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Smart design of steel fiber effects on soft computing of steel fiber reinforced self-compacting concrete

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Abstract. This research investigates the innovative design of steel fibers and their effects on the soft computing methodologies applied to steel fiber reinforced self-compacting concrete (SFRSCC). The study aims to enhance the mechanical properties and durability of SFRSCC through the strategic integration of steel fibers, utilizing advanced soft computing techniques. The fraction of steel fibers of the SFRSCC is 0.5 vol.%,1.5 vol.% and 2.0 vol.% respectively. In conclusion, the research underscores the potential of SFRSCC as a high-performance material that addresses the challenges faced in contemporary construction. By leveraging innovative design strategies and advanced computational techniques, the study contributes to the ongoing evolution of concrete technology, paving the way for more sustainable and efficient building practices. Future research should continue to explore the long-term durability and environmental impact of SFRSCC, further solidifying its role in the advancement of construction materials.

Keywords: coupled systematic criterion; mechanical performance; self-compacting; steel fiber

1. Introduction

The construction industry is undergoing significant transformations, driven by the need for more efficient, durable, and sustainable building materials. Self-compacting concrete (SCC) has emerged as a groundbreaking innovation, characterized by its ability to flow under its own weight, filling complex forms without the need for mechanical vibration (Okamura and Ouchi 2003). This property not only enhances workability but also improves the overall quality of concrete structures by minimizing the risk of segregation and voids. However, despite its advantages, the mechanical properties of SCC can be further enhanced through the incorporation of steel fibers.

Steel fiber reinforced self-compacting concrete (SFRSCC) combines the benefits of SCC with the mechanical reinforcement provided by steel fibers. The addition of steel fibers significantly

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improves the toughness, ductility, and post-cracking behavior of concrete, addressing common challenges such as shrinkage and tensile strength deficiencies (Zhang *et al.* 2015). The effectiveness of steel fibers in enhancing the performance of concrete is influenced by various factors, including fiber type, geometry, aspect ratio, and distribution within the matrix (Bhandari *et al.* 2020). Therefore, optimizing the design of steel fibers in SFRSCC is essential for maximizing its performance.

In recent years, soft computing techniques, such as artificial neural networks and genetic algorithms, have gained traction in material science and engineering. These methodologies provide powerful tools for modeling complex relationships between variables and predicting the behavior of composite materials (Khan *et al.* 2018). By leveraging soft computing approaches, researchers can efficiently explore the effects of different steel fiber configurations on the properties of SFRSCC, leading to smarter design processes.

This research aims to develop a comprehensive understanding of the effects of steel fiber design on the mechanical properties of SFRSCC through the application of soft computing techniques. By integrating these advanced methodologies, the study seeks to establish guidelines for optimizing fiber content and distribution, ultimately contributing to the advancement of concrete technology. The findings are expected to promote the use of innovative materials that meet the evolving demands of modern construction practices.

2. Material composition of SFRSCC and basic experiment

2.1 Properties of materials

The material composition of Steel Fiber Reinforced Self-Compacting Concrete (SFRSCC) is critical for achieving the desired mechanical properties and workability. The primary component is Ordinary Portland Cement (OPC), typically used in quantities ranging from 350 to 450 kg/m³, depending on the specific strength requirements. Fine aggregates, such as natural sand with a maximum size of 4.75 mm, are incorporated at approximately 600 to 800 kg/m³, while coarse aggregates, usually crushed stone or gravel with a maximum size of 20 mm, are included at around 800 to 1000 kg/m³. Water is another essential ingredient, with clean, potable water being used in quantities of about 150 to 200 liters/m³, adjusted as necessary to achieve the desired workability.

Steel fibers play a significant role in enhancing the mechanical properties of SFRSCC. Typically, hooked-end or straight steel fibers are used, characterized by an aspect ratio ranging from 30 to 60. The volume fraction of steel fibers varies between 0.5% to 2% of the concrete mix, depending on the required performance characteristics. In addition to these primary materials, chemical admixtures such as polycarboxylate-based superplasticizers are added to improve workability and reduce water content, usually comprising 0.5% to 2% of the weight of cement. Viscosity modifying agents (VMAs) may also be included to enhance stability and prevent segregation. Optional mineral admixtures, like fly ash, silica fume, or Ground Granulated Blast Furnace Slag (GGBFS), can be incorporated to improve durability and workability, typically making up 10% to 30% of the cement weight.

The experimental phase of this research focuses on evaluating the effects of various steel fiber configurations on the mechanical properties of SFRSCC, while also applying soft computing techniques to optimize the mix design. The first step involves preparing different mix designs, where the type, aspect ratio, and volume fraction of steel fibers are varied, keeping other

components constant. Preliminary tests are conducted to assess the workability of each mix using slump flow and V-funnel tests, ensuring that the SCC meets the necessary performance criteria.

Once the mix designs are finalized, concrete specimens are cast in standard molds to create cubes, cylinders, and beams for subsequent testing. Proper curing is essential, with specimens typically submerged in water for 28 days to facilitate optimal strength development. After curing, a series of tests are performed, including compressive strength tests on concrete cubes to evaluate load-bearing capacity, flexural strength tests on beams to assess tensile performance, and split tensile strength tests on cylinders to determine tensile strength. Additionally, durability tests, such as water absorption and permeability assessments, are conducted to gauge the long-term performance of SFRSCC.

The data collected from these experiments are analyzed to understand the influence of steel fiber characteristics on the mechanical properties of SFRSCC. By employing soft computing techniques like artificial neural networks (ANN) and genetic algorithms (GA), the research aims to model the complex relationships between fiber parameters and concrete performance. This innovative approach not only enhances the understanding of SFRSCC but also contributes to the development of efficient and sustainable concrete materials in modern construction practices.

2.2 Workability and mechanical properties of SFRSCC

Using the splitting tensile test to evaluate the tensile properties of SFRSCC allows authors to gain valuable insights into the material's performance, particularly in applications where tensile forces are significant. This test helps in understanding how the incorporation of steel fibers affects the mechanical properties of concrete, ensuring better design and application in construction. By employing these strategies, we can effectively control load increases in specimens with micro-cracks, ensuring safety and performance in structural applications. Monitoring, material selection, and gradual loading are key components in managing the behavior of materials under stress. The workability of Steel Fiber Reinforced Self-Compacting Concrete (SFRSCC) is a critical factor that influences its performance in construction applications. Workability refers to the ease with which concrete can be mixed, placed, and finished without segregation or bleeding. In this study, various tests, including the slump flow test and V-funnel test, are employed to evaluate the workability of SFRSCC mixes. The inclusion of steel fibers can impact the flowability of the concrete; however, with the appropriate dosage of superplasticizers and viscosity modifying agents, SFRSCC can achieve excellent workability. The results indicate that well-designed SFRSCC mixes maintain adequate flow characteristics, allowing them to fill complex forms and achieve uniformity without the need for mechanical vibration. This enhanced workability is essential for ensuring high-quality construction and reducing labor costs associated with traditional compaction methods.

In addition to workability, the mechanical properties of SFRSCC are significantly influenced by the type, aspect ratio, and volume fraction of the steel fibers used. The compressive strength tests reveal that the incorporation of steel fibers enhances the load-bearing capacity of SFRSCC, with optimal fiber content leading to substantial improvements in strength compared to conventional SCC. Flexural strength tests further demonstrate that SFRSCC exhibits superior ductility and toughness, making it more resistant to cracking under tensile stresses. The split tensile strength tests indicate a marked increase in tensile strength with the addition of steel fibers, which effectively bridge cracks and distribute stress across the concrete matrix. Overall, the mechanical properties of SFRSCC are enhanced through the strategic design of steel fiber configurations, resulting in a composite material that meets the demands of modern construction

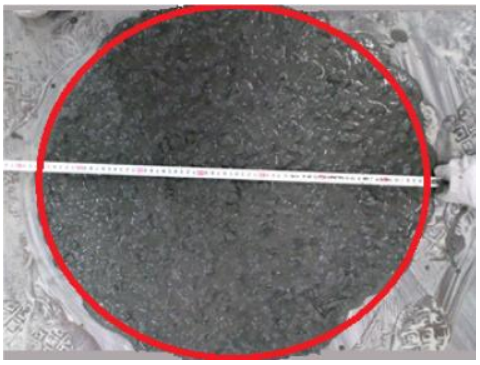
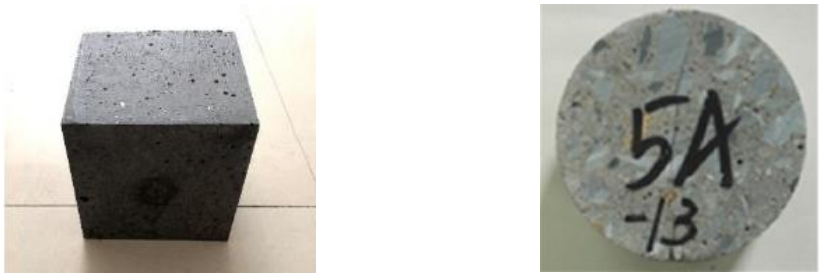


Fig. 1 Measurement of slump flow diameter



(a) Uniaxial compression (b) Brazilian disc splitting

Fig. 2 The specimens of mechanical test

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

Fig. 3 Typical shooting range test specimens

while providing improved durability and performance.

The findings from this research highlight the critical interplay between workability and mechanical properties in SFRSCC. By utilizing soft computing techniques, the study aims to optimize the design parameters, ensuring that the concrete achieves the desired balance between flowability and strength. The results underscore the potential of SFRSCC as a high-performance material in construction, capable of addressing the challenges associated with traditional concrete mixes. Ultimately, this research contributes to the advancement of concrete technology by providing insights into the effective design and application of steel fiber reinforcement in self-compacting concrete.

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. 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.

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.

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. The mass of the bullet is about 180 g, and the incident velocity ranges from 177.6 m/s to 456 m/s. 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.

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 the neural network-based approach (3.1) can be described as follows.

$$\dot{X}(t) = \Psi^S(W^S\Psi^{S-1}(W^{S-1}\Psi^{S-2}(\cdots\cdots\Psi^S(W^2\Psi^1(W^1\Lambda(t)))\cdots\cdots))), \tag{3.1}$$

where $\Lambda^T(t) = [X^T(t)\ U^T(t)]$, $X^T(t) = [x_1(t)\ \ x_2(t)\ \ \cdots x_\delta(t)\ ]$, as $x_1(t) \sim x_\delta(t)$. The input to S the layered network R^σ is $u_1(t) \sim u_m(t)$ $(\sigma = 1,2,\cdots,S)$ neuron. $\boldsymbol{W}^\sigma$ Shows σ^{th} the layer weights and transfer functions $\Psi^\sigma(v) \equiv [T(v_1)\ \ T(v_2)\ \ \cdots\ \ T(v_{R^\sigma})]^T$.

The Neural Network Difference Inclusion (NNDI) method can represent the state space and is described as follows.

$$\dot{Y}(t) = A\big(a(t)\big)Y(t),\ A(a(t)) = \sum_{i=1}^{r} h_i(a(t))\bar{A}_i.$$

where $a(t)$ the notation for its elements is $h_i(\cdot)$ a vector, that is, $h_i(a(t)) \equiv h_i(a_1(t), a_2(t)\cdots, a_n(t))$ a constant $a(t) = [a_1(t), a_2(t)\cdots, a_n(t)]^T$ matrix $\bar{A}_i$ and $Y(t) = [y_1(t)\ \ y_2(t)\ \cdots\ y_j(t)]^T$.

The interpolation method is analyzed in Eq. (1). (3.2)

$$\begin{aligned}\dot{X}(t) &= [\sum_{\varsigma^S=1}^{2} h_{\varsigma^S}(t) G_{\varsigma}^{S}(W^S[\cdots[\sum_{\varsigma^2=1}^{2} h_{\varsigma^2}(t) G_{\varsigma}^{2}(W^2[\sum_{\varsigma^1=1}^{2} h_{\varsigma^1}(t) G_{\varsigma}^{1}(W^1\Lambda(t))])]\cdots])] \\ &= \sum_{\varsigma^S=1}^{2}\cdots\sum_{\varsigma^2=1}^{2}\sum_{\varsigma^1=1}^{2} h_{\varsigma^S}(t)\cdots h_{\varsigma^2}(t) h_{\varsigma^1}(t) G_{\varsigma}^{S}W^S\cdots G_{\varsigma}^{2}W^2 G_{\varsigma}^{1}W^1\Lambda(t) \\ &= \sum_{\Omega^\sigma} h_{\Omega^\sigma}(t) E_{\Omega^\sigma}\Lambda(t)\end{aligned} \tag{3.2}$$

Where

$\sum_{\zeta^\sigma} h_{\zeta^\sigma}(t) \equiv \sum_{q_1^\sigma=1}^{2}\sum_{q_2^\sigma=1}^{2}\cdots\sum_{q_{R^\sigma}^\sigma=1}^{2} h_{q_1^\sigma}(t) h_{q_2^\sigma}(t)\cdots h_{q_{R^\sigma}^\sigma}$ for $\zeta = 1,2,\cdots, R^\sigma$; $E_{\Omega^\sigma} \equiv G_{\varsigma}^{S}W^S\cdots G_{\varsigma}^{2}W^2\ G_{\varsigma}^{1}W^2$, $\sum_{\Omega^\sigma} h_{\Omega^\sigma}(t) \equiv \sum_{\zeta^S=1}^{2}\cdots\sum_{\zeta^2=1}^{2}\sum_{\zeta^1=1}^{2} h_{\zeta^S}(t)\cdots h_{\zeta^2}(t) h_{\zeta^1}(t)$.

Finally, according to the formula. (3.2), the NN dynamics were rewritten in NNDI in Eq. (3.2). (3.3)

$$\dot{X}(t) = \sum_{i=1}^{r} h_i(t)\bar{E}_i\Lambda(t), \tag{3.3}$$

is a random matrix $\bar{E}_i$ with scale corresponding to E_{Ω^σ}. The NNDI format looks like this

$$\dot{X}(t)\sum_{i=1}^{r} h_i(t)\{A_i\ X(t)\}, \tag{3.4}$$

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. The calculation results of penetration depth are smaller than he 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 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. 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 antipenetration 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

This research paper provides a comprehensive analysis of the effects of steel fiber design on the properties of Steel Fiber Reinforced Self-Compacting Concrete (SFRSCC) through the application of soft computing techniques. The findings demonstrate that the incorporation of steel fibers significantly enhances the mechanical properties of SFRSCC, including compressive strength, flexural strength, and tensile strength. Optimal fiber configurations, characterized by appropriate type, aspect ratio, and volume fraction, contribute to improved ductility and toughness, making SFRSCC a superior alternative to conventional self-compacting concrete.

The study also emphasizes the importance of workability in the performance of SFRSCC. With the right combination of chemical admixtures, SFRSCC can achieve excellent flow characteristics, allowing for efficient placement and minimizing the risk of segregation. The successful balance between workability and mechanical performance is crucial for the practical application of SFRSCC in construction, ensuring that it meets the demands of modern engineering practices.

Moreover, the application of soft computing methodologies, such as artificial neural networks and genetic algorithms, offers a powerful approach for optimizing the design parameters of SFRSCC. These techniques enable the modeling of complex relationships between various factors, facilitating the identification of ideal conditions for achieving desired performance outcomes. The insights gained from this research not only advance the understanding of SFRSCC but also provide valuable guidelines for future studies and practical implementations in the field.

In conclusion, the research underscores the potential of SFRSCC as a high-performance material that addresses the challenges faced in contemporary construction. By leveraging innovative design strategies and advanced computational techniques, the study contributes to the ongoing evolution of concrete technology, paving the way for more sustainable and efficient building practices. Future research should continue to explore the long-term durability and environmental impact of SFRSCC, further solidifying its role in the advancement of construction materials.

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