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Experimental investigation of steel fiber effects on anti-penetration performance of self-compacting concrete

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Abstract. Steel fiber reinforced self-compacting concrete (SFRSCC) has good workability such as high flowability and good cohesiveness. The workability, compressive strength, splitting tensile strength, and anti-penetration characteristics of three kinds of SFRSCC were investigated in this paper. The fraction of steel fibers of the SFRSCC is 0.5%, 1.5% and 2.0% respectively. The results of the static tests show that the splitting tensile strength increases with the increase of fraction of steel fibers, while the compressive strength of 1.5% SFRSCC is lowest. It is demonstrated that the anti-penetration ability of 1.5% SFRSCC subjected to a velocity projectile (200-500 m/s) is better than 0.5% and 2.0% SFRSCC according to the experimental results. Considering the steel fiber effects, the existing formula is revised to predict penetration depth, and it is revealed that the revised predicted depth of penetration is in good agreement with the experimental results. The conclusion of this paper is helpful to the experimental investigations and engineering application.

Keywords: anti-penetration; mechanical performance; self-compacting; steel fiber

1. Introduction

In the protection design of military facilities and civil applications, suppressing missile perforation failure is usually considered as a priority. At the same time, maximizing human safety and minimizing property damage in the event of concrete scabbing are a priority for general infrastructure design. Steel fiber reinforced self-compacting concrete (SFRSCC) has good workability such as high flowability and good cohesiveness, which can pass through the obstacles, wrap up the steel bars, and get to the right place without any mechanical vibration. Therefore, it is very necessary to use steel fiber in self-compacting concrete (SCC), which can significantly reduce brittle fracture and suppress the missile perforation failure propagation. Different types, aspect ratios and volume fractions of steel fiber commonly used in SCC were discussed by Al-Rawi and Taysi (2018) and Ding *et al*. (2019). The workability and mechanical properties of steel fiber reinforced self-compacting concrete (SFRSCC) were compared and analysed under various loads (Li *et al*. 2020a, Mohamed *et al*. 2019, Iqbal *et al*. 2015). SFRSCC has a significant improvement in the resistance and energy absorption capacity especially under the impact loads and blast loads (Mahakavi and Chithra 2019, Zhang *et al*. 2017, Zarrin and Khoshnoud 2019). The steel fibers are considerably efficient to enhance the stress transfer capability beyond elastic state and improve the energy absorption capacity (Soufeiani *et al*. 2016). However, the steel fibre reinforcement is greatly dependent on the fibre content and shape (Wu *et al*. 2016). Li *et al*. (2020b, 2018) investigated the influence of key parameters (i.e., steel fibre type and dosage, matrix strength, coarse basalt aggregates, and target thickness) on in-service bullet impact resistance of UHPFRC. Feng *et al*. (2019a, b) found that the mechanical strengths of UHPFRC are influenced by the steel fibre types and contents, thus affecting the impact resistance. With the rapid development of conventional lethal weapons, the penetration of various types of projectiles into fiber reinforced concrete targets is still a hot issue at present according to Gülşan *et al*. (2019).

The anti-penetration tests were carried out on concrete slabs with different steel fiber content. Tai (2009) have studied that the area of damage zone can be reduced by about 50% with increasing 1% steel fibers. Because the impact resistance is mainly determined by the toughness and fracture energy, which are related to steel fiber content, the damage of the target decreases with the increase of the steel fiber volume, and the range of the damage area decreases with the increase of the steel fiber content. By adding different content of steel fibers, high strength concrete with good ductility was designed, so that the back of the wall does not collapse to the maximum extent and can prevent penetration (Cánovas and Gaitan 2012). Sovják *et al*. (2015) and Máca *et al*. (2014) carried out several impact tests of ultra-high performance fiber reinforced

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concrete (UHPFRC) plates with different fiber contents. The results showed that the steel fiber content significantly improved the impact resistance of the target to the deformed projectile. It was also pointed out that the sample with 2% fiber content had the best resistance to impact loads. Almusallam *et al*. (2013) and Wang *et al*. (2016) have studied the impact resistance of steel fiber and hybrid fiber concrete. The hybrid fiber in concrete reduced the volume of crater and spalling damage and prevents the development of cracks. Wu *et al*. (2015a, b) carried out a series of penetration experiments of high-speed projectiles (500-1320 m/s) against SFRC targets, and proposed a method for predicting the ballistic limit of steel fiber reinforced high-strength concrete. Yu *et al*. (2016) and Prakash *et al*. (2017) have studied the improvement of mechanical properties of UHPFRC by different kinds of steel fibers. Under the impact of high-speed projectile, hybrid fiber concrete has better energy absorption effect than single end-hook steel fiber concrete. Lovichov *et al*. (2017) studied the effect of casting target plates on the penetration of steel fibers under different directions with transparent viscous liquid based on ultrasonic gels, and most of the components perpendicular to the bullets had higher penetration resistance. Experimental studies on penetration of SFRC under different water cement ratios are carried out by Nili *et al*. (2016). Lee *et al*. (2018) conducted penetration tests on steel fiber reinforced concrete plates with different warhead shapes, and studied the impact of steel wire mesh and polymer on the penetration effect. It is shown that the scope of research is gradually expanding, and more materials or structures with superimposed anti-penetration effect with steel fiber have been tried to study (Liu *et al*. 2017, Zhang *et al*. 2007). A series of anti-penetration experiments were conducted on steel fiber reinforced concrete (SFRC), but the research on the anti-penetration performance of SFRSCC is less.

At present, in the study of material response under impact and penetration, the measurable evaluation quantities such as penetration depth, crater size and collapse damage level are still the most concerned, which are related to the velocity, volume shape and material properties of the impact penetrator. The relationship between them is mostly given by empirical and semi-empirical formulas (Yarin *et al*. 1995, Xu *et al*. 1997, Chen and Li 2002, Li and Chen 2003, He *et al*. 2011). Since the last century, a large number of empirical and semi-empirical formulas have been developed, such as the Berezan formula of the former Soviet Union, the Army Corps of Engineers formula (US Army 1986), the Young formula of the Sandia National Laboratory (Young 1997), and so on, as well as the revised or newly proposed formulas considering more factors on their basis by Li *et al*. (2005). However, no enough attention has been paid to the effect of steel fiber on anti-penetration performance of SFRSCC.

This paper mainly discusses the influence of steel fibers on rheological properties, mechanical properties and anti-penetration characteristics of SFRSCC, and the existing formula was revised to predict the penetration depth of projectile to SFRSCC targets. The rheological properties of SFRSCC are tested by the Abrams cone and L-box. The uniaxial compressive strength and tensile strength are tested by the hydraulic universal testing machine. The penetration depth formula is derived on the basis of the assumption that the mean resistive pressure consists of three parts: quasi-static resistive pressure due to the elastic-plastic deformations, dynamic resistive pressure arising from velocity effects and the effect of steel fibers. The computed results of the revised formula are compared with the experimental results.

2. Material composition of SFRSCC and basic experiment

2.1 Properties of materials

SFRSCC is composed of P•O 42.5 Portland cement, fly ash, Quartz sand, crushed stone, steel fiber, water and additive. The main components of SFRSCC are summarized in Table 1. The steel fiber is straight, whose yield strength is 780 MPa, and the aspect ratio is about 33 with the length ≈ 6.5 mm. The moisture contents of quartz sand and crushed stone are 0.48% and 0.76% respectively, and the cement is dry. In order to improve the bonding coefficient of cement and steel fiber, water-cement ratio was selected as 0.32, and the additive is 2.67 kg/m^3. The specimens of SFRSCC were made by the secondary synthesis method (Zhang *et al*. 2018), and the fiber volume fractions of 0.5%, 1.5% and 2.0% were used. The mixture proportions for all specimens are shown in Table 2.

Table 1 Main components of SFRSCC

Cement	P•O 42.5 Portland cement Apparent density = 3130 kg/m^3
Fine aggregate	Quartz sand Apparent density = 2690 kg/m^3, Fineness modulus = 2.39
Coarse aggregate	Crushed stone Apparent density = 2650 kg/m^3, Particle size = 5~16 mm
Admixture	Fly ash Density = 2360 kg/m^3
Fiber	Steel fiber Density = 7750 kg/m^3, Diameter = 0.20 mm
Additive	Polycarboxylate Superplasticizer

Table 2 Mixture proportions of SFRSCC

V_f (%)	Cement (kg/m^3)	Fly ash (kg/m^3)	Quartz sand (kg/m^3)	Crushed stone (kg/m^3)
0.5%	432.0	108.0	733.3	873.3
1.5%	432.0	108.0	730.0	860.0
2.0%	432.0	108.0	726.7	853.0

*Notations: V_f = Steel fiber volume fraction;
Water/(cement+flyash) ratio = 0.3

2.2 Workability and mechanical properties of SFRSCC

The manufacture of SFRSCC is one of the most difficult to perform. The difficulties originate from the effect of steel fiber and initial requirements for self-consolidating, which is a pair of contradictory relationship that needs to be balanced. The manufacturing process of SFRSCC was determined as follows: Firstly, the dry mixture composed of quartz sand, crushed stone, Portland cement, fly ash and steel fiber was stirred evenly in the cement mixer; Secondly, the water and polycarboxylate superplasticizer were mixed into the dry mixture. After stirring uniformly, the mixture was poured into the mold box, which would suffer from vibrating and smoothing. The blocks were demolded after 24h, and then cured in the curing room for 28 days. Finally, the blocks were cored, cut and polished to prepare the specimens.

The workability includes flowability, anti-segregating and passing ability. The slump for the mixtures (i.e., 0.5%, 1.5% and 2.0% SFRSCC) was tested by Abrams cone, as shown in Fig. 1. The blocking ratios of them were tested by the L-box. The mixture had acceptable filling ability, no signs of segregation were found, and good uniformity and adhesion were maintained, which is in line with the characteristic of self-compacting concrete. The test results are shown in Table 3. The mechanical properties of SFRSCC were obtained by uniaxial compression test and Brazilian disc splitting test. As the specimens shown in Fig. 2, the size of uniaxial compression test specimens is 150 mm × 150 mm × 150 mm, and the specimens of Φ70 × 35 mm were adopted in Brazilian disc splitting tests. Also, the results of mechanical properties of SFRSCC are shown in Table 3.

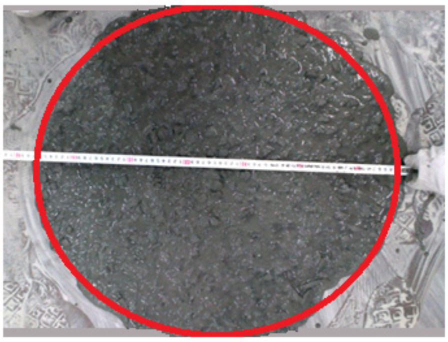


Fig. 1 Measurement of slump flow diameter

(a) Uniaxial compression (b) Brazilian disc splitting

Fig. 2 The specimens of mechanical test

It can be seen that the workability of SFRSCC decreases as steel fiber volume fraction increasing from Table 3. When the fiber volume fraction increases from 0.5% to 2.0%, it is an increase of the splitting tensile strength f_t that was on a big base of 36 percent, while the compressive strength f_c of 1.5% SFRSCC is lowest. Because the blocking ratios and compressive strength are closely related, which of 1.5% SFRSCC (h_2/h_1 = 0.93) is slightly higher than the other two, the segregation of the mixtures results in the decrease of its compressive strength. In short, the effects of steel fiber on workability and mechanical properties of SFRSCC is inconsistent.

In order to investigate the anti-penetration performance of SFRSCC, the square target samples were made for the shooting range test. The manufacturing procedure of test specimens is introduced as same as mentioned above. SFRSCC specimens were divided into three kinds of steel fiber fractions: 0. 5%, 1.5% and 2.0%. The size of specimen is 350 mm × 350 mm × 200 mm, as shown in Fig. 3. The introduction and results of shooting range test will be described in detail in the next section.

3. Shooting range test of SFRSCC

3.1 Test arrangement

A large number of studies have shown that SFRSCC has better penetration resistance than plain concrete. In order to further understand the anti-penetration law and mechanism of SFRSCC, two kinds of SFRSCC target plates with steel fiber content of 0.5% and 1.5% were tested in the Key Ballistic Laboratory of Nanjing University of Technology. The main components of SFRSCC target plates are steel fiber, P.O42.5 Portland cement, quartz sand, 5-16 mm gravel and polycarboxylic superplasticizer, as described

Table 3 Workability and mechanical property of SFRSCC

V_f (%)	P (kg/m^3)	Slumps (mm)	h_2/h_1	f_c (MPa)	f_t (MPa)
0.5%	2.22	795	0.91	49.8 ± 0.18	3.78 ± 0.12
1.5%	2.38	750	0.93	46.6 ± 0.42	4.34 ± 0.25
2.0%	2.42	710	0.90	48.8 ± 0.31	5.14 ± 0.20

*Notations: h_1 and h_2 are the height of the outflow segment and the flow end of L-box

(a) Before the test (b) After the test

Fig. 3 Typical shooting range test specimens

Fig. 4 Tungsten alloy projectile

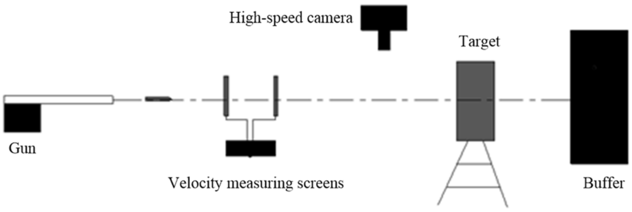


Fig. 5 Schematic diagram of the test device

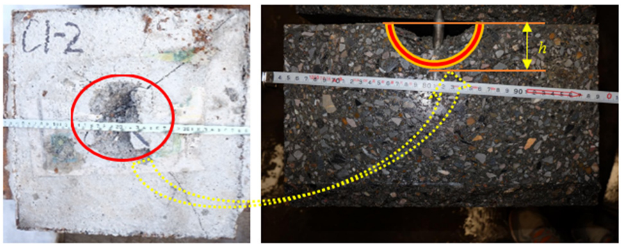


Fig. 6 The measurement of penetration depth

Table 4 Penetration test results

V_f (%)	Bullet weight (g)	Explosive quantity (g)	v (m/s)	h (cm)
0.5	175.66	6	246	9.5
	180.35	6	252	10.2
	180.47	8	299	13.1
	178.92	14	456	punctured
	180.6	10	360	punctured
1.5	180.05	8.5	321	14.5
	179.04	7	273	10.05
	179.69	6	239	7.75
	180.21	5	209	7.3
	180.34	8	310	14.2
	180.46	6.5	248	7.9
2.0	179.78	6	223	8.1
	179.29	5	217	7.6
	179.96	5.5	225.5	8.7
	180.23	6	246	9.2
	180.23	6.5	241	9.15
	179.54	7	287	12.7
	179.92	7.5	292	12.3
	178.72	8	307.5	13.9

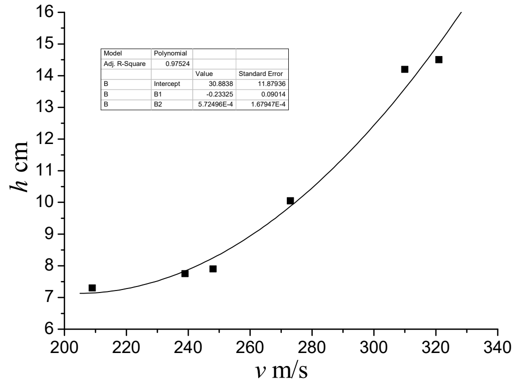


Fig. 7 Relation between incident velocity and penetration depth

previously. The projectile is made of tungsten alloy rod with a length of 9.5 cm, a diameter of 1.27 cm and CRH = 3, as shown in Fig. 4. The schematic diagram of the test device is shown in Fig. 5. The projectile is propelled by explosive and its incident velocity is measured by a high-speed camera. The penetration depth of SFRSCC Target is measured after the experiment. Basically, the projectiles can be regarded as a rigid body because of no deformation and no mass loss.

3.2 Test results

After the experiment, when the bullet penetrated the target, it is necessary to cut the target plate from the middle to measure the penetration depth of the bullet, as shown in Fig. 6. The mass of the bullet is about 180 g, and the incident velocity ranges from 177.6 m/s to 456 m/s. The experimental results are shown in Table 4. It can be seen that the penetration resistance of 1.5% SFRSCC is increased by more than 20% compared with 0.5% SFRSCC at the incident velocity of around 245 m/s when the 6 g explosive is used. Compared with the experimental results of 0.5% SFRSCC, the penetration resistance of 2.0% SFRSCC is almost not improved, which will be reflected in the revised model below. By analyzing the relationship between incident velocity and penetration depth about 1.5% SFRSCC, it is found that with the increase of incident velocity, penetration depth increases significantly, and there is a quadratic function relationship between them, as shown in Fig. 7.

4. Analysis of anti-penetration model

4.1 Existing model of penetration depth

Based on the existing penetration empirical formula, in recent years, scholars have introduced target toughness, energy absorption factor, aggregate hardness and other factors to consider the penetration resistance calculation formula of new composite materials. Similarly, for SFRSCC materials, the effect of steel fiber must also be considered in order to obtain the accurate penetration formula of SFRSCC. As a general rule, penetration depth can reflect the anti-penetration ability of concrete, which is mostly given by empirical and semi-empirical formulas. In the process of projectile penetrating concrete, the average resistance of projectile is composed of static resistance caused by elastic-plastic deformation of material and dynamic resistance caused by velocity effect, according to Wen and Yang (2014). Considering the influence of different parameters such as warhead shape, penetration rate and unconfined compressive strength, assuming that there is no erosion on the projectile, they proposed a simple penetration depth prediction formula

$$h = \frac{4}{\pi \sigma d^2} E_k \tag{1}$$

$$E_k = \frac{1}{2} m v_0^2 \tag{2}$$

where h is the penetration depth of the projectile, E_k is the kinetic energy change of the projectile, m is the mass of the projectile, v_0 is the penetration speed. In the process of penetrating SFRSCC material, the average resistance σ of the projectile includes the static pressure σ_s caused by elastic-plastic deformation and the dynamic pressure σ_d caused by velocity effect, we can see that

$$\sigma = \sigma_s + \sigma_d \tag{3}$$

where $\sigma_s = \delta_s \sigma_c$, $\sigma_d = \delta_d \sqrt{\frac{\rho}{\sigma_c}} v_0 \sigma_c$, δ_s and δ_d are constants determined by warhead shape and target material. ρ is the density of the target, and σ_c is the quasi-static strength of the target (such as compressive strength, splitting strength, shear strength, etc.).

According to Wen's literature (Wen and Yang 2014) and the effect of steel fibers from the experiments, we can give the values of each parameter as follows

$$\delta_s = \frac{2}{3}\left[1 + ln \frac{E}{3(1-\upsilon) f_c}\right], \quad \delta_d = \frac{3}{4CRH} \tag{4}$$

where E and v are modulus of elasticity and Poisson's ratio of the target material respectively, *CRH* is caliber radius head.

According to the above discussion, E_k can be calculated from v_0 and m, and σ can be calculated based on σ_s and σ_d, whose values are obtained by CRH, V_f, E, f_c and υ, which are always given through a series of experiments. If E is not available, it can be given by f_c determined by the following equations (Demir 2008, ACI Committee 2008)

$$E = \begin{cases} 4733\sqrt{f_c}, & f_c < 21\text{MPa} \\ 3300\sqrt{f_c} + 6900, & f_c \geq 21\text{MPa} \end{cases} \tag{5}$$

The only remaining parameter. σ_c is shear strength, which is an important parameter that determines the penetration resistance of the target. Wen's literature (Wen and Yang 2014) gives the empirical formula of σ_c based on the analysis of ordinary concrete test data

$$\sigma_c = 1.4 f_c + 45, f_c \leq 75\text{MPa} \tag{6}$$

For this experiment, CRH = 3 and υ = 0.25, 0.24, and 0.23 for V_f = 0.5%, 1.5% and 2.0% respectively.

The modified National Defense Research Committee (NDRC) formula (Kennedy 1976) is also widely used to estimate the penetration depth of concrete targets under projectile impact. The ratio of penetration depth h to the projectile's diameter d is given as

$$\begin{cases} \frac{h}{d} = 2G^{0.5} & for\ G \leq 1 \\ \frac{h}{d} = G + 1 & for\ G > 1 \end{cases} \tag{7a}$$

where

$$G = 3.8 \times 10^{-5} \frac{NM}{d\sqrt{f_c}} \left(\frac{V_0}{d}\right)^{1.8} \tag{7b}$$

where N is the projectile nose geometry factor, which is equal to 0.72, 0.84, 1.0 and 1.14 for flat, hemispherical, blunt, and very sharp noses, respectively. The parameters M and V_0 are the mass and the striking velocity of the projectile, while f_c is the compressive strength of the concrete target.

Almusallam *et al*. (2015) introduced an exponential term in the impact function G (Eq. (7b)) in order to account for the effectiveness of the fibers. The proposed modified impact function, G, is given by

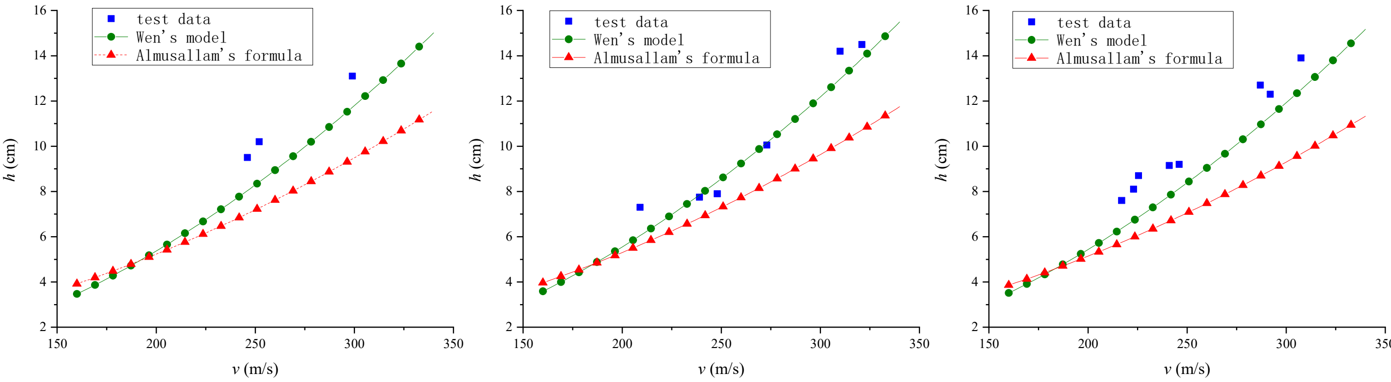
$$G = \frac{3.8 \times 10^{-5}}{\exp\left(\left\{\frac{1}{2}\sum_{i=1}^{n} \alpha_i\, p_i\right\}^{2.5}\right)} \frac{NM}{d\sqrt{f_c}} \left(\frac{V_0}{d}\right)^{1.8} \tag{8}$$

where p_i is the volume fraction of ith fiber and α_i, is a constant which depends on fiber properties. It is defined for the ith fiber as

$$\alpha_i = \frac{k_i l_i}{d_i} \frac{E_i}{E_s} \tag{9}$$

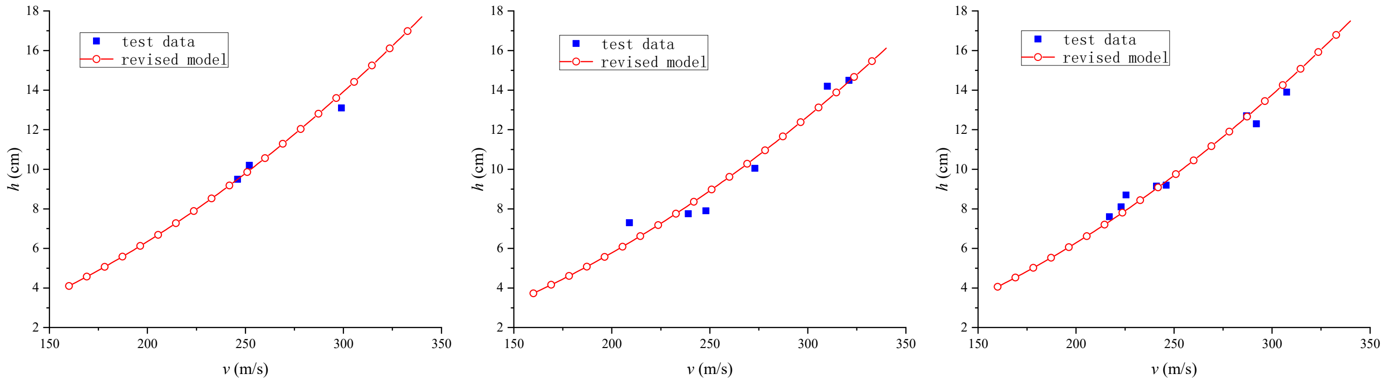
where, k_i is the bond factor of fibers; l_i is the length of fibers; d_i is the diameter (or equivalent diameter for non-circular sections) of fibers; E_i and E_s are the modulus of elasticity of the material of ith fibers and steel respectively. The value of bond factor, k_i, for hooked and crimped fibers is 1.0 whereas for plain fibers it is 0.8.

The penetration depths of SFRSCC target with different steel fiber content of 0.5~2.0% are calculated according to the Wen's model and Almusallam's formula, and compared with the test results. As shown in Fig. 8, the calculation results of penetration depth are smaller than the test results. It indicates that the anti-penetration performance is better than the actual results on the basis of predicted results. Wen's model is basically in good agreement with the existing normal concrete penetration test data, and Almusallam's formula may be suitable for hybrid-fiber reinforced concrete, but for SFRSCC material, they can't predict the penetration depth well. It is obvious that the penetration depth of SFRSCC due to projectile impact does



(a) $V_f = 0.5\%$ (b) $V_f = 1.5\%$ (c) $V_f = 2.0\%$

Fig. 8 Comparison of test results and predicted penetration depth from empirical formulas



(a) $V_f = 0.5\%$ (b) $V_f = 1.5\%$ (c) $V_f = 2.0\%$

Fig. 9 Comparison of test results and predicted penetration depth from revised model

not depend only on compressive strength, but also on the amount of steel fibers, the tensile strength and rheological characteristics of material. To accurately predict the depth of SFRSCC penetration, it is necessary to develop a new model based on experimental results that considers factors such as compressive strength and fiber content.

4.2 Revised model of penetration depth

Generally speaking, the workability of medium and high strength SCC classes is reduced by increasing the steel fiber volume fraction, and using high percentages of fibers led to decrease of other rheological characteristics. On the contrary, splitting tensile strength, flexural strength, and flexural toughness are increased by increasing the percentage of fibers; however compressive strength is decreased by increasing the percentage of fibers, which have been specified by Khaloo *et al*. (2014). The change of comprehensive performance will also lead to the change of anti-penetration performance of SFRSCC which is different from the previous cognition. For SFRSCC materials, based on the existing test data and considering the effect of steel fibers, we modify the Wen's model by revising the form of σ_c (Eq. (6)). So, a revised form of σ_c was proposed by regression analysis as follow

$$\sigma_c/f_c = 1.34 + 1.49V_f - 0.58V_f^2 \qquad (10)$$

Where f_c is compressive strength of SFRSCC, and V_f is the volume fraction of steel fiber.

As shown in Fig. 9, it is revealed that the calculation results of predicted penetration depth of SFRSCC is in good agreement with the experimental results. It indicates that the revised model of penetration depth is consistent with the actual results. Therefore, according to the revised model of penetration depth, the anti-penetration performance with the higher the content of steel fiber is not necessarily better.

This further confirms that both the rheological properties and mechanical properties have an effect on anti-penetration of SFRSCC. However, the influence of the relevant parameters of steel fiber has yet to be explored, and the range of initial velocity for which the formula is applicable needs to be further studied, which is the next focus in the future.

5. Conclusions

The SFRSCC were made by the secondary synthesis method, which has good workability based on the characteristic of self-compacting concrete with high flowability and good cohesiveness. Based on the experimental results, the following conclusions have been made on how steel fiber content on the workability, mechanical properties and anti-penetration ability of

SFRSCC can affect it. The conclusions are as follows:

a) With the steel fiber content from 0.5% to 2.0%, the workability and compressive strength of SFRSCC become worse, while the splitting tensile strength has an increase of 36%.

b) The penetration resistance of 1.5% SFRSCC is better and increased by more than 20% compared with 0.5% and 2.0% SFRSCC at the incident velocity of around 245 m/s. A quadratic function relationship is found between incident velocity and penetration depth for 1.5% SFRSCC, and with the increase of incident velocity, penetration depth increases significantly.

c) Based on the existing empirical penetration model of concrete and considering the effects of steel fiber, the revised formula of relevant parameter for predicting the penetration depth of SFRSCC is proposed according to the experiment results. It is demonstrated that the calculation results of the modified model are in good agreement with the SFRSCC penetration test data. The conclusion of this paper is helpful to the experimental investigations and engineering application.

Acknowledgments

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