination of them together. In this respect, the combination of fiber-reinforced concrete and SCC and FA together and performance of new composite was investigated in order to elucidate the situation and possibly develop materials with improved properties.

2. Materials and Methods

2.1. Aggregates

Given that aggregates typically constitute 70–80 wt% of concrete, aggregate types and sizes play an essential role in modifying concrete properties; the influence of type and grading of aggregate on the mechanical properties of concrete is important [10]. We have created plain concrete using limestone-based aggregates with three different grain sizes: up to 3 mm size crushed stone (CSt-I), up to 7 mm size natural river stone (NRS) and 7–15 mm size crushed stone II (CSt-II). The aggregates were graded, washed and cleaned of clay and silts. To reduce difficulties of producing, mixing and placing of concretes and to prevent segregation of aggregates in the fresh concretes, the maximum aggregate size was selected as 15 mm diameter. Results of sieve analysis of fine and coarse aggregates used and mixture are presented in Table 1. Physical and mechanical properties and mixing ratios of all aggregates are presented in Table 2.

2.2. Cement

The cement used in all the concrete mixtures corresponds to CEM II/A-M (P-LL) 42.5 N Portland cement. Physical and mechanical properties and chemical analysis of cement are presented respectively in Tables 3 and 4. We note more than doubling of the compressive strength between 2 and 28 days and nearly doubling the flexural strength in the same period.

The Le Chatelier method of cement characterization is based on using a 30 mm longitudinally split cylindrical mold with 2 indicators containing the cement paste

Table 1.
Aggregate gradations

	16 mm	12.5 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	600 μm	300 μm	150 μm	75 μm
NRS	100.0	100.0	100.0	96.0	81.0	53.0	32.0	18.0	5.0	1.0
CSt-I	100.0	83.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CSt-II	100.0	35.0	12.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0
Mixture	100.0	82.8	69.9	53.3	44.6	29.2	17.6	9.9	2.8	0.6

Table 2.
Physical properties of aggregates

Aggregate codes	Specific gravity (g/cm^3)	Loose unit weight (g/cm^3)	Dry rod unit weight (g/cm^3)	Water absorption (%)	Mixing ratio (%)
CSt-I	2.69	1.913	2.151	2.91	30
NRS	2.67	1.830	1.974	3.02	25
CSt-II	2.70	1.676	1.594	0.93	45

Table 3.
Physical and mechanical properties of Portland cement

Compressive strength (MPa)			Flexural strength (MPa)			Initial setting time (h)	Final setting time (h)	Le Chatelier (mm)	Specific gravity (g/cm^3)	Blaine (cm^2/g)
2 Days	7 Days	28 Days	2 Days	7 Days	28 Days	2.25	3.15	1	3.15	4150
22.5	36.6	47.8	3.7	5.6	6.9					

Table 4.
Chemical analysis of the Portland cement used

Compound	Weight%
Total SiO_2	22.9
Al_2O_3	5.32
Fe_2O_3	3.63
CaO	55.83
MgO	1.99
SO_3	2.62
Cl	0
LOI*	4.2
Free CaO	0.82
Total admixture	19.45

* Loss of ignition.

— exposed to boiling water at the atmospheric pressure for 3 h. The cement is acceptable if the distance between the indicators is $\leqslant$10 mm (European Committee on Standardization).

The Blaine method follows the ASTM C-204-07 standard. The Blaine air permeability apparatus allows for drawing a definite quantity of air through a prepared bed of cement of definite porosity. The permeability cell is a rigid cylinder made of stainless steel. The specific surface area is in cm^2/g.

2.3. *Fly Ash*

Class F of fly ash (FA) was used in this study. Its chemical composition is presented in Table 5. The Blaine fineness was 5.23×10^3 cm^2/g. Specific gravity was 2.1 g/cm^3. It is important to have a sufficient amount of cement paste in SCC since it is an agent to carry the aggregates. As a consequence, FA has been used in order to increase the amount of cement paste [11].

2.4. *Superplasticizer*

A superplasticizer (SP) based on a modified polycarboxylate was employed to obtain a satisfactory workability of fresh concrete for the different mixes. Properties of the mixture are presented in Table 6. In developing a SCC, usually a new gen-

Table 5.
Chemical analysis of fly ash

Compound	Weight%	ASTM C618 limit (Class F)
Total SiO_2	57.2	
Al_2O_3	25.5	
Fe_2O_3	6.01	
S+A+F	89.0	>70.00
CaO	1.14	
MgO	2.42	
TiO_2	1.16	
SO_3	0.16	<5.00
K_2O	4.60	
Na_2O	0.42	
Cl	0.014	
LOI*	1.12	<10.00
Free CaO	0.12	

* Loss of ignition.

Table 6.
Properties of the chemical admixture

Specific gravity (g/cm^3)	pH	Solid content (%)	Recommended (% cement content)	Main component
1.08	5.7	40	0.5–2.5	Polycarboxylic ether

Table 7.
Properties of steel fibers

Length (mm)	Diameter (mm)	Aspect ratio	Tensile strength (MPa)	Elasticity modulus (MPa)	Specific gravity (g/cm^3)
30	0.5	60	1.25×10^3	2.0×10^5	7.48

eration polycarboxylic based superplasticizers are used together with either some chemical or mineral admixtures that provide the appropriate viscosity range.

2.5. *Fibers*

The properties of steel fibers are presented in Table 7. In this work, type of steel fiber having aspect ratio of 60 and geometry of cylindrical with hooked ends was used. It is a well-known property of these fibers that they resist fracture under tensile forces. The steel fibers are zinc galvanized wires with silver color.

There are many kinds of fibers, metallic or polymeric, coated, uncoated, or irradiated, widely used in concrete engineering for their advantages [12–17]. However,

Table 8.
Mix proportions in mass (kg/m^3)

Mix no.	Cement	Water	SP	FA	Fiber	CSt-I	NRS	CSt-II
1	400	160	6	120	0	523.6	433.0	788.3
2	400	160	6	120	15	521.9	431.7	785.8
3	400	160	6	120	30	520.4	430.4	783.4
4	400	160	6	120	45	518.7	429.0	781.0
5	400	160	6	120	60	517.1	427.7	778.5

the steel fibers have high elastic modulus and stiffness so they can improve compressive strength and toughness of concrete [18].

2.6. *Mix Proportions*

Five mixtures, one control and five fiber-reinforced, were prepared. Cement content and aggregate grading were kept constant in all mixtures. Mixture proportions were presented in Table 8. Water cement ratio, cement content and fly ash content were kept constant. Cement content was 400 kg/m^3 and w/c ratio was 0.40. For the mixtures with steel fibers, the fiber ratios were 15, 30, 45 and 60 kg/m^3. These ratios correspond to fiber volume fractions V_f of 0.2%, 0.4%, 0.6% and 0.8%, respectively. The SP and FA content were 1.5% and 30% of the cement content by weight, respectively. The coarse aggregate (crushed limestone) had a 15 mm maximum size. The maximum aggregate size was selected 15 mm in order to avoid subsequent blocking effects.

2.7. *Mixing, Casting, Curing and Testing Specimens*

In a typical mixing procedure, the materials were placed in the laboratory mixer with capacity of 60 dm^3 in the following sequence: first, coarse aggregates and fine aggregates and fibers together followed by cement, initially dry material mixed for 1 min; finally, addition of 80% of water. After 1.5 min of mixing, the rest of the mixing water together with the SP was added. All batches were mixed for a total time of 5 min; in order to prevent fresh concrete from segregation, the mixing duration was kept as low as possible. Specimens for the testing of the hardened properties were prepared by direct pouring of concrete into molds without compaction.

From each concrete mixture, six specimens were cast in cylindrical molds of 150 mm diameter and 300 mm height. Six 150 mm cubes were cast. The cubes were used for the compressive strength, ultrasonic pulse velocity tests, Schmidt hardness and the cylinders were used for elasticity modulus, and splitting tensile strength tests. After casting, the concrete specimens were covered with wet burlap and polyethylene sheets and kept in the laboratory at room temperature for 24 h. After demolding, they were placed in a saturated limewater bath until the time of testing. Curing was done in accordance with ASTM C511 standard. It is well recognized that adequate curing of concrete is very important not only to achieve the desired compressive strength but also to make durable concrete. The compressive strength tests were carried out in accordance with ASTM C39-86 at 28 days. The splitting tensile strength tests were done according to ASTM C496-87 at 28 days. The Schmidt hardness measurements were done after 28 days of curing. Schmidt hardness, ultrasonic pulse velocity, flexural strength and elasticity modulae were determined according to ASTM C805-85, ASTM C597, ASTM 293-94 and ASTM C469-87, respectively.

Fresh concrete is a mixture from coarse and fine aggregates which are suspended in binder paste matrix. The viscosity of the mortar, the volumetric fraction of aggregate and the fibers control the flow behavior.

Numerous test methods are available for measuring the rheological behavior and the workability of concrete with or without fiber reinforcement, such as those used by Martinez–Barrera and coworkers [16, 17]. Workability methods used in this study standardized by the Self-Compacting Concrete Committee of EFNARCS [19] were followed.

To evaluate workability of fresh concrete, slump flow test, J-ring test and V-funnel test were used. These three test procedures were discussed by Sahmaran and Yaman [20] and are briefly described below.

The slump flow is used to evaluate the horizontal free flow (deformability) of SCC in the absence of obstructions. The test method is very similar to the test method for determining the slump of concrete. The difference is that, instead of the loss in height, the diameter of the spread concrete is measured in two perpendicular directions and recorded as slump flow. The higher the slump flow, the larger is concrete's ability to fill formworks. During the slump flow test, the time required for the concrete to reach a diameter of 500 mm is also measured and recorded as t_{500}. This parameter is an indication of the viscosity of concrete and indicates the stability of the concrete. A lower time points to a greater fluidity or smaller workability loss.

A J-ring test is used to determine the passing ability of the concrete. It is an extension of the slump flow test in which a ring apparatus (Fig. 1) is used and that inside (h_1) and outside (h_2) of the ring is measured. This gives an indication of the passing ability and restricted deformability of concrete.

The V-funnel test is used to determine the fluidity or viscosity of concrete. The V-funnel (Fig. 2) is filled with concrete and the time it takes for the concrete to flow through the apparatus is measured. Good flowable and stable concrete would take a short time to flow out.

3. Results and Discussion

3.1. Physical Properties of Concretes

No problems in mixing have been encountered; the fiber distribution was uniform. All mixes had good fluidity and exhibited self-compacting characteristics.

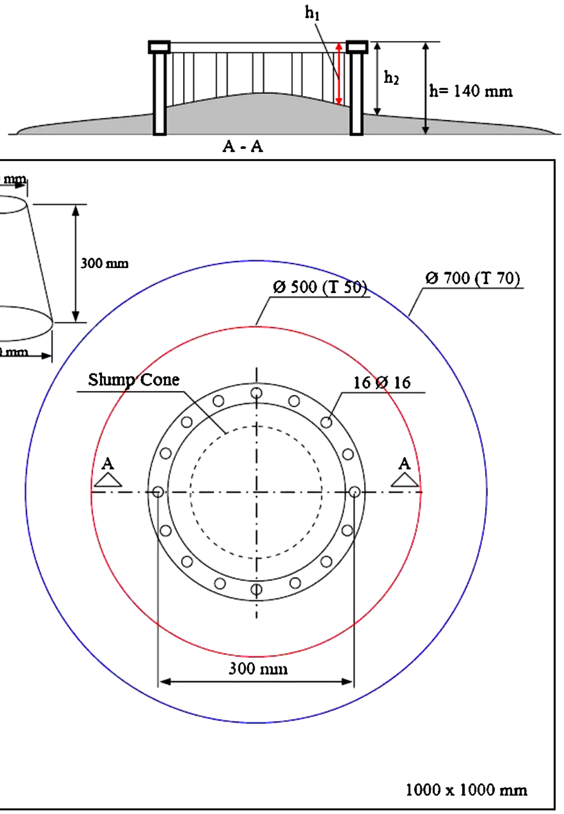

Figure 1. Workability tests and apparatus for slump flow and J-ring.

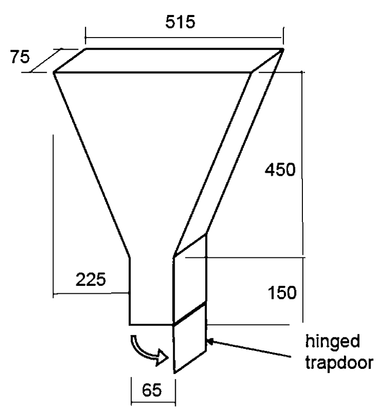

Figure 2. V-funnel test apparatus.

Basic workability requirements to be successful for casting of SCC are summarized by Khayat [21] as deformability, good stability and low risk of blockage. The properties of our fresh self-compacting concretes are presented in Table 9, including

Table 9.
Tests on fresh concrete

Mix no.	Slump flow		V-funnel (s)	J-ring (mm)	
	D (mm)	t_{500} (s)		h_1	h_2
1	769	4.1	14.1	12.0	12.6
2	692	4.3	16.4	11.7	12.0
3	645	4.6	18.6	11.2	11.8
4	603	4.5	19.3	10.7	11.4
5	582	4.7	20.7	10.1	10.8

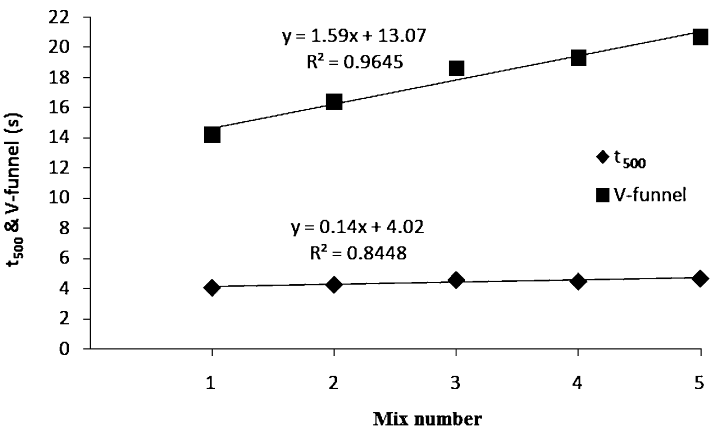

Figure 3. t_{500} and V-funnel test results.

slump flow, J-ring height differences and V-funnel flow times. As for slump flow, all SCCs exhibit satisfactory results in the range of 550–800 mm, an indication of a good deformability. In other words, all mixes had enough deformability under their own weight and had a moderate viscosity, attributes necessary to avoid segregation. In V-funnel tests, all SCCs show flow time values in the range of 14–20 s. The slump flow values and the V-funnel flow times are in good agreement. The t_{500} measurements of slump flow and V-funnel test are affected by the fiber inclusion — as seen in Fig. 3. In J-ring tests, SCCs exhibit differences in heights of the concrete inside and outside of the ring, approximately 115 mm on the average. Fibers with hooked ends cause blocking of particles during flow; obviously, the magnitude of this effect depends on fiber content in the mixture.

Important for good mixing is the presence of fly ash. The fiber–matrix adhesion as well as the geometry of the fibers affect pullout behavior of the fibers. FA helps to evenly disperse fibers during mixing. Approximately spherical FA particles provide ball bearing effects and reduce internal friction in fresh concrete and thus increase the flow ability and compaction of that concrete [22]. Since the fly ash provides

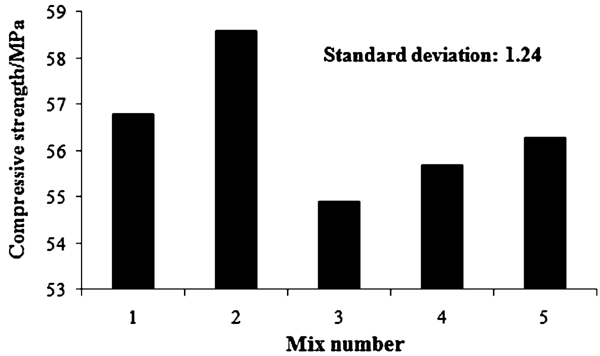

Figure 4. Compressive strength results.

the smallest particles of the matrix, it fills the gaps, resulting in an increased fiber–matrix adhesion.

3.2. Mechanical Properties

3.2.1. Compressive Strength

The compressive loading tests on concretes were carried out on a machine with the capacity 2000 kN. A loading rate of 0.25 kN/s was applied. The results presented in Fig. 4 are averages each for 3 specimens. Comparing with plain concrete, adding steel fibers at 15, 30, 45 and 60 kg/m^3 can increase the compressive strength by 3.2% and decrease by 3.4%, 2.0% and 1.0%, respectively. Addition of steel fibers aids in converting the properties of brittle concrete to a ductile material, generally improving the compressive strength. Earlier work reported a variety of effects of addition of steel fibers on compressive strength — from marginal up to 25% reported by Balaguru and Shah [23]. Our results show effects that are not large. Figure 4 shows that the diagram of the compressive strength as a function of the concentration of steel fibers exhibits a maximum. Apparently, two factors are at play here. Thus, first addition of steel fibers provides a reinforcement. Higher fibers concentrations, however, disrupt the homogeneity of concrete and cause a decrease of the compressive strength. As still more steel fibers included, the reinforcement effect provides a gradual increase of the strength.

Although steel fibers have higher elastic modulus than nylon or polypropylene fibers, irradiated nylon fibers have increased compressive strength of concrete up to 112 MPa; the value depends on the radiation dose applied [24, 25]. Let us compare values of the elongation at break in tensile testing ε_b for a number of polymers and for steel — as discussed in an earlier paper [26]. The value for steel at room temperature is 45.6%; the respective value for polypropylene is 120%. Most other polymers also have ε_b values much higher than steel or aluminum (18.5%). Thus, adaptability to external deformations as represented by ε_b seems to enhance the compressive strength. At the same time and as discussed in [25], irradiation increases the effective surface of the fibers; this apparently enhances the strength of the fiber–concrete interactions in concrete containing polymeric fibers. Kopczynska

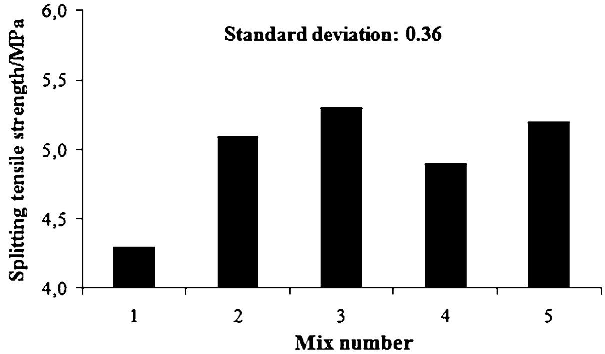

Figure 5. Splitting tensile strength results.

and Ehrenstein [27] have discussed the decisive role of interfaces for properties of composites.

3.2.2. Splitting Tensile Strength

The splitting tensile strength test results for concrete with fibers and without them are presented in Fig. 5.

As seen in Fig. 5, in general there is an increase in splitting tensile strength with the addition of fibers. When compared with plain concrete, splitting tensile strength of fiber-reinforced concrete increases by 18.6%, 23.3%, 14.0% and 21.0% for mixes 2, 3, 4 and 5, respectively. Thus, the increases are significant; the highest value is seen in mix 3. Split tensile strength varies between 8.4% and 10% of 28-day compressive strength of the concrete [28]. There are numerous fibers bridging the microcracks and preventing the expansion. When the tensile stress is transferred to fibers, the transfer can arrest the propagating macrocracks and substantially improve the splitting tensile strength of the concrete.

Crack control plays a crucial role in the performance of concrete in service. The loads may overstress hardened concrete for cracking, leading from cracking to substantial failure in concrete. Thus, incorporation of discrete fibers into vulnerable concrete is useful and effective. The resulting fiber-reinforced concrete exhibits satisfactory resistance to crack formation and propagation.

Figure 6 shows the average ratio between splitting tensile strength and compressive strength. We note that the ratio increases significantly as the fiber volume fraction increases.

3.2.3. Flexural Strength and First Crack Width

The results of flexural strength tests are presented in Fig. 7. As expected, the flexural strength is affected by the fibers significantly. When compared with plain concrete, the flexural strength of fiber-reinforced concrete is higher by 13.1%, 24.2%, 40.6% and 51.7% for mix 2, 3, 4 and 5, respectively. Thus, the highest value is seen in mix 5 which has the highest fiber content. This can be explained as follows. Under center point loading, the concrete prism beam specimen is subjected to bending; hence tensile and compressive strength depend on the distance from the neutral axis

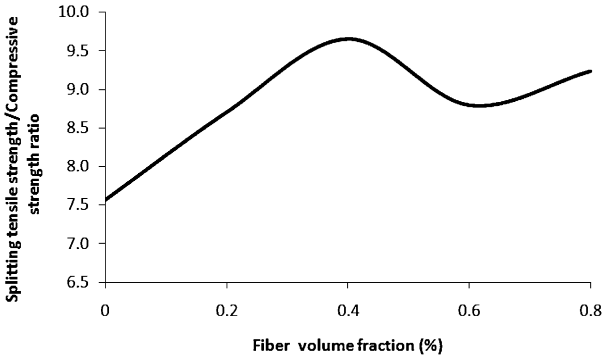

Figure 6. Splitting tensile strength/compressive strength ratio.

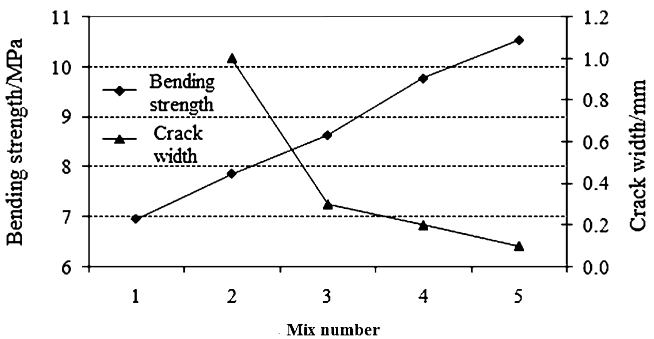

Figure 7. Flexural tensile strengths of concretes and crack widths.

[28–30]. At the failure load, the compressive stress is 6–10% of the compressive strength of the material; hence it is a relatively minor contributor to the failure. By contrast, the flexural stress or strength plays an important role in the failure of the beam. Randomly distributed steel fibers control such cracks and 'stitch' them. Therefore, the presence of the fibers increases the load needed to fail the beam specimen [31]. The higher is the amount of steel fiber in the concrete, the larger is the increase in flexural strength [32].

First crack widths of concretes are presented in Fig. 7. When the first crack occurs in bending, its width is measured with an optical microscope with $\times 400$ magnification. A sudden failure occurred in mix 1, so there is no crack width to report. Exceeding the fiber content of 15 kg/m^3 (mix 2), we observe a sharp decrease in crack width.

3.2.4. Pulse Velocity

The ultrasonic pulse velocities are presented in Fig. 8. The very small variations observed seem to be an indication of the uniformity of concrete matrix in all mixes.

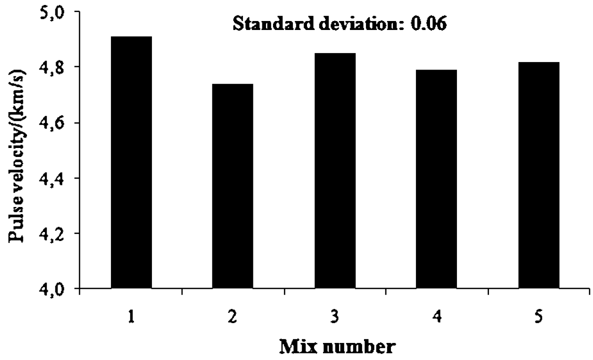

Figure 8. Pulse velocity in concretes.

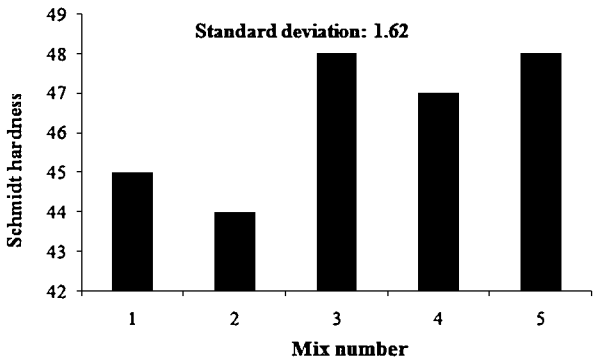

Figure 9. Schmidt hardness results.

3.2.5. Schmidt Hardness

The results of Schmidt hardness tests conducted on concrete samples are presented in Fig. 9. As seen there, when compared with plain concrete, the Schmidt hardness of fiber-reinforced concrete is higher by 6.7%, 4.4% and 6.7% for mix 2, 3, 4 and 5, respectively. Thus, the highest hardness is seen in mix 3 and mix 5.

3.2.6. Elasticity Moduli and Toughness

The moduli of elasticity have been obtained from the stress–strain curves. The values correspond to 40% of the maximum stress. The fibers embedded in the matrix affect both stress and strain, enhancing stress redistribution and reducing strain localization; thus, the ductility of the concrete under load is increased by fiber content. The results are presented in Fig. 10.

One measure of toughness is the energy absorption capacity of the fibers as characterized by the area under the load–deflection curve up to a specific deflection [33, 34]. Several definitions are in use [35]. Fanella and Naaman have defined the toughness of FRC as the ratio of toughness of the fiber-reinforced matrix to that of the unreinforced control matrix [36]. In this study, the toughness was measured as the total area under the stress–strain curve up to a strain of 0.015. That area increases

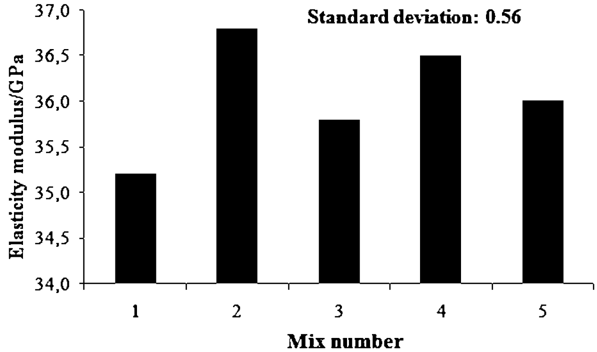

Figure 10. Elasticity modulus of concretes.

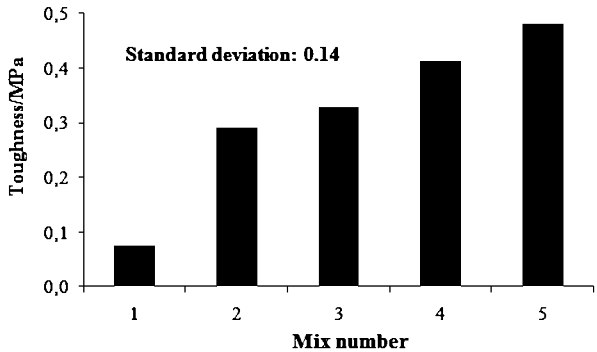

Figure 11. Toughness of concretes.

with the increase in fiber content, as seen in Fig. 11. The figure shows that even for 15 kg/m^3 fiber inclusion into concrete, the toughness is increased dramatically.

4. A Survey of Results

We have evaluated deformability with the slump test. The V-funnel flow test evaluates the ability to achieve smooth flow through restricted spacing without blockage. We had no problems in mixing and the fiber distribution was uniform for all mixtures tested. Although all mixes had good fluidity and exhibited self-compacting characteristics, the flow behavior of steel fiber-reinforced concrete differs from that of plain self-compacting concrete. The fiber inclusion reduced the fluidity, which is the ability of fresh concrete to flow and fill the mold. However, all of the high volume fiber-reinforced mixes exceeded the minimum limits suggested for t_{500} and slump flow required by EFNARC (European Federation for Specialist Construction Chemicals and Concrete Systems). In order to retain high level workability or fluidity with fiber reinforcement, the amount of paste in the mix should be increased to provide better dispersion of fibers. Increasing cement content, increasing fine aggregate content or using pozzolanic and chemical admixtures constitute other options available.

Mechanical properties of concrete can be improved by the addition of steel fibers. However, the improvement in compressive strength does not always increase with a larger content of fibers. In the present study, although concretes including higher fiber content did not have the highest compressive strength, they demonstrated the best ductility under flexural, splitting tensile and compressive loads. Mix 2 has the highest compressive strength value of 58.6 MPa. Especially the effect of steel fiber inclusion in flexural strength was remarkably high at 51.7%. Fibers prevent concrete from a sudden failure since randomly distributed steel fibers bridge internal microcracks and transfer the load by stitching the cracks in the concrete. Thus, concretes with fibers also exhibit better resistance to crack formation. Splitting tensile strength results show an increase of 23.3% for mix 3. The modulus of elasticity was improved only slightly with increasing fiber content. A significant improvement in the energy absorption and ductility in compression is achieved by adding fibers to concrete. The higher is the fiber content, the greater is the toughness.

References

1. H. Okamura and M. Ouchi, Self-compacting concrete, *J. Adv. Concr. Technol.* **1**, 5–15 (2003).
2. B. Persson, A comparison between mechanical properties of self-compacting concrete and the corresponding properties of normal concrete, *Cement Concr. Res.* **31**, 193–198 (2001).
3. X. Youjun, L. Baoju, Y. Jian and Z. Shiqiong, Optimum mix parameters of high-strength self-compacting concrete with ultrapulverized fly ash, *Cement Concr. Res.* **32**, 477–480 (2002).
4. P. Dinakar, K. G. Babu and M. Santhanam, Durability properties of high volume fly ash self-compacting concretes, *Cement Concr. Compos.* **30**, 880–886 (2008).
5. R. Khurana and R. Saccone, Fly ash in self-compacting concrete, fly ash, silica fume, slag and natural pozzolans in concrete, *ACI Mater. J.* **199**, 259–274 (2001).
6. I. B. Topcu and M. Canbaz, Effect of different fibers on the mechanical properties of concrete containing fly ash, *Construct. Bldg Mater.* **21**, 1486–1491 (2007).
7. W. Chalee, P. Ausapanit and C. Jaturapitakku, Utilization of fly ash concrete in marine environment for long term design life analysis, *Mater. Design* **31**, 1242–1249 (2010).
8. D. J. Hannant, *Fiber Cement and Fiber Concrete*. Wiley, Chichester, UK (1987).
9. X. Luo, W. Sun and Y. N. Chan, Characteristics of high performance steel fiber reinforced concrete subject to high velocity impact, *Cement Concr. Res.* **30**, 907–914 (2000).
10. A. R. Bunsell and J. Renard, *Fundamentals of Fibre Reinforced Composite Materials*. Institute of Physics, Philadelphia, USA (2005).
11. I. B. Topcu and T. Bilir, Experimental investigation of some fresh and hardened properties of rubberized self-compacting concrete, *Mater. Design* **30**, 3056–3065 (2009).
12. M. Kakemi and D. Hannant, Effect of autoclaving on cement composites containing polypropylene, glass and carbon fibres, *Cement Concr. Compos.* **18**, 61–66 (1996).
13. P. S. Song, S. Hwang and B. C. Sheu, Strength properties of nylon and polypropylene fiber reinforced concretes, *Cement Concr. Res.* **35**, 1546–1550 (2005).
14. W. Wang, S. Wu and H. Dai, Fatigue behavior and life prediction of carbon fiber reinforced concrete under cyclic flexural loading, *Mater. Sci. Eng. A* **434**, 347–351 (2006).

15. M. Hsie, C. Tu and P. S. Song, Mechanical properties of polypropylene hybrid fiber reinforced concrete, *Mater. Sci. Eng. A* **494**, 153–157 (2008).
16. G. Martínez-Barrera, A. L. Martínez-Hernández, C. Velasco-Santos and W. Brostow, Polymer concretes improved by fiber reinforcement and gamma irradiation, *e-Polymers* **103**, 1–14 (2009).
17. E. A. Bobadilla-Sanchez, G. Martínez-Barrera, W. Brostow and T. Datashvili, Effects of polyester fibers and gamma irradiation on mechanical properties of polymer concrete containing $CaCO_3$ and silica sand, *Express Polym. Lett.* **3**, 615–620 (2009).
18. L. Taerwe and A. V. Gysel, Influence of steel fibers on design stress–strain curve for high-strength concrete, *J. Eng. Mech.* **22**, 695–704 (1996).
19. EFNARC, *Specification and Guidelines for Self-compacting Concrete*, English edn. European Federation for Specialist Construction Chemicals and Concrete Systems, Norfolk, UK (2002).
20. M. Sahmaran and I. O. Yaman, Hybrid fiber reinforced self-compacting concrete with a high volume coarse fly ash, *Construct. Bldg Mater.* **21**, 150–156 (2007).
21. K. H. Khayat, Workability, testing, and performance of self consolidating concrete, *ACI Mater. J.* **96**, 346–354 (1999).
22. S. F. U. Ahmed, M. Maalej and P. Paramasivam, Flexural responses of hybrid steel–polyethylene fiber reinforced cement composites containing high volume fly ash, *Construct. Bldg Mater.* **21**, 1088–1097 (2007).
23. N. Balaguru and S. P. Shah, *Fiber Reinforced Cement Composites*. McGraw-Hill, New York, USA (1992).
24. G. Martinez-Barrera, E. Vigueras-Santiago, S. Hernandez-Lopez, C. Menchaca-Campos and W. Brostow, Concrete reinforced with irradiated nylon fibers, *J. Mater. Res.* **21**, 484–491 (2006).
25. C. Menchaca-Campos, G. Martinez-Barrera, M. C. Resendiz, V. H. Lara and W. Brostow, Long-term irradiation effects on gamma-irradiated Nylon 6,12 fibers, *J. Mater. Res.* **23**, 1276–1281 (2008).
26. W. Brostow and H. E. Hagg Lobland, Brittleness of materials: implications for composites and relation to impact strength, *J. Mater. Sci.* **45**, 242–250 (2010).
27. A. Kopczynska and G. W. Ehrenstein, Polymeric surfaces and their true surface tension in solids and melts, *J. Mater. Ed.* **29**, 325–340 (2007).
28. R. J. Hoyle, Design of composite beams, *J. Mater. Ed.* **6**, 927–938 (1984).
29. M. E. Criswell, Design of columns, *J. Mater. Ed.* **8**, 305–315 (1986).
30. A. M. Neville, *Properties of Concrete*. Wiley, New York, NY, USA (1996).
31. P. K. Mehta, *Concrete, Structure, Properties and Materials*. Prentice-Hall, Englewood Cliffs, NJ, USA (1986).
32. C. D. Atis and O. Karahan, Properties of steel fiber reinforced fly ash concrete, *Construct. Bldg Mater.* **23**, 392 (2009).
33. M. C. Nataraja, N. Dhang and A. P. Gupta, Stress–strain curves for steel-fiber reinforced concrete under compression, *Cement Concr. Compos.* **21**, 383 (1999).
34. Y. Ding and W. Kusterle, Compressive stress–strain relationship of steel fibre reinforced concrete at early age, *Cement Concr. Res.* **30**, 1573 (2000).
35. W. Brostow, H. E. Hagg Lobland and M. Narkis, The concept of materials brittleness and its applications, to appear.
36. D. A. Fanella and A. E. Naaman, Stress–strain properties of fiber reinforced mortar in compression, *ACI Mater. J.* **82**, 475–483 (1985).