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# Effect of fiber type and content on properties of high-strength fiber reinforced self-consolidating concrete

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**Abstract.** Effects of polypropylene (PP) fibers, steel fibers (SF) and hybrid on the properties of high-strength fiber reinforced self-consolidating concrete (HSFR-SCC) under different volume contents are investigated in this study. Comprehensive laboratory tests were conducted in order to evaluate both fresh and hardened properties of HSFR-SCC. Test results indicated that the fiber types and fiber contents greatly influenced concrete workability but it is possible to achieve self consolidating properties while adding the fiber types in concrete mixtures. Compressive strength, dynamic modulus of elasticity, and rigidity of concrete were affected by the addition as well as volume fraction of PP fibers. However, the properties of concrete were improved by the incorporation of SF. Splitting tensile and flexural strengths of concrete became increasingly less influenced by the inclusion of PP fibers and increasingly more influenced by the addition of SF. Besides, the inclusion of PP fibers resulted in the better efficiency in the improvement of toughness than SF. Furthermore, the inclusion of fibers did not have significant effect on the durability of the concrete. Results of electrical resistivity, chloride ion penetration and ultrasonic pulse velocity tests confirmed that HSFR-SCC had enough endurance against deterioration, lower chloride ion penetrability and minimum reinforcement corrosion rate.

**Keywords:** polypropylene fibers; steel fibers; high-strength self-consolidating concrete; mechanical properties; durability

## 1. Introduction

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Concrete technology is one of the fastest growing sectors and also the concrete's versatility, raw materials availability, durability, and economy have made it the world's most used construction material. Therefore, the limited properties of concrete such as flow ability and accessibility in a very narrow gap of reinforcement bars while fresh state; brittleness, weak in tension, shrinkage and crack in harden state have developing considerable research solutions and application.

High strength concrete (HSC) has been found to be more brittle as compared to normal strength concrete (NSC). This weakness is due to the inability of the materials to prevent small cracks from becoming unstable under small tensile stresses (Padmarajaiah and Ramaswamy 2004). Moreover, brittle materials are considered to have no significant post-cracking ductility. When subjected to tension, these unreinforced brittle matrices initially deform elastically. The elastic response is followed by microcracking, localized macrocracking, and finally fractures. Introduction of fibers into the concrete results in post-elastic property changes that range from subtle to substantial (ACI Committee 544 2009). Other studies on fire resistance also have clearly indicated that HSC has lower fire performance as compared to NSC due to strength loss and explosive spalling; however, fibers are often added to overcome the adverse effects of fire induced spalling (Khaliq and Kodur 2011). The addition of fibers on concrete will result in a loss of slump and reduction of workability which is a handicap for on-site applications. Furthermore, for better efficiency the positions of fibers are discontinuous and should be distributed randomly oriented throughout the concrete matrix. The report summarized by Shah *et al*. (2010) show that, the synergy between self-consolidating concrete (SCC) and steel fiber-reinforced concrete (SFRC) technologies may yield several interesting peculiar advantages that can be fruitfully exploited by the construction industry, mainly in the field of precast construction, such as better controlled fiber dispersion, improved fiber-matrix bond, and enhanced concrete durability. Therefore in the current study, the combination between high strength fiber reinforced concrete (HSFRC) and SCC can achieve superior properties in both fresh and hardened states.

The objective of this study is to assess the influence of fibers addition on the properties of high-strength fiber reinforced self-consolidating concrete (HSFR-SCC) for different fiber types (polypropylene fibers, steel fibers and hybrid) and volume contents. Slump depth, slump flow, flow time, unit weight and air content tests were performed to evaluate the workability of fresh concrete. Moreover, the mechanical and durability properties were studied with compressive strength, splitting tensile strength, flexural strength and toughness index, dynamic modulus of elasticity and rigidity, chloride ion penetration, electrical resistivity and ultrasonic pulse velocity.

## 2. Experimental program

### 2.1 Materials

#### 2.1.1 Cementitious materials

In this study, ASTM Type I ordinary Portland cement from Taiwan Cement Company was used as major binder matrix and additional other pozolanic materials of fly ash and slag from China Steel Company, ASTM C1240-03 silica fume from Elkem Materials Company were used to produce SCC. The chemical compositions and physical properties of the cementitious materials used are given in Table 1.

Table 1 Chemical analysis and physical properties of cement and pozzolans

| Items | Cement | Fly ash | Slag | Silica fume |
|---|---|---|---|---|
| Specific gravity | 3.15 | 2.17 | 2.85 | 2.2 |
| Chemical composition (wt%) | | | | |
| $SiO_2$ | 22.01 | 60.58 | 34.86 | 84.04 |
| $Al_2O_3$ | 5.57 | 18.54 | 13.52 | 0.43 |
| $Fe_2O_3$ | 3.44 | 11.39 | 0.52 | 0.71 |
| CaO | 62.80 | 5.24 | 41.77 | 2.01 |
| MgO | 2.60 | 1.67 | 7.45 | 2.87 |
| $Na_2O$ | 0.4 | 0.51 | 1.0 | 0.74 |
| $K_2O$ | 0.8 | 1.23 | - | 6.26 |
| $SO_3$ | 2.1 | 0.58 | 1.88 | - |
| $P_2O_5$ | - | - | - | 1.93 |


Polypropylene Fiber Steel Fiber

Fig. 1 Types of fibers

Table 2 Mixture proportions, kg/m$^3$

| Mix | Type and amount of fiber | | Cement | Slag | Fly ash | Silica fume | Sand | Stone | Fiber | Water |
|---|---|---|---|---|---|---|---|---|---|---|
| | Type | Volume (%) | | | | | | | | |
| PP201500 | - | 0 | 408.83 | 136.28 | 99.91 | 28.19 | 954.48 | 718.34 | 0 | 134.64 |
| PP201505 | PP | 0.5 | 409.97 | 136.66 | 99.08 | 27.95 | 946.60 | 712.38 | 4.5 | 134.73 |
| PP201510 | PP | 1.0 | 411.11 | 137.04 | 98.25 | 27.71 | 938.64 | 706.42 | 9 | 134.82 |
| PP201515 | PP | 1.5 | 412.25 | 137.42 | 97.42 | 27.48 | 930.72 | 700.46 | 13.5 | 134.92 |
| HF201510 | PP+SF | 0.5+0.5 | 411.27 | 137.09 | 98.24 | 27.71 | 938.49 | 706.31 | 43.5 | 134.86 |
| SF201510 | SF | 1.0 | 411.43 | 137.14 | 98.22 | 27.71 | 938.34 | 706.20 | 78 | 134.90 |

### *2.1.2 Aggregates*

Aggregates were provided from local quarries in Taipei city. The maximum size of coarse aggregates used was 12.5 mm (the residue was sieved with a No. 4 mesh) with fineness modulus and water absorption of 6.30 and 1.77% respectively. Whereas the diameter particles used as fine aggregate were 4.75 mm maximum size (the residue was sieved with a No. 100 mesh) with fineness modulus and water absorption of 3.10 and 1.36% respectively. All the natural aggregates used for this study were in the dry form.

### *2.1.3 Fibers and chemical admixture*

Two types of fiber were used in the investigation: polypropylene (PP) and steel fibers (SF) as shown in Fig. 1, additionally a hybrid fiber (HF) which is a blend of PP and SF were used for better understanding of the effect of fibers. The physical properties of polypropylene fibers had a shape of chain-type with a length of about 46mm and aspect ratio (L/D) of 40 ~ 45. The steel fiber used also had a shape of both ends bent hook-type which is confirmed to ASTM A820 requirements with a length of 30mm and aspect ratio (L/D) of 50 ~ 60. Type G superplasticizer, having 43% solid content with specific gravity of 1.06 ± 0.02, was used to achieve the desired workability. The mixing water was tap water. All materials conform to the related ASTM standards.

## *2.2 Mix proportions*

The concrete mix design in this study has been followed according to the densification theory, which is a combina tion of both densified mixture design algorithm (DMDA)(Hwang and Hung 2005, Chang 2004) and Fuller's ideal gradation curves, to enable full packing with all solid particles from millimeter size (aggregates) to nano-particle size (silica fume). Hwang *et al*. (2012) also researched the application and advantages of this concrete design method. Total six samples of mixture proportions were designed as shown in Table 2 with 0.20, 0.33 and 15μm constant proportion of water-to-binder ratio, water-to-cement ratio and coating thickness of lubricating paste respectively. The amount of fibers added were calculated by total volume of concrete: PP fibers varied from 0% to 1.5% (i.e., specimen notation from PP201500 to PP201515); similarly, the steel fiber (SF201510) and hybrid fiber (HF201510) samples were designed only with 1% volume addition. In order to optimize the densified solid particles in the concrete; the stone, sand, fly ash, slag, and silica fume were proportioned based on their particle size distribution. Moreover, for better durability endurance of the concrete, the amount of water used in the mix was minimized and limited only for cement hydration with help of superpalsticizer.

## *2.3 Testing program*

The workability of the concrete was measured mainly by slump flow test according to ASTM C1611, which is the simplest and most commonly adopted test method for evaluating the flowability of SCC quality. According to Naik *et al*. (2012), measurement of slump-flow also determines the consistency, cohesiveness and capability of concrete to deform under its own weight with no other external resistance present. And further more it can also give an indication of filling ability and susceptibility to segregation of the SCC. Therefore, the slump and slump flow spread of concrete in this study were controlled to 250−280 mm and 600−750 mm respectively in order to meet the requirement of SCC (Domone 2006). Moreover, the air content and unit weight of the concrete were measured for better understanding while in its fresh state. And then after casting the specimens were cured in saturated limewater at the temperature of 23 ± 2℃.

The test programs on harden concrete had broadly investigated on both the mechanical strength and durability properties. The test for mechanical strength properties of axial compressive strength, splitting tensile strength, and dynamic modulus of elasticity and rigidity were examined based on ASTM C39, ASTM C496 and ASTM C215 respectively by prepared a cylindrical specimen of Ø100 mm × 200 mm height. In addition, in the standard reference as per the recommendation of American Concrete Institute (ACI) 544 report (ACI Committee 544 2009), two beam specimens with a dimension of 150 mm (width) × 150 mm (depth) × 500 mm (length)

3. Summary of HFDMDA Mix design procedure:

**1. Material Selection**

**2. Select Maximum Aggregate size, $D_{max}$**

**3. Calculate volume proportion ratio of blended materials**

***i.*** *Apply Fuller's curve*

$$P = 100\left(\frac{d}{D_{\max}}\right)^{h} \quad \text{where} \quad h = \frac{1}{3} \sim \frac{1}{2}$$

***ii.*** *Determine optimal blended volume ratio*

*i.e. Coarse aggregate : Sand : Fly ash*

**4. Decide best aggregate densified structure**

***i.*** *Power law (**h**) under Fuller's curve*

***ii.*** *Choose best dry loose density, $U_{max}$*

**5. Determine the least void, $V_v$**

***6. Estimate total surface area of blended aggregates, S***

***7. Design the amount of each constituent***

***i.*** *Select w/b ratio based on Strength and Durability*

***ii.*** *Lubricating cementing paste,* $V_p = V_v + S \times t$

*i.e. Amount of Cement, Fly ash, Slag, Silica fume and water*

***iii.*** *Volume of aggregate,* $V_{agg} = 1 - V_p$

***8. Trial Batch***

***i.*** *Adjust water content*

***ii.*** *Adjust mixture proportion*

Table 3 Properties of fresh concretes.

| Specimen No. | w/b | SP % | Fresh properties | | | Unit weight (kg/m$^3$) | Air content (%) |
|---|---|---|---|---|---|---|---|
| | | | Slump (mm) | Slump flow (mm) | Flow time (s) | | |
| PP201500 | 0.20 | 2.7 | 280 | 740 | 165 | 2458 | 1.95 |
| PP201505 | 0.20 | 2.7 | 280 | 700 | 180 | 2445 | 1.97 |
| PP201510 | 0.20 | 3.5 | 270 | 650 | 150 | 2443 | 2.64 |
| PP201515 | 0.20 | 3.5 | 270 | 620 | 270 | 2429 | 2.95 |
| HF201510 | 0.20 | 3.3 | 260 | 630 | 280 | 2479 | 2.25 |
| SF201510 | 0.20 | 3.69 | 265 | 680 | 240 | 2481 | 2.34 |

were prepared for the flexural strength and toughness index tests. On the other side, the tests for concrete durability properties of ultrasonic pulse velocity (UPV), chloride ion penetration and electrical resistivity were carried out according to ASTM C597, ASTM C1202 standards and four-point Wenner array probe test method respectively. The electrical resistivity test was used to measure the surface resistivity of water-saturated cylinders concrete specimen of Ø 100 × 200 mm and provide an indication of its permeability. The test result is a function of the electrical resistance of the specimen. Ramezanianpour *et al*. (2011) indicted that the Wenner array probe resistivity technique is a promising alternative test to characterize the chloride penetration resistance of concrete.

## 3. Results and discussion

### *3.1 Workability*

The test results of the fresh HSFR-SCC are summarized in Table 3. Since the study applied different type and dosage of fibers, then different amount of Superplasticizer (SP) was required to achieve good flowing concrete workability. The amount of SP used to the mix is reported here as the percentage of the total cementing materials used. The slump flow experimental results showed that the fiber reinforced concrete has a decreasing trend when the fiber volume dosage rate increases. The average diameter of slump flow for the control concrete (PP201500) was obtained 740mm, but even if used more SP for better workability, the addition of fibers of PP, HF and SF the slump flow dropped to 620 mm, 630 mm and 680 mm respectively. This result also corresponds to the study reported by El-Dieb and Reda Taha (2012); the inclusion of both steel and polypropylene fibers has a direct effect on the flow characteristics of SCC, as a result , the flow characteristics decrease proportionally with increasing the fiber volume. Similarly, Khayat and Roussel (2000) found that the relationship between the restricted flow capacity and slump flow is dependent on the fiber volume, consequently the result shows the increase in fiber volume had a significant impact on restricted flow properties. However, as we can see in Table 3, with the help of superplasticizer the workability of all mixtures of HSFR-SCC was controlled within the slump flow of 620–740 mm that can satisfy the requirements for SCC. The slump depth and slump flow time were obtained in the range of 260–280 mm and 150–280sec respectively.

For better understanding on the properties of fresh concrete of HSFR-SCC the unit weight and air content measurements were also carried out as presented in Table 3. The results indicate that for the PP fiber addition, the unit weight of concrete decreased continuously with the increase in fiber content. Whereas in both the steel and hybrid fiber additions, the unit weight of HSFR-SCC was higher than that of the control concrete. This is due to the fact that the specific gravity of steel fibers is higher than that of other concrete components. The fresh air content of the HSFR-SCC varied between 1.95–2.95%. Generally, as the amount of SP and fiber content increases the entrapped air voids also increase. In addition, the utilization of more than 2.5% of SP in the mixes would induce too many air bubbles into the mix (Mazaheripour *et al*. 2011).

### *3.2 Compressive strength*

Behavior of concrete in uniaxial compression was studied at curing ages of 3, 7, 28, 56 and 91 days and the results obtained are reported in Fig. 2. The influence of PP fibers on compressive strength as present in Fig. 2a, the results show that there were some improvements of compressive strength with addition of PP fibers at the early ages but after 28 days the compressive strength of HSFR-SCC reduced around 5% in comparison to that of concrete without PP fibers. The addition of PP fibers aids in converting the brittle properties of concrete into a ductile material. According to some researchers test results (Khaliq and Kodur 2011, Mazaheripour *et al*. 2011, You *et al*. 2011), polypropylene fibers do not have any impact on compressive strength of the material. In addition, Boulekbache *et al*. (2010) studied that the presence of fibers in concrete has reduced the compression strength by around 7% for ordinary fiber-reinforced concrete, 6% for fiber-reinforced self-consolidating concrete and 10% for high-strength fiber reinforced concrete. They concluded with an idea of the mechanical role and beneficial uses of fibers were activated only after the appearance of cracking, particularly at the post-peak stage.

Fig. 2b shows the effect of steel and hybrid fibers on compressive strength. The test result

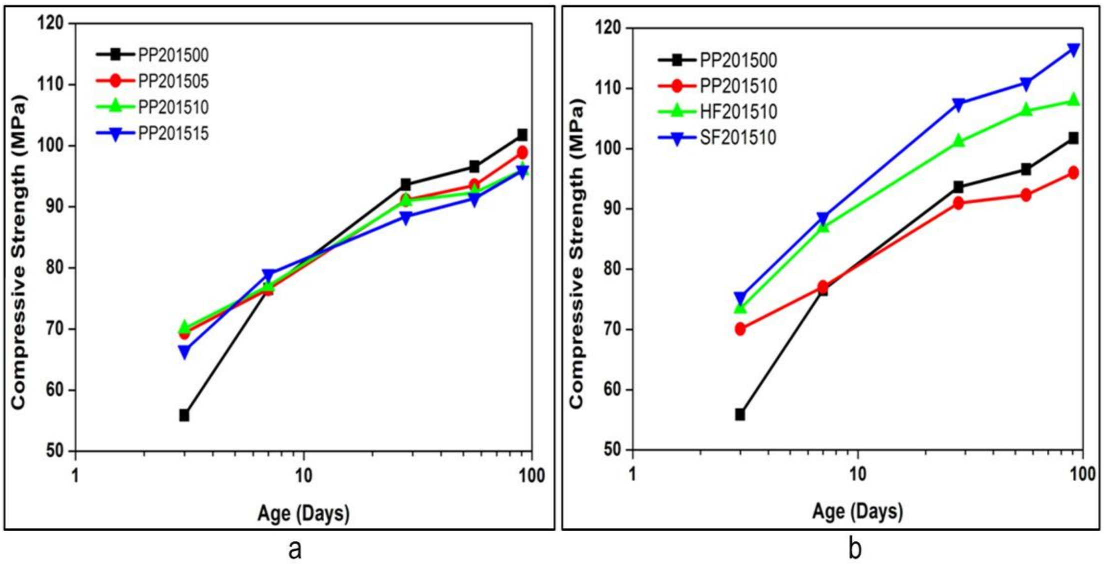



Fig. 2 The development of compressive strength of concretes with ages under: (a) different volume fractions of PP fibers and (b) different types of fibers

illustrated the addition of steel fibers had a positive effect at all ages of the concrete. At early ages of 3 days the average compressive strength of both steel fiber (SF201510) and hybrid fiber (HF201510) had 30% much higher than the control concrete (PP201500). Similarly at later ages of 91 days still the HSFR-SCC showed 14% and 6% higher strength than the control for the steel and hybrid fibers respectively. Therefore, addition of steel fibers or making hybrid fibers has better effect on the compressive strength, minimizes crack propagation and in general improves the ductility of high strength concrete.

### *3.3 Splitting tensile strength*

Splitting tensile strength tests were carried out in order to investigate the tensile strength properties of HSFR-SCC as shown in Fig. 3. Test results in Fig. 3a indicated that the addition of polypropylene fibers to concrete increased the splitting tensile strength at all ages and also prevented the specimen cylinder from rupturing at the ultimate loading. At early ages the higher fiber addition would be the better result on splitting strength of the concrete but at the later ages it becomes lower. In general, added polypropylene fibers could increase the tensile behavior of high strength SCC by more than 17% at the age of 91 days. However, the inclusion of steel fiber or making hybrid the polypropylene fiber with steel fiber was obtained much better result. As Fig. 3b shows, the splitting tensile strength at the age of 91 days for the steel and hybrid fibers was increased by more than 25% and 21% respectively as compared with the control concrete. The study by Khaliq and Kodur (2011) also strengthened the current result: the addition of polypropylene fibers can increase tensile strength of SCC and the rate is enhanced based on the volume percentage of the fabrics. Similarly, Mazaheripour *et al*. (2011) concluded that tensile strength of steel fiber reinforced high strength concrete was significantly higher; which was attributed to effectiveness of steel fibers in bridging the cracks under tensile loading.

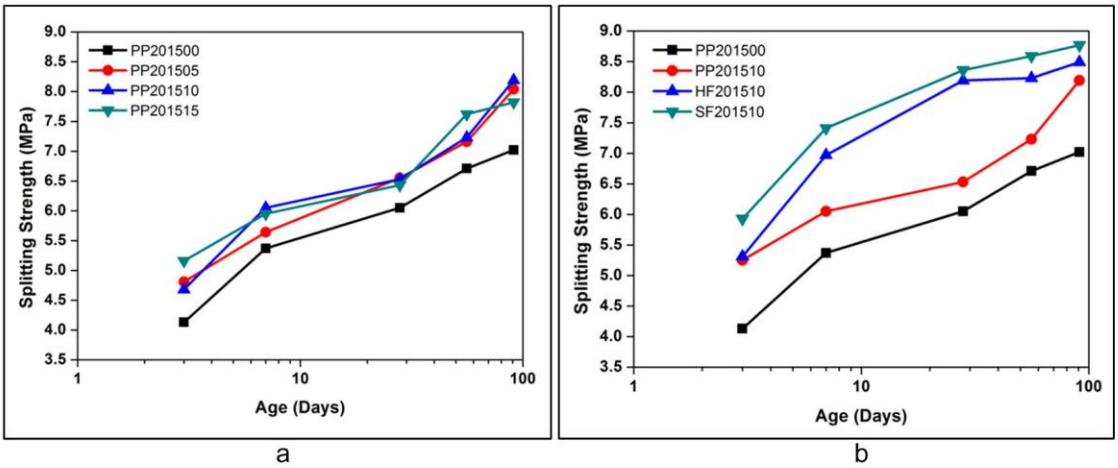



Fig. 3 The development of splitting tensile strength of concretes with ages under: (a) different volume fractions of PP fibers and (b) different types of fibers

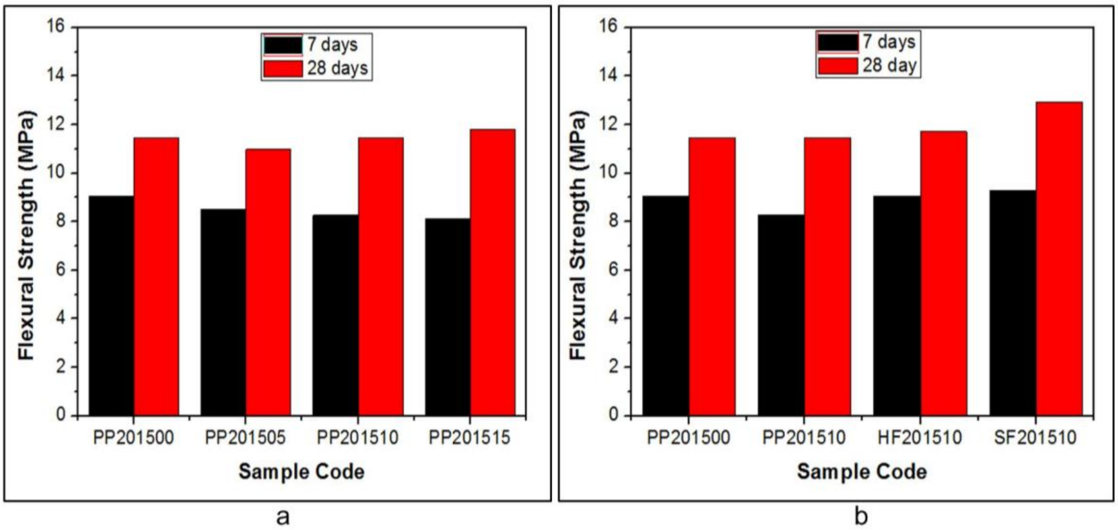



Fig. 4 The development of flexural strength of concretes at 7 days and 28 days under: (a) different volume fractions of PP fibers and (b) different types of fibers

### *3.4 Flexural strength and toughness*

Generally, fiber reinforced concrete development is hindered by a general lack of confidence in its design, particularly for flexural loads. This is mainly due to the result of a lack of appropriate analytical design methods associated with material property tests which measure approximate flexural toughness (or strength) parameters (Robins *et al*. 2002). Similarly, the report of ACI (ACI Committee 544 2009) shows that since many researchers obtain different results, there is no consensus in the published literatures about the effect of adding polypropylene fibers on the first-

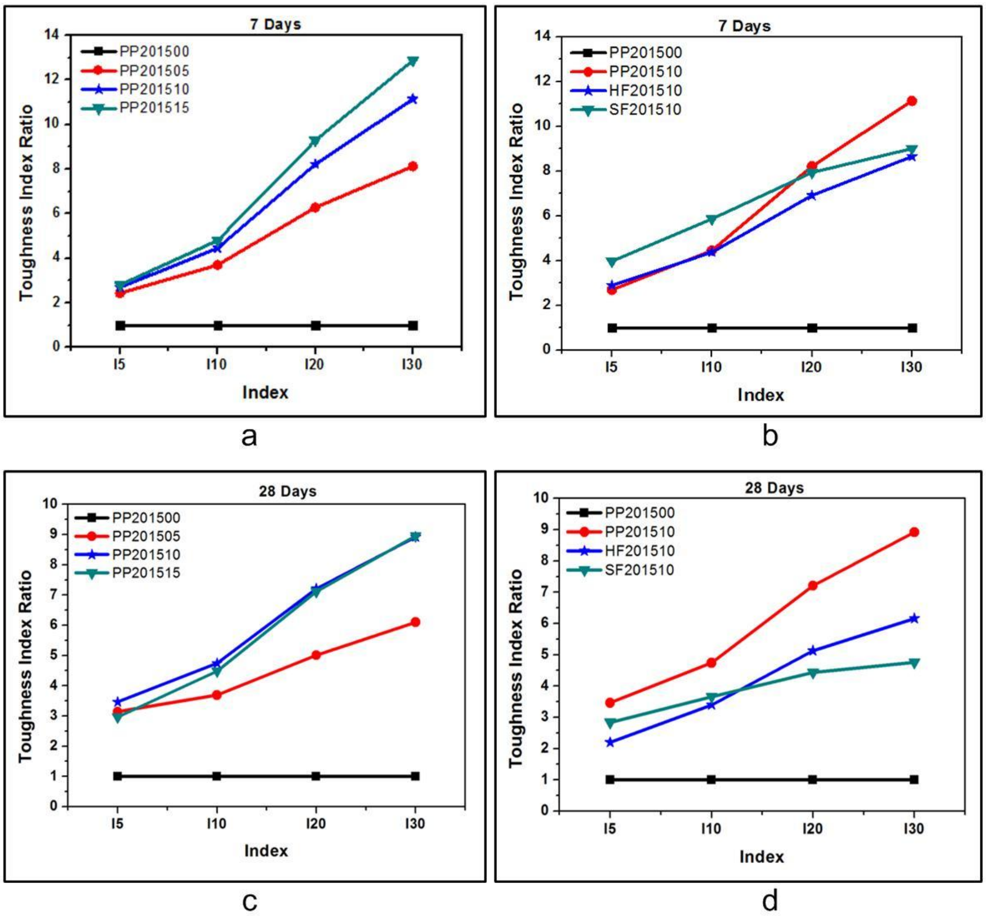



Fig. 5 The development of flexural toughness of concretes: (a) and (c) at 7 and 28 days for different volume fractions of PP fibers, (b) and (d) at 7 and 28 days for different types of fibers

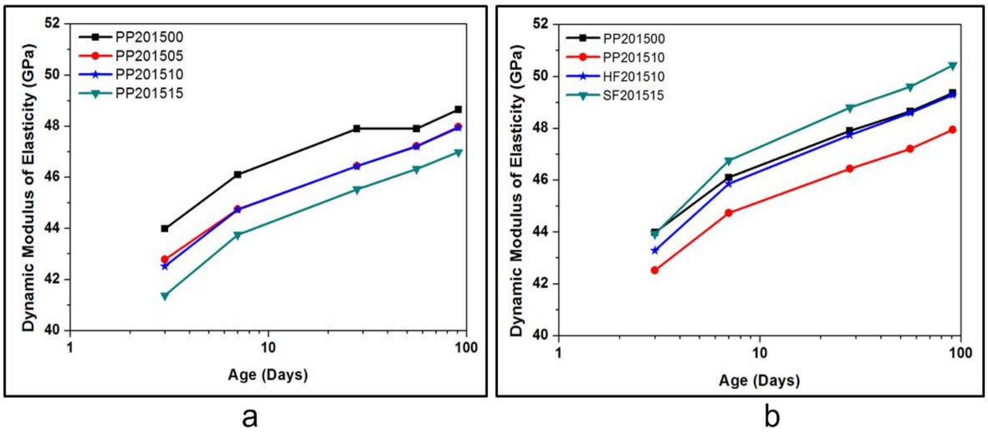



Fig. 6 The development of dynamic modulus of elasticity of concretes with ages under: (a) different volume fractions of PP fibers and (b) different types of fibers

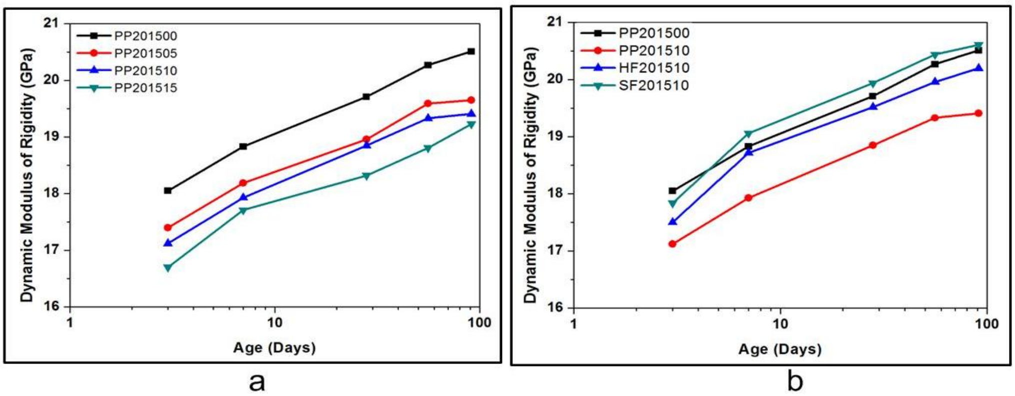



Fig. 7 The development of dynamic modulus of rigidity of concretes with ages under: (a) different volume fractions of PP fibers and (b) different types of fibers

crack strength and modulus of rupture. Therefore, in this study it was tried to investigate the toughness index properties of HSFR-SCC in addition to the direct flexural strength or modulus of rupture.

Flexural behavior of concrete was studied at curing ages of 7 and 28 days and the results are reported in Fig. 4. The results obtained in Fig. 4a showed that the effectiveness of polypropylene fibers was insufficient in improving the flexural behavior of concrete. At the early ages there was a reduction in strength but at later ages of 28 days the flexural behavior was obtained some improvement. On the other hand, in Fig. 4b the addition of steel fibers showed a better performance in the flexure with respect to both the reference mixtures without fibers and with polypropylene fibers. The hybrid fiber (HF201510) also can be a good example for the flexural strength improvement with help of steel fiber both at early and later ages of concrete.

Fig. 5 shows the result obtained while measuring the ductility behavior of HSFR-SCC in terms of toughness indexes. As the result shown in Figs. 5a and b, the behavior of toughness at the early age of 7 days, the specimens without fibers or control concrete were failed immediately after first cracking. Consequently, the ductility index for the concrete is equal to 1. Toughness index ratios increased with increasing polypropylene fibers content at all indexes, especially the higher fiber addition the better toughness strength. However, the addition of both polypropylene and steel fibers was resulted a dramatic improvement in an I30 index, which increased up to 13 and 8 respectively. Similarly, in Fig. 5c and d, the 28 days age toughness behavior of the HSFR-SCC still showed great achievement but lower value than the early age results, due to the high strength concrete development properties. In this study the results showed that polypropylene fibers had better efficiency in the improvement of ductility or toughness than steel fibers; but in general, addition of fibers in the concrete increases the behavior in bending, reduced the crack width, delayed the final crushing of concrete, and as a result it can make worthwhile and structurally interesting material. The studies by Mariano and Buyukozturk (1994) and also Boulekbache *et al*. (2010) obtained similar results and supported with conclusion of: a cracked concrete continues to support further increases in loading without worsening the crack width through fiber crack stitching and through the deformation of the fibers, which causes increased crushing and splitting of the matrix. At the final stage, failure is very ductile and soft since most of the energy is absorbed by the deformed fibers.

### 3.5 Dynamic modulus of elasticity and rigidity

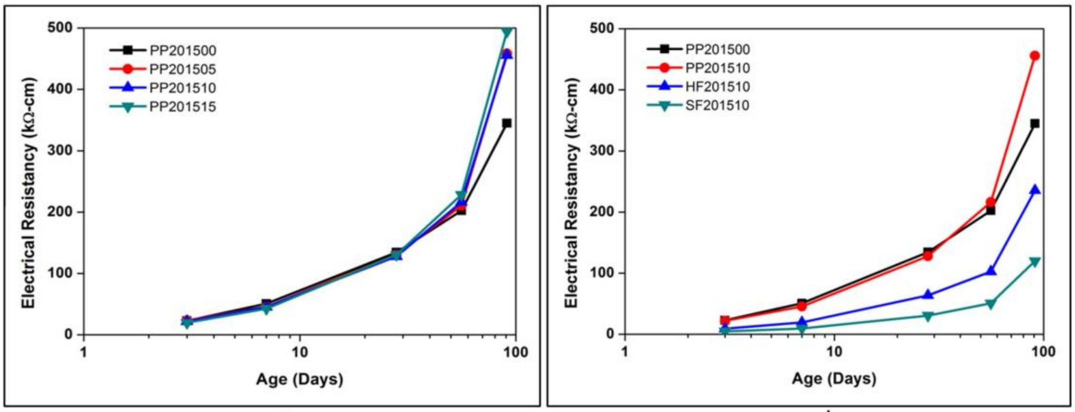
In the measurement of modulus of elasticity, a nondestructive technique of dynamic modulus of elasticity (ASTM C215) is most widely used and can successfully replace the standard in destructive methods (ASTM C469) due to simplicity, time consuming and possibility to evaluate a concrete as soon as cement hydrates (Cornelia Magureanu 2012, Habib A. Mesbah 2002, Hansen 1986). Therefore, the modulus of elasticity for the HSFR-SCC was investigated based on dynamic method and results shown in Fig. 6. From the test results in Fig. 6a the dynamic modulus of elasticity was 48.65 and 46.98GPa for the concretes without fibers and with 1.5% addition of polypropylene fibers respectively. In general, it was found that the modulus of elasticity decreased when polypropylene fibers were added to the concrete. However, the inclusion of steel fibers was increased the modulus of elasticity of concrete as presented in Fig. 6b. Since the modulus of elasticity is usually expressed as a function of compressive strength, many authors have investigated the relationship between them. Hansen (Hansen 1986) has studied and generated relationships between dynamic modulus using the resonant frequency method and compressive strength. Similarly, in this study the same results were obtained, the addition of polypropylene fibers decreased the properties of both compressive strength and dynamic modulus of elasticity especially at later ages. In the contrary, the addition of steel fibers increased both properties as discussed above.

Fig. 7 shows the test results for the dynamic modulus of rigidity. The addition of high dosage of polypropylene was obtained a significant reduction in the rigidity of concrete but steel fibers increased slightly.

### 3.6 Electrical resistivity and Chloride ion penetration

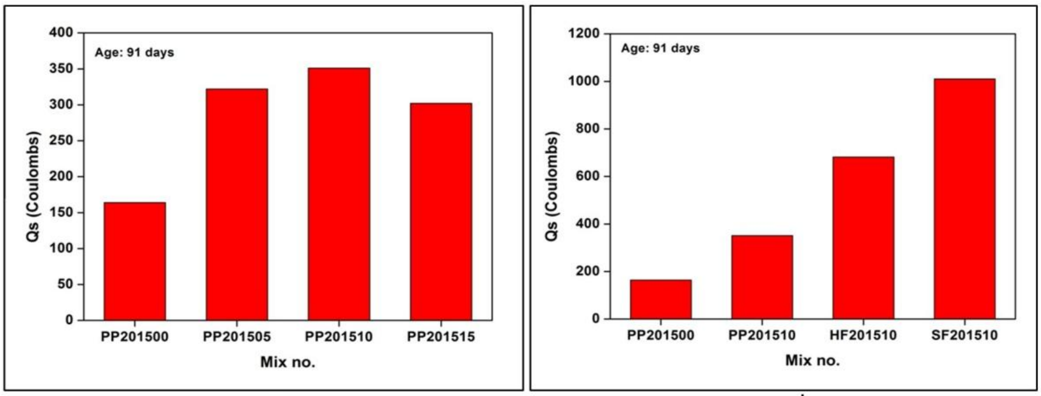
The effectiveness of improving mechanical properties of concrete, such as addition of fibers, should have followed by the assurance of concrete durability. The presence or penetration of soluble chlorides can cause deterioration of concrete, further leads to corrosion of reinforcements and steel fibers. Nowadays a great deal of attention has been paid to research and development of sustainable concretes. Therefore, in this study durability tests of electrical resistivity, ultrasonic pulse velocity and chloride ion penetration were done. Theoretical and experimental studies have indicated a correlation between concrete resistivity and chloride ingress; the chloride diffusion coefficient is inversely proportional to the concrete resistivity. Within a particular structure, more permeable zones will have a comparatively lower resistivity and higher chloride penetration (Ramezanianpour *et al*. 2011).

Hornbostel *et al*. (2013) *summarized* different literature reviews on the relationship between concrete resistivity and corrosion rate. Even though the electrical resistivity threshold values for reinforcement corrosion resistance observed by different literatures have a high variation but the upper limit of 100–200 kΩ.cm can be identified from the all comparisons over which the reinforcement corrosion rate will be very low. Fig. 8a indicates that the addition of polypropylene fibers had no improvement at the early ages but at later ages it was increased up to 344.75 and 494.38 kΩ.cm for the concretes without fibers and with 1.5% polypropylene fibers dosage respectively. Similarly in Fig. 8b, the addition of 1.0% of steel fibers decreased the electrical resistivity to 120 kΩ.cm, which is a significant reduction more than 65% as compared with the concrete without fibers. However, the reduction of electrical resistivity for steel fibers reinforced concrete is highly affected due to conductivity of the steel fibers. This indicates that the steel fibers




a b

Fig. 8 The development of electrical resistivity of concretes with ages under: (a) different volume fractions of PP fibers and (b) different types of fibers




a b

Fig. 9 Chloride ion penetration results of concretes at 56 days under: (a) different volume fractions of PP fibers and (b) different types of fibers

were conducting when measuring the electrical resistivity and the results will be underestimated. The result obtained in this study is in line with the experimental reported by Solgaard *et al*. (2013) and Tsai *et al*. (2009), the electrical resistivity was reduced more than 50% for an addition of 1.0% of steel fibers. Therefore the reduction in electrical resistivity for steel fibers reinforced concrete is as expected decreased but still the result obtained in this study satisfy the requirement for best reinforcement corrosion resistance limit discussed above.

The test results of chloride ion penetration on 91-day water cured specimens are shown in Fig. 9. The total transferred charge between the NaCl and NaOH cells with electrical potential of 60 V in 6 h was in the range of 100-1000 coulombs. The significant increment on chloride ion penetration of concrete having the steel fiber added probably has the same reason as discussed above on electrical resistivity test due to the conductivity effect of the steel fibers. However, according to the ASTM C1202-12 standard classification, the qualitative indications of the chloride ion penetrability of all the concretes produced in this study are classified as “very low” chloride permeability concretes.

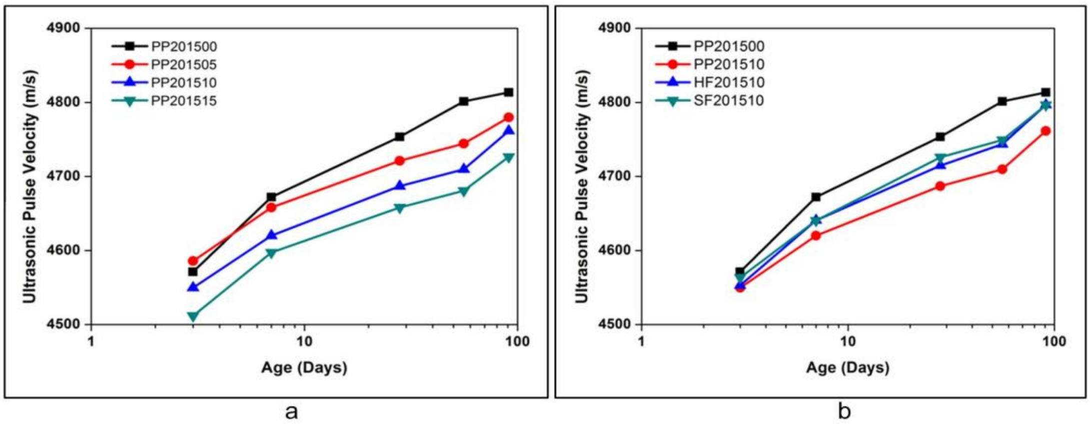



Fig. 10 The development of ultrasonic pulse velocity of concretes with ages under: (a) different volume fractions of PP fibers and (b) different types of fibers

### *3.7 Ultrasonic pulse velocity*

Measurement of ultrasonic pulse velocity (UPV) is means of assessing different properties of concrete in non-destructive technique. So far, UPV has been used for estimating concrete strength through detecting internal defects of voids and cracks. As an example Yiching Lin *et al*. (2007) developed UPV and strength relation curves, which were verified to be suitable for prediction of hardened concrete strength with a measured UPV value. Nowadays, an ultrasonic test has been also developed for non-destructive durability assessment based on correlations established between UPV, porosity and permeability (Lafhaj *et al*. 2006).

The UPV test result for the HSFR-SCC in this study is presented in Fig. 10. The UPV results as shown in Fig. 10 a support the findings in compressive strength test. It is clearly shown that the higher the addition of polypropylene fibers the lower the results observed by the UPV and similarly the lower compressive strength result confirmed as discussed above. In the case of steel fibers addition, Fig. 10b, even though the result from UPV showed the concrete without fibers had higher values but the addition of steel fibers was more effective than the polypropylene fibers, which is still in line with the result obtained by compressive strength. In general based on the UPV result obtained in this study, the additions of both steel and polypropylene fibers have some negative effects on the durability of the concrete.

However, the 91-day UPV of all concrete mixtures were above 4500 m/s. The review paper of Carino (1994) introduced a tentative classification of using pulse velocity as an indicator of quality published by Whitehurst (1951). Based on the tentative classification a concrete can be grouped as excellent, good, doubtful, poor and very poor for UPV values of 4500 m/s and above, 3500−4500, 3000−3500, 2000−3000, and 2000 m/s, respectively. Therefore, all concretes produced were classified as excellent as all results of UPV were greater than 4500 m/s.

## 4. Conclusions

In this study the effects of polypropylene fibers, steel fibers and hybrid on the properties of high-strength fiber reinforced self-consolidating concrete under different volume contents were investigated. Based on the studies and results the following conclusions can be drawn:

- The fibers reinforced concretes have showed a decreasing trend on workability when the fibers volume dosage rate increased but the workability of all mixtures of HSFR-SCC was controlled within the slump flow of 620– 740 mm that can satisfy the requirements for SCC.
- The addition of PP fibers showed the decrease in the compressive strength but the increase in the splitting tensile behavior of HSFR-SCC by more than 17% at the age of 91 days. However, the addition of steel fibers had significant improvements on both compressive and splitting tensile strengths. The dynamic modulus of elasticity test showed that, the same results as compressive strength test were obtained for both PP and steel fibers additions. The addition of high dosage of PP fibers was obtained the significant reduction in the rigidity of concrete but steel fibers increased slightly. Similarly, the additions of PP and steel fibers had some improvement on the flexural strength whereas the toughness behavior showed dramatic improvement for both fiber types. In general, addition of fibers in the concrete increased the behavior in bending, reduced the crack width, delayed the final crushing of concrete but the specimens without fibers or control concrete were failed immediately after first cracking.
- The durability test results from electrical resistivity and ultrasonic pulse velocity showed that all designed HSFR-SCC have enough endurance against deterioration of concrete and penetration of any foreign soluble chemicals, and then the reinforcement corrosion rate would be very low. In the same way, the qualitative indications of the chloride ion penetrability for all concrete samples conducted in this study were classified as “very low”.

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