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# INFLUENCE OF RECYCLED STEEL FIBER ON THE PROPERTIES OF SELF-COMPACTING CONCRETE WITH HIGH FLY ASH CONTENT

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**Abstract**

The recycled steel fibers from waste steel cables have properties suitable for enhancing the load-bearing capacity, impact resistance, and shrinkage reduction of Self-Compacting Concrete (SCC). The use of a high content of fly ash in SCC reduces production costs and is environment friendly by minimizing the amount of cement in the mix. This article presents the experimental research results on the influence of the content of recycled steel fibers on the properties of high-fly-ash SCC. The research utilized recycled steel fibers from elevator steel cables with volume percentages of 0%, 0.5%, 1% and 1.5% respectively in SCC, with a fly ash content in the SCC mix of 50% by volume of powder. The evaluated properties included workability, plastic shrinkage, drying shrinkage compressive strength, and tensile strength. The results indicate that using recycled steel fibers with a maximum content of 1% enables the production of SCC that meets European standards for workability. In addition, when comparing SCC with 0.5% and 1% recycled steel fiber content to control SCC samples (without steel fibers), the compressive strength of SCC increased by 5.04% and 7.56% respectively, the tensile strength increased by 2.99% and 5.97% respectively, plastic shrinkage decreased by 27.34% and 30.47% respectively, and 28-day drying shrinkage decreased by 3.2% and 4.6% respectively. Using recycled steel fibers combined with high-volume fly ash is a reasonable solution to save production costs and be environmentally friendly. Additionally, this solution not only improves the compressive and tensile strength but also limits plastic and drying shrinkage deformations of SCC. As a result, the durability of SCC is enhanced.

*Keywords:* self-compacting concrete; workability; concrete strength; plastic shrinkage; drying shrinkage.

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## 1. Introduction

Self-Compacting Concrete (SCC) is a specialized type of high-strength concrete with excellent workability. The concrete mixture can flow through the formwork corners under its own gravity without the need for vibration, ensuring a tight compaction [1]. The use of SCC offers numerous benefits, including faster construction, reduced reliance on labor and equipment, improved working conditions for workers, noise reduction, and environmental protection. However, SCC's drawback is its high material cost [2], and being a heavyweight concrete, it is prone to cracking due to shrinkage and creep, with lower tensile and flexural strength as well as poor impact resistance. Therefore, it is necessary to research suitable material solutions to contribute to mitigating the drawbacks of SCC.

The incorporation of steel fibers into concrete dates back to the 1960s [3]. Studies have shown that the use of steel fibers in concrete enhances the compressive, tensile and flexural strength of SCC [4]. Additionally, the elasticity of concrete significantly increases when fiber reinforcement is introduced [5]. Nevertheless, steel fibers can reduce the workability of concrete [2]. The effectiveness of using

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fiber reinforcement depends on concrete grade, fiber orientation ratio [6], fiber shape, surface characteristics and fiber content in concrete [5]. Amalia's research [4] employed recycled steel fibers at 1% content and 5% rice husk fly ash to produce SCC with an 8.45% increase in compressive strength, a 28.15% increase in tensile strength, and a 9.3% increase in flexural strength compared to the control sample without steel reinforcement. On the other hand, Najim [7] used 60 kg/m$^3$ of recycled steel fibers, resulting in a 7.9% improvement in compressive strength and a 60% enhancement in flexural strength of SCC. Simalti [8] demonstrated that utilizing 1.5% content of recycled steel fibers derived from car tires yielded the best compressive strength, flexural strength and chloride ion permeability performance compared to SCC use steel fibers. In addition, the use of recycled steel fibers is a sustainable and economically viable solution. Furthermore, Mastali [9] showed that replacing steel fibers with 15-30% recycled steel significantly increased the flexural strength and fracture index. Groli [10] indicated that the use of 1% recycled steel fibers effectively enhanced SCC's crack resistance. Meng and Khayat [11] demonstrated that the concrete shrinkage decreased by 30% when increasing the steel fiber content from 2% to 5%, while the flow time through the V funnel increased by 61.5%. Bensaci [12] observed that although the shrinkage of SCC decreased by 33% when increasing the steel fiber content from 0% to 1%, the workability became compromised as the T500 value increased by 81.4%. Maameri [13] studied the influence of recycled steel fibers from tires on the workability and mechanical properties of SCC. The results showed that using recycled steel fibers reduced the rheological properties of SCC. However, the use of 15% and 25% granulated glass blast furnace slag as a replacement for cement helped mitigate the effect of recycled steel fibers on the rheological properties of SCC. The use of recycled steel fibers enhanced the compressive and flexural strengths, elastic modulus, and reduced shrinkage of SCC. Zhang [14] demonstrated that using recycled steel fibers from tires could replace newly manufactured steel fibers in construction applications, providing a low-cost and environmentally friendly solution. The use of recycled steel fibers not only delays the propagation of cracks but also improves the shrinkage and impact resistance of concrete. However, the chloride ion corrosion resistance of recycled steel fibers from tires is higher than that of newly manufactured steel fibers. However, it is worth noting that most studies on recycled steel fibers have been conducted with conventional SCC, and research on the application of steel fibers in combination with high-volume fly ash in SCC production remains limited.

Elevator steel ropes are used for lifting and lowering the elevator car and counterweight, serving as the main load-bearing ropes responsible for carrying the entire load of the car and passengers. Safety regulations for steel cable usage are stringent. For instance, safety regulations for elevator cables [15] mandate that cables must be removed if their diameter decreases by 6% from the nominal diameter. The demand for elevators in high-rise buildings, public infrastructure, and urban areas in Vietnam is increasing significantly. According to statistics, in 2022, approximately 24,600 new elevators were installed. With an annual growth rate of elevator production of about 8%, the number of elevators is expected to continue increasing in the future [16]. During elevator maintenance, the need for replacement of steel ropes that do not meet usage requirements will be substantial. Elevator ropes, located within the building structure, are not susceptible to corrosion due to climate factors. Therefore, even if elevator ropes no longer ensure safe operation as per regulations, if recycled and cut into smaller pieces for use as fiber reinforcement in concrete, they can still meet the requirements. However, it is essential that steel cables are classified and cleaned to remove undesirable elements such as oil, rust, and low-quality fibers in order to enhance the reliability of using recycled steel fibers in concrete [17]. Meanwhile, fly ash is a by-product from the thermal power generation industry. High-content fly ash is used to reduce the production cost of SCC [18]. Fly ash also reduces permeability, water demand, and hydration temperature, enhancing the workability of SCC [19]. The use of high-volume fly ash significantly improves the shrinkage resistance of SCC [20]. Therefore, the combined use of high-content fly ash and recycled steel fibers can overcome the limitations of steel fibers in concrete.

(a) Elevator cables


(b) Steel fibers processing

Figure 1. Recycled steel fiber cut from elevator cable

In Vietnam, there is currently a lack of standards and regulation for the application of steel fibers in concrete, which has led to challenges in implementing this technology in construction projects. Moreover, most steel fibers are primarily imported directly from foreign countries, resulting in relatively high costs. Meanwhile, research on the utilization of recycled steel fibers for the production of SCC is a completely new in the field of construction. In this study, the author conducted research on simultaneously using recycled steel cables from elevator cables and high-content fly ash to manufacture SCC. The fiber steel content surveyed included 0.5%, 1% and 1.5% of concrete volume, fly ash content used 50% of powder volume. Properties evaluated included workability, plastic shrinkage, drying shrinkage, compressive strength and tensile strength in bending. Thus, the influence of the recycled steel fiber ratio on SCC properties was elucidated. Fig. 1 shows recycled steel fiber cut from elevator cable.

SCC is a high-quality concrete type that has been widely used worldwide. In Vietnam, SCC remains a special type of concrete due to its high material costs. The research results will provide a foundation for the production of SCC with better quality, lower costs, environmental friendliness and better compliance with diverse construction requirements in Vietnam.

## 2. Materials, mix and experimental methods

### *2.1. Materials*

The materials used in the experiment include: Vicem But Son PCB40 cement; SongHong golden sand with a fineness modulus of 2.76; crushed stone with $D_{max}$ = 20 mm, density 2.75 g/cm$^3$; fly ash: Pha Lai thermal power plant fly ash, Type F according to ASTM C618 standards; superplasticizer (SP): BiFi-HV298 new-generation superplasticizer, improved polymer-based, with a density of 1.05, compliant with ASTM C-494 Type G; VMA modifying agent: Culminal MHPC400 type viscosity-modifying agent. The Chemical composition of Pha Lai fly ash is detailed in Table 1. The particle composition of sand and stone is illustrated in Figs. 2 and 3.

The steel fibers used in the study were cut from an elevator hoist rope segment, with a diameter of 9 mm. It consisted of ten strands with a diameter of 0.4 mm and nine strands with a diameter of

Table 1. Chemical composition of Pha Lai fly ash

| The composition | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ |
|---|---|---|---|---|---|---|
| % | 54.38 | 18.96 | 6.23 | 2.8 | 1.05 | 0.3 |

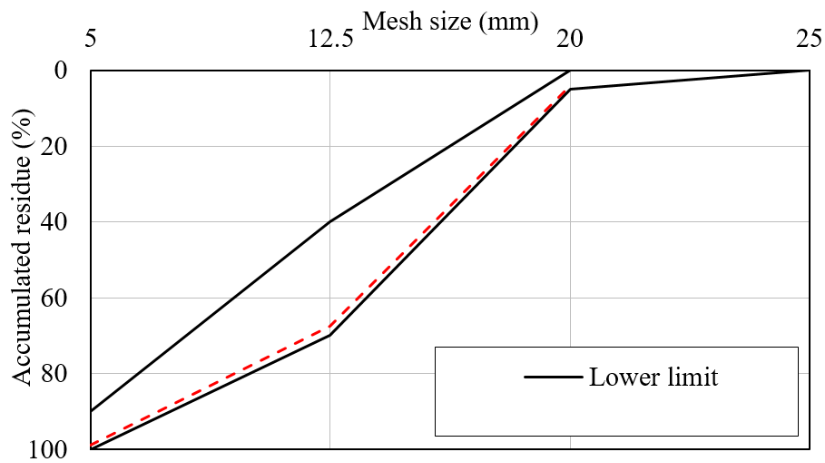


Figure 2. Particle size distribution curve of crushed stone

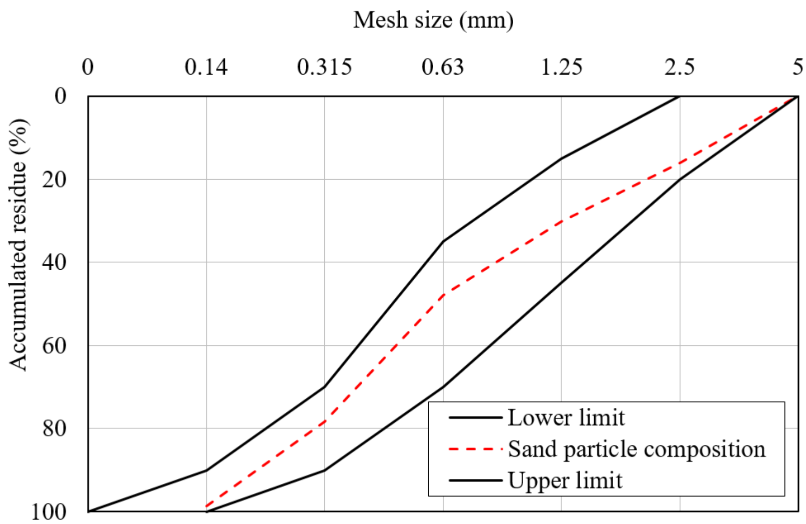


Figure 3. Particle size distribution curve of sand

0.2 mm. The length of the steel fibers varied between 20-25 mm. The tensile strength of the cable strands was 1620 N/mm$^2$. After being cut, the steel fibers were cleaned to remove rust-preventive oil and oil-coated fibers. The shape of the steel fibers after cut exhibited a wavy curvature, with a smooth and round surface. Visual assessment indicated that the cleaned steel fibers had similar quality to new steel cables.

### 2.2. *Experimental concrete mix*

The SCC mix design was carried out using the method proposed by Akamura and Ozawa [21]. According to this method, the fine aggregate (sand) is fixed at 40% of the paste volume, the coarse aggregate (stone) occupies for 50% of the concrete volume, and the W/P is assumed to be in the range of

0.9-1 by volume, with the superplasticizer properly adjusted for workability. In the experiment, a total of 4 different mix designs were used for evaluation. These mix designs were created by varying the steel fiber content, including 0%, 0.5%, 1% and 1.5% respectively, while keeping the fly ash/powder ratio fixed at 0.5 and the water/powder ratio at 0.35. Based on experimental observations, to achieve the desired flowability of the control mix (SF0) within the range of 650-800 mm, the amount of superplasticizer admixture was determined to be 1% of the mass of powder, and the amount of VMA was determined to be 0.00035% of the mass of powder. The mix proportions for 1 $m^3$ of concrete are detailed in Table 2.

Table 2. Mix proportions for 1 $m^3$ of SCC mix

| Mix | Cement (kg) | Fly ash (kg) | Sand (kg) | Stone (kg) | Superplasticizer (kg) | VMA (kg) | Water (kg) | SF (kg) |
|---|---|---|---|---|---|---|---|---|
| SF0 | 108.5 | 433.9 | 748.8 | 770 | 5.42 | 0.19 | 189.8 | 0 |
| SF0.5 | 108.5 | 433.9 | 748.8 | 770 | 5.42 | 0.19 | 189.8 | 39 |
| SF1 | 108.5 | 433.9 | 748.8 | 770 | 5.42 | 019 | 189.8 | 78 |
| SF1.5 | 108.5 | 433.9 | 748.8 | 770 | 5.42 | 0.19 | 189.8 | 117 |

### *2.3. Experimental method*

a. Workability test of SCC mixtures: The workability of SCC was evaluated according to TCVN 12209:2018 standard [22], various test parameters are considered, including: slump flow ($SF$), slump flow time ($T_{500}$), passing ability J-ring ($J_{ring}$), passing ability L-box ($L_{box}$), V-funnel flow time ($V_{funnel}$) and segregation resistance ($Sr$).

b. SCC compressive strength test: The concrete mixtures were sampled, cast into specimens and cured according to TCVN 3105:2022 [23] guidelines. The specimens used to determine compressive strength had dimensions of 10x10x10cm. The specimens were cast and initially cured under standard conditions for the first day, after which they were submerged in water starting from the second day. Compressive strength testing of the specimens was carried out following TCVN 3118:2022 [24].

c. SCC tensile strength test: The concrete specimens were cast and cured following TCVN 3105:2022 [23] guidelines. The specimens had dimensions of $150 \times 150 \times 600$ mm. Tensile strength along the axis of the concrete was determined according to the instructions of TCVN 3119:2022 [25].

d. SCC plastic shrinkage test: Plastic shrinkage is a physical process that occurs in the early stage when concrete begins to set and harden. Soft shrinkage occurs after a few hours of concrete mixing, primarily due to rapid evaporation of water, which increases negative pressure in the capillaries and tends to pull aggregate particles closer together, resulting in deformation within the concrete. In this study, soft shrinkage was determined using two strain gauges with an accuracy of 0.002 mm placed at both ends of concrete specimens measuring $10 \times 10 \times 30$ cm. The gauges were installed after 2 hours of pouring the concrete into the molds. Measurements were taken at one-hour intervals, continuously over an 8-hour period starting from the first measurement. The specimens were tested for soft shrinkage under autumn climate conditions (September 2023) with sunny weather, an ambient temperature of 38°C and approximately 61% humidity. The concrete's soft shrinkage value is the sum of the readings from the two strain gauges. The strain shrinkage of SCC is shown in Fig. 4.

(a) Prepare the plastic shrinkage measurement experiment sample

(b) Measure plastic shrinkage

Figure 4. Plastic shrinkage of SCC mixtures

e. SCC drying shrinkage test: Concrete specimens were cast and cured according to TCVN 3105:2022 [23]. The specimens had dimensions of 75×75×285 mm. Drying shrinkage of SCC was determined following the guidelines of TCVN 3117:2022 [26]. Fig. 5 illustrates the process of measuring the drying shrinkage of SCC.

(a) Prepare the dry shrinkage measurement experiment sample

(b) Measure drying shrinkage

Figure 5. The process of measuring the drying shrinkage of SCC

## 3. Experimental results and discussions

### *3.1. Workability test of SCC mixtures*

As per [27], the acceptable ranges for these values are as follows: $SF$ should be in the range of 650-800 mm, $T_{500}$ should fall between 2-5 seconds, $J_{ring}$ should be between 0-10 mm, $V_{funnel}$ flow time should be within 6-12 seconds and Sr should range from 5-15%. The experimental results for slump flow (SF), $T_{500}$, $J_{ring}$, $L_{box}$, $V_{funnel}$ and $Sr$ are presented in Table 3, Fig. 6 and Fig. 7 illustrate the experimental setup for SCC workability testing.

The mixtures SF0, SF0.5 and SF1 all exhibit workability that meets the requirements outlined in EFNARC [27] guidelines. The workability parameters have the following values: slump flow ranges

Table 3. Workability test results according to European Guidelines [28]

| Mix | $SF$ (mm) | $T_{500}$ (second) | $V_{funnel}$ (second) | $L_{box}$ | $J_{ring}$ (mm) | $Sr$ (%) |
|---|---|---|---|---|---|---|
| SF0 | 740 | 3.75 | 11.2 | 0.88 | 9.1 | 7.05 |
| SF0.5 | 710 | 4.15 | 11.5 | 0.85 | 9.3 | 6.95 |
| SF1 | 651 | 4.97 | 11.8 | 0.81 | 9.9 | 6.87 |
| SF1.5 | 540 | 5.72 | 12.9 | 0.71 | 11.8 | 6.81 |

Figure 6. Passing ability L-box of SF1

Figure 7. Slump flow of SF1

from 651 mm to 740 mm, flow time ($T_{500}$) ranges from 3.75 seconds to 4.97 seconds and V-funnel flow time ranges from 11.2 seconds to 12.9 seconds. The ability to pass the L-box test ranges from 0.81 to 0.88 and the J-ring flow ranges from 9.1 to 9.9 mm. All these mixtures demonstrate good flowability without any signs of blockages at any point. Besides, segregation resistance ranges from 6.87% to 7.05%. The use of high-fly ash content in combination with VMA additives has improved the slump flow and contributed to the stability of the concrete mixture. Additionally, when visually inspecting the concrete rings following the VSI guidelines of ASTM standard [29], based on the distribution of aggregates, steel fibers show that the SCC mixture is quite uniform with good dispersion of aggregates and steel fibers (Fig. 6). However, there still exists a mixture, SF1.5, which does not meet the workability requirements according to EFNARC [27] guidelines. Its slump flow ($SF$) is 540 mm, $T_{500}$ is 5.72 seconds, V-funnel is 12.9 mm and L-box is 0.71. Therefore, this mixture's performance in terms of hardened properties is not evaluated in this study, as presented in the subsequent section.

The experimental results also indicate that increasing the steel fiber content reduces the slump flow ($SF$) of SCC mixtures. When using steel fiber contents of 0.5%, 1% and 1.5%, the slump flow decreases by 4%, 12% and 27% respectively, compared to the mixture without steel fibers (Table 3). Additionally, increasing the steel fiber content results in longer flow times for T500 and V-funnel. This demonstrates that the addition of steel fibers makes the SCC mixtures less fluid. Furthermore, a maximum steel fiber content of 1.5% does not meet the requirements under European guidelines. Furthermore, when using steel fiber contents of 0.5%, 1% and 1.5%, the segregation resistance of the mixtures tends to decrease slightly compared to the mixture without steel fibers: decreasing by 1.4%, 2.5% and 3.4% respectively. The mixtures ability to pass the L-box and J-ring tests is also reduced with increasing steel fiber content. Increasing the fiber content reduces the workability and increases the flow stress of the SCC mix, as explained by the author Martine [30]. When introduced into the SCC mix, the steel fibers create a network that impedes the flow of concrete. In addition, according to authors Bayasi and Parviz [31], the high surface area of the fibers increases the air content. The increased air content in SCC leads to a decrease in flowability and workability of the mixture [32, 33].

### *3.2. Experimental results on the compressive strength*

The compressive strength results for the mixtures with steel fiber proportions of 0%, 0.5% and 1% are as follows: at 7 days of age, they measured 22.8 MPa, 23.1 MPa and 23.7 MPa respectively; at 28 days of age, they measured 35.7 MPa, 37.5 MPa and 38.4 MPa respectively. The use of 0.5% and 1% steel fibers increased the compressive strength of SCC compared to the mixture without steel fibers by 1.32% and 3.95% respectively at 7 days of age, and by 5.04% and 7.56% respectively at 28 days of age (Table 4). The increase in compressive strength of SCC with the addition of steel fibers above 0.5% by volume of concrete is consistent with the findings of Libre [34]. The addition of steel fibers has led to a significant increase in the bonding strength at the interface between steel fibers and the matrix [28, 33].

The experimental results demonstrate that workability significantly influences the compressive strength of SCC. In this study, the steel fibers were cut from steel cables with a length of approximately 2cm (roughly equal to the Dmax of the coarse aggregates) and they were straight, round, and did not obstruct the flow of SCC. Therefore, the SCC exhibited good slump flow and passing ability, which contributed to high compactness and strength of the concrete. The results show that SCC with a 1% steel fiber content, with good workability characteristics, had the highest compressive strength.

The study conducted by Anil [5], using new steel fibers with a length of 35 mm and hooks at both ends, showed a 7.3% increase in compressive strength with a 1% steel fiber content compared to samples without steel fibers. In this study, recycled steel fibers from elevator cables, with a length of 2.5 cm, achieved a 7.56% increase in compressive strength at a 1% steel fiber content compared to samples without steel fibers. The comparison with Anil's research [5], thereby, suggests that using recycled steel cables is almost as effective as using new steel fibers in terms of enhancing concrete strength.

Table 4. The compressive strength of SCC mixtures

| Mix | Compressive strength (MPa) | | % Variation in compressive over control mix | |
|---|---|---|---|---|
| | 7 days | 28 days | 7 days | 28 days |
| SF0 | 22.8 | 35.7 | 0 | 0 |
| SF0.5 | 23.1 | 37.5 | 1.32 | 5.04 |
| SF1 | 23.7 | 38.4 | 3.95 | 7.56 |

### *3.3. Experimental results on the tensile strength*

The experimental results for the flexural tensile strength of the SF0, SF0.5 and SF1 mix designs are 4.47 MPa, 4.60 MPa and 4.73 MPa, respectively. The tensile strength along the longitudinal axis for the SF0, SF0.5 and SF1 mix designs is 2.59 MPa, 2.67 MPa and 2.75 MPa, respectively. The results indicate an increase in flexural tensile strength and tensile strength along the longitudinal axis of SCC when steel fibers are added. The increase was 2.99% when 0.5% steel fibers were added and 5.97% when 1% steel fibers were added (Table 5). Adding steel fibers to the concrete creates a bond that transfers the load between the concrete and the steel fibers, resulting in stress being distributed from the concrete to the steel fibers. The increase in tensile strength of the concrete is due to the cumulative effect of the bond between the concrete and individual steel fibers resisting the tensile force.

Table 5. The tensile strength of SCC mixtures

| Mix | Flexural tensile strength (MPa) | Axial tensile strength (MPa) | % Variation in Tensile over control mix |
|---|---|---|---|
| SF0 | 4.47 | 2.59 | 0 |
| SF0.5 | 4.60 | 2.67 | 2.99 |
| SF1 | 4.73 | 2.75 | 5.97 |

In reinforced concrete structures, the bending moment is primarily carried by the steel reinforcement and the concrete's tensile strength is not typically considered for bending. However, the tensile strength of the concrete plays a role in limiting cracking due to shrinkage. High tensile strength concrete is less prone to cracking due to shrinkage. According to the standard 3118:2022 [24] with concrete compressive strength values of 35.7 MPa, 37.5 MPa and 38.4 MPa, the corresponding requirements for flexural tensile strength are 4.28 MPa, 4.50 MPa and 4.60 MPa respectively. The experimental results show that all SCC specimens meet the necessary requirements for the correlation of tensile strength in bending according to current regulations.

Figure 8. Compression destroys SF0

Figure 9. Compression destroys SF1

Through visual analysis of the bending test images of the SCC specimens, it is evident that the concrete specimen with 1% steel fiber content exhibited cracks at the compression points with a width of approximately 3-5 mm at the time of failure (Fig. 9). In contrast, the specimen without steel fibers suffered complete fracture (Fig. 8). This demonstrates that the steel fibers, when used, formed connecting bridges to reduce the width of cracks under increasing loads, increasing the ductility of the concrete structure.

The research conducted by author Setiawan [4], using recycled steel fibers with a length of 50 mm and a diameter of 0.8 mm at a 1% steel fiber content, resulted in a 6.98% increase in tensile strength in bending compared to samples without steel fibers. In this study, recycled steel fibers from elevator cables with a length of 2 cm and a 50% orientation ratio, at a 1% steel fiber content, achieved a 5.97% increase in tensile strength in bending compared to samples without steel fibers. The experimental results demonstrate the effectiveness of recycled steel fibers in enhancing the tensile strength in bending, which aligns well with the findings of author Setiawan [4]. This indicates that using recycled steel fibers adds value in enhancing the flexural tensile strength of SCC and is comparable to the use of new steel fibers.

### *3.4. Experimental results on the shrinkage*

a. Plastic shrinkage of SCC

The experimental results indicate that, for all three steel fiber ratios, the soft deformation process mainly occurs in SCC during the first 6-7 hours after concrete mixing. The sample with a 1%

steel fiber ratio (SF1) exhibited the smallest soft deformation, measuring 0.67 mm/m at 8 hours after pouring. In comparison, the sample with a 0.5% steel fiber ratio (SF0.5) had a soft deformation of 2.15 mm/m, while the sample without steel fibers (SF0) experienced the largest soft deformation, measuring 2.37mm/m (Fig. 10).

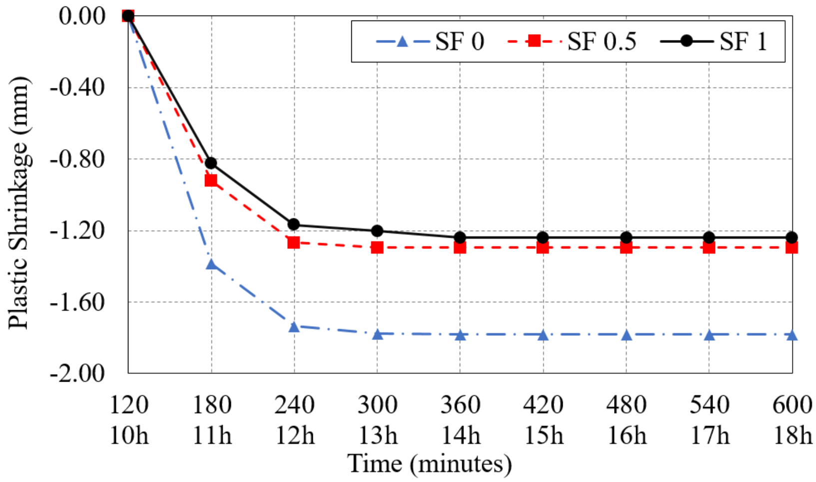


Figure 10. Plastic shrinkage chart in hot weather conditions

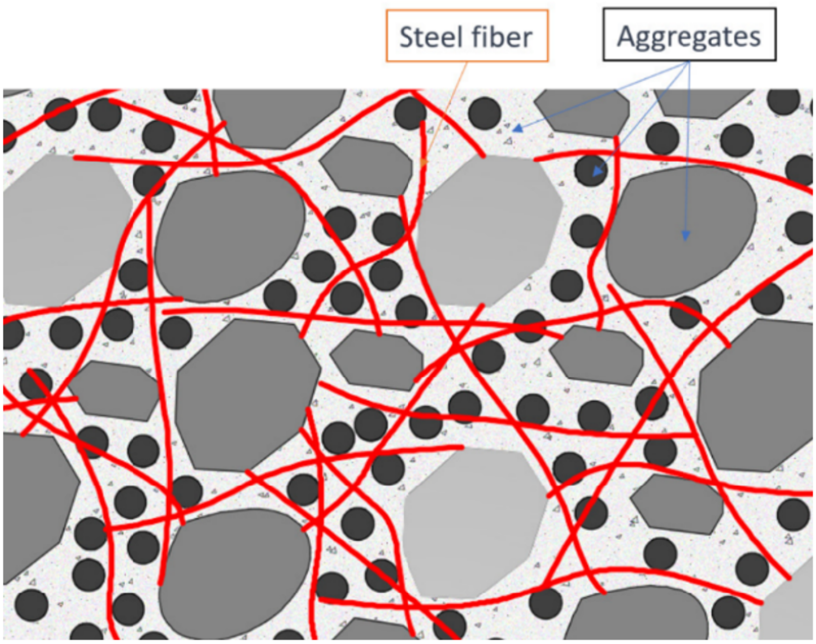


Figure 11. Illustration of the principle of steel fibers limiting deformations in concrete

Thus, under hot weather conditions (autumn season) and with the concrete mixtures specified in Table 1, steel fibers effectively reduced soft deformation during the initial setting period of SCC. A higher steel fiber content resulted in a greater reduction in soft deformation. Compared to the mixture without steel fibers (0% steel fiber ratio), the mixtures with 0.5% and 1% steel fiber ratios reduced soft deformation by 27.34% and 30.47% respectively. The rapid evaporation of water in hot weather conditions led to negative pressures that pulled aggregate particles closer together and caused deformation. However, steel fibers are unevenly distributed and intertwined between the aggregate particles, acting to anchor and preventing the movement of the aggregate particles closer to each other. Therefore, deformation in concrete tends to decrease when using steel fibers. Fig. 11 illustrates the principle of steel fibers restricting deformation in concrete.

b. Drying shrinkage of SCC

At 28 days of age, the drying shrinkage values for mixtures with steel fiber ratios of 0%, 0.5% and 1% were 0.28 mm/m, 0.271 mm/m and 0.267 mm/m, respectively. Therefore, the use of steel fibers had a negligible effect on reducing drying shrinkage, approximately 3.2-4.6% reduction compared to the mixture without steel fibers (Table 6). According to 22TCN 60-84 [35], the concrete's drying shrinkage typically falls within the range of 1 mm/m to 2.5 mm/m under conditions of constant temperature and humidity. This indicates that the drying shrinkage of SCC mixtures is very low. In addition, when comparing it with the plastic deformation values in Table 5, drying shrinkage only represents 0.1-0.15 times the plastic deformation values. The reason for this is that the specimens had a high content of fly ash, which resulted in low heat of hydration, and non-hydrated components acted as aggregates that largely limited drying shrinkage [36]. Therefore, the contribution of steel fibers to reducing drying shrinkage in this case is not significant compared to the contribution of high-content fly ash.

Table 6. 28-day plastic shrinkage and drying shrinkage of SCC mixtures

| Mix | Plastic shrinkage of SCC (mm/m) | Drying shrinkage of SCC (mm/m) | % reduction in drying shrinkage | % reduction in plastic shrinkage |
|---|---|---|---|---|
| SF0 | 2.55 | 0.280 | 0 | 0 |
| SF0.5 | 1.85 | 0.271 | 27.34 | 3.2 |
| SF1 | 1.77 | 0.267 | 30.47 | 4.6 |

It can be observed that increasing the steel fiber content does not significantly reduce the drying shrinkage value. Therefore, when using steel fibers alone to reduce drying shrinkage, the fiber content must be very high. However, the workability of SCC will be decreased, and the construction work may become challenging when dealing with structures having a dense network of thick reinforcement. Additionally, higher percentages of steel fiber can be costly for SCC fabrication. From an economic perspective, Prisco [37] suggests that the optimal steel fiber content should be around 1% of the concrete volume for structural applications.

On the other hand, for fly ash usage, given its much lower cost compared to cement's cost, the higher the replacement ratio, the lower the cost of SCC production. Moreover, increasing the fly ash content helps reduce the concrete shrinkage [20]. Therefore, choosing a reasonable amount of steel fibers, combined with a high content of fly ash, will effectively reduce shrinkage and the production cost of SCC.

## 4. Conclusions

The research results indicate that the use of recycled steel fibers up to 1%, combined with high-content fly ash (accounting for 50% of the binder volume), produces SCC that meets the European guidelines. The mechanical properties of SCC are enhanced when using recycled steel fibers in combination. With a recycled steel fiber content of 0.5% and 1%, the compressive strength of SCC increases by 5.04% and 7.56%, respectively. The flexural tensile strength of SCC increases by 2.99% and 5.97%, respectively. The plastic deformation of SCC decreases by 27.34% and 30.47%, respectively, and the drying shrinkage of SCC at 28 days of age decreases by 3.2% and 4.6%, respectively.

The use of recycled steel fibers demonstrates its effectiveness in enhancing the compressive and flexural strength, reducing plastic and drying shrinkage, as well as improving the overall stiffness of SCC. Furthermore, combining recycled steel fibers with high-content fly ash helps reduce the production cost of SCC and has a positive impact on environmental conservation.

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