Properties of Self-Compacting Concrete Containing Synthetic Fibers

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Abstract. Self-Compacting Concrete (SCC) is valued in civil construction for its capability to flow and compact solely due to gravity without external vibration, which enhances ease of construction, surface finish, and reduces labor costs. Concrete exhibits excellent compressive strength and relatively weak tensile strength and addition of synthetic fibers to SCC may introduce several benefits, such as improved tensile strength, ductility, and crack resistance. This research investigates the impact of 0.5%, 1%, and 1.5% synthetic fiber on the fresh and mechanical characteristics of SCC with 16 mm downgraded stone aggregate. The findings reveal that increasing fiber content reduces flowability, decreases slump flow, increases V-funnel flow time, and lowers the L-box blocking ratio. Despite these reductions, the fresh properties of the SCC remained within acceptable limits as per EFNARC standards. Moreover, the incorporation of synthetic fibers decreases the compressive strength in each age of testing but a notable increase in splitting tensile strength. Therefore, the fibers show the ability to enhance the splitting tensile capacity of SCC. Furthermore, the SCC specimens without fibers exhibit catastrophic failures and break into small pieces due to combined failure whereas SCC specimens containing synthetic fibers failed smoothly by producing minor cracks. Therefore, synthetic fibers aid in resisting the propagation of cracks and making self-compacting concrete more ductile by developing the linking effect between cracks. The study concludes that although synthetic fibers can adversely affect the compressive strength and modulus of elasticity, they significantly improve the splitting tensile strength of SCC and the resistance to crack propagation.

Keywords: Self-Compacting Concrete, Synthetic Fiber, Fresh Properties, Compressive Strength, Splitting Tensile Strength.

1 Introduction

Self-compacting concrete (SCC) represents an innovative advancement in the concrete industry. SCC is developed to flow under self-weight and fill formwork without requiring the mechanical vibration, which ensures complete reinforcement encapsulation and mitigates compaction-related issues. Additionally, SCC presents several advantages

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over traditional concrete such as reducing labor costs and construction time. The necessity for self-compacting concrete was first suggested by Okamura in 1986. The prototype of SCC was first completed in 1988 by Professor Hajime Okamura and his team at the University of Tokyo, Japan. They developed this prototype using materials that included a high amount of fine materials, superplasticizers, and carefully selected aggregates to achieve the desired properties of SCC [1]. The workability of fresh SCC, testing of mechanical properties, and performance of self-consolidating concrete using various mix proportions found that rich mix proportions showed significant improvement in mechanical properties [2]. Furthermore, the fluidity of SCC ensures concrete filling even in the intricate and densely reinforced areas, minimizes voids, and provides more durable concrete with a high-quality surface finish. Also, the noises produced from the vibration can be controlled for projects with strict noise regulations by employing SCC in construction work. Moreover, SCC improves on-site safety by reducing the need for manual vibration, thereby minimizing potential injuries. Finally, it contributes to sustainability by requiring less energy for concrete placement and compaction [3].

Worldwide researchers have investigated various characteristics of self-compacting concrete (SCC) using different aggregates and additive materials. [4] studied the effect of fiber type on the workability and mechanical properties of SCC and found that fibers significantly increase the viscosity, which in turn impacts the passing and filling ability of SCC. The flexural performance of self-compacting concrete incorporating various types of steel fibers was investigated by [5] and found that the flexural performance of SCC is like normally vibrated concrete with rich volume ratio of fibers leading to enhancement of the parameters. The addition of sisal fiber in SCC impacts fresh and mechanical properties, especially the reduction in workability can be mitigated by incorporating mineral admixture, superplasticizer, and viscosity modifying agent [6]. The distribution of fibers affects the shear strength and flexural properties of self-compacting concrete reinforced with synthetic fibers. Polypropylene fibers demonstrated superior mechanical performance compared to polypropylene/polyethylene fibers, attributed to their effective anchorage, which enhanced the stress transfer from the concrete matrix to the fibers [2]. In the past, synthetic fiber was used in different types of concrete applications. Some were used in the conventional concrete industry with varying types of aggregate [8].

This research focuses on the integration of synthetic fibers into SCC. As it is known, one of the biggest advantages of SCC is that it can be placed in heavily congested reinforcing areas, and it is possible to reduce the reinforcing congestion by introducing synthetic fiber-reinforced SCC. Therefore, different percentages of fiber were used in SCC to study its fresh and mechanical properties. This research explored the integration of synthetic fibers as an addition to SCC with stone aggregate aiming to enhance its mechanical properties and durability. Initially, the mix ratio of the SCC was determined, and its fresh properties including flowability, filling ability, and passing ability were assessed by incorporating synthetic fibers produced and evaluating their characteristics. Subsequently, the changes in the mechanical performances such as compressive strength, splitting-tensile strength, and modulus of elasticity of SCC with the incorporation of synthetic fibers were investigated.

2 Materials

The materials used in SCC are similar to those employed in conventional concrete comprising cement, aggregates, and water. However, the proportions of these materials are carefully adjusted in SCC and additional admixtures are incorporated to achieve the desired flow properties and self-consolidating characteristics.

2.1 Aggregates

Aggregates serve as fillers in concrete and affect the properties of SCC, such as workability, strength, and durability, depending on their size, shape, texture, and grading. The range of the size of coarse aggregate is restricted to 20 mm-12 mm according to the EFNARC specification. Therefore, this research used 20 mm down-graded crushed stones as coarse aggregate and well-graded coarse sand was used as fine aggregate for the preparation of SCC. For this research, all the tests required for aggregate were performed according to ASTM specifications. The test data of both fine and coarse aggregates are shown in Table 1.

Table 1. Properties of aggregate

Type of coarse aggregates	FM	Bulk specific gravity			Unit weight kg/m^3	Water absorption (%)
		Oven Dry	SSD	Apparent	Dense	
Stone chips	6.63	2.76	2.83	2.95	1654	2.22
Coarse sand	3.12	2.61	2.63	2.65	1600	0.33

2.2 Binder and Admixture:

Binding material is a substance with both adhesive and cohesive properties, allowing it to bind inert aggregates into a strong and durable compact mass. This study utilized Ordinary Portland Cement (BDS EN 197-1:2010/CEM I) as the binding material to comply with the EFNARC specifications. The normal consistency was 30%, and the initial and final setting times were 150 minutes and 315 minutes respectively of the cement used in this research. Additionally, a locally available superplasticizer called Con-Lub SP (Type A, F & G) shown in Figure 1, which fully complies with ASTM, 2017 [9] standard, was used to prepare the SCC for this research. This ready-to-use liquid superplasticizer significantly enhances the flowability of the mix by reducing the demand for additional water beyond that required for the hydration of cement. Con-Lub SP, a polycarboxylate superplasticizer specially formulate for use in both ready-mixed and precast concrete production, is tailored to meet the demands for high durability and performance.

2.3 Fiber

The locally available synthetic fiber was used for the production of SCC made with stone aggregate. After collecting the bundle of long treads, it is divided into smaller pieces. The length of the synthetic fiber pieces is 25 mm, and the diameter is 0.8 mm. Different percentages of fiber ratio are used in the SCC mix include 0.5%, 1%, and 1.5% by the concrete volume. The photograph of synthetic fiber is illustrated in Figure 1.

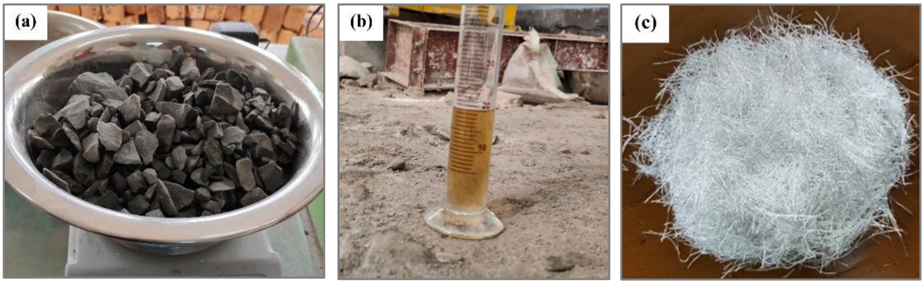

Fig. 1. Materials used in this study - (a) stone aggregate (b) superplasticizer, and (c) synthetic fiber

3 Methodology

The production of synthetic fiber SCC typically involves several steps, materials selection, mix design, evaluation of fresh properties, placing and curing, and investigation of mechanical properties. The experimental investigation of the synthetic fiber SCC used in this research is described below.

3.1 Mix Design of SCC

The SCC mix design process performs a crucial role in concrete research projects and the practical implementation. The trial mixes of SCC were proportioned according to the EFNARC guideline in the laboratory due to the absence of any standard method. SCC mix design can be formulated by either from the relationship between the compressive strength and water-cement (w/c) ratio or by choosing appropriate w/c ratio to satisfy the desired workability, compressive strength, and durability criteria. For the mix design, volume is a key parameter because of the necessity of overfilling the voids space among the aggregate particles. Initially, the water requirements were determined to optimize the flow and stability, followed by the determination of the proportion of the sand and the admixture doses. With experience and judgment, one can also establish the proportions of fine and coarse aggregate. Several trial batches are then produced with varying aggregate, cement contents and w/c ratio to identify the optimal proportions that yield a workable mix with minimal paste content. To obtain a fixed water-cement ratio, the fresh properties of newly mixed concrete were evaluated to ensure compliance with the standard requirements of SCC mix design. After establishing a control mix design ratio, various percentages, 0.5%, 1%, and 1.5% of synthetic fibers are introduced by the volume of concrete. Subsequent trial batches were prepared again to ensure the fresh properties criteria of SCC. Both the unsuccessful and successful proportions of the trial mixes of SCC are presented in Table 2.

Table 2. Proportion of the trial mixes

Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Cement (kg/m^3)	Fiber (%)	w/c ratio	Admixture Dosage (%)	Comments
750	780	420	-	0.35	1.3	Unsuccessful
730	800	420	-	0.36	1.2	Unsuccessful
700	800	430	-	0.36	1.2	Unsuccessful
705	835	430	-	0.37	1.1	Unsuccessful
705	835	450	-	0.37	1.1	Successful
705	835	450	0.5	0.37	1.1	Successful
705	835	450	1	0.37	1.1	Unsuccessful
705	835	450	1	0.37	1.1	Successful
705	835	450	1.5	0.37	1.2	Successful

3.2 Fresh Properties of SCC

The fresh properties are crucial to producing SCC and to ensure these properties, the Slump-flow, V-funnel, and L-box tests were performed to determine the filling ability, viscosity, and passing ability of the SCC as shown in Figure 2. A tilting-type mixture machine was used in this research for the production of self-compacting concrete. In the beginning, the aggregates were mixed for about 30 seconds. After that, 75% of the fresh mixing water, then the cementitious materials, and an additional minute of mixing. and the mixture was stirred for five minutes. Eventually, the rest of the water and the water-reducing admixture (HRWRA) were included, and the mixing was stirred for 15 minutes more. The mixing process led to the formation of large bubbles when the HRWR was introduced, which facilitated the deflocculation of cement particles and enhanced the fluidity of the fresh concrete. Mixing continued until the bubbles disappeared from the concrete surface, resulting in a total mixing time of approximately 22-25 minutes.

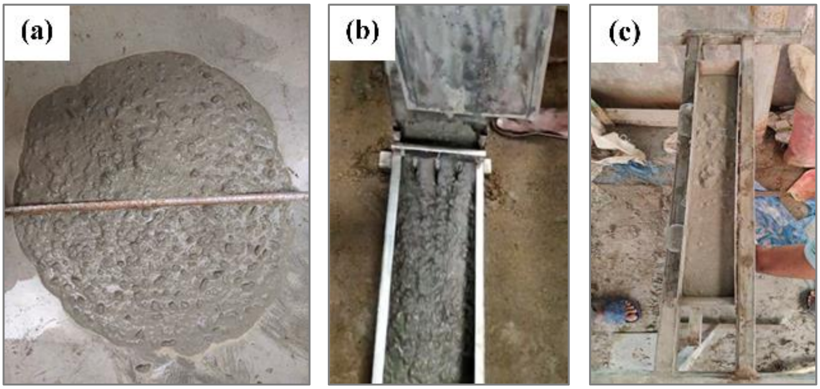

Fig. 2. Investigation of fresh properties - (a) Slump flow (b) L-box, and (c) V-funnel

3.3 Hardened Properties of SCC

The freshly mixed concrete was carefully poured to fill the cylindrical molds with dimensions of diameter of 100 mm, and the height is 200 mm to determine its hardened properties such as compressive strength, splitting tensile strength, and modulus of elasticity. After 48 hours, the solid cylindrical concrete specimens were removed from the mold. Careful attention was given during the removal process to avoid damaging the specimens. Acknowledging the critical role of water in activating cement hydration, effective curing of the concrete was essential. In this investigation, the submerged water curing technique was implemented, and the sample was immersed in a curing tank for a duration of 7, 28, and 56 days to ensure adequate curing and optimal test outcomes. This research includes testing of the concrete sample of cylindrical shape to determine their mechanical properties which are compressive strength, splitting tensile strength, and modulus of elasticity as shown in Figure 3, with the analysis of these results providing valuable insights.

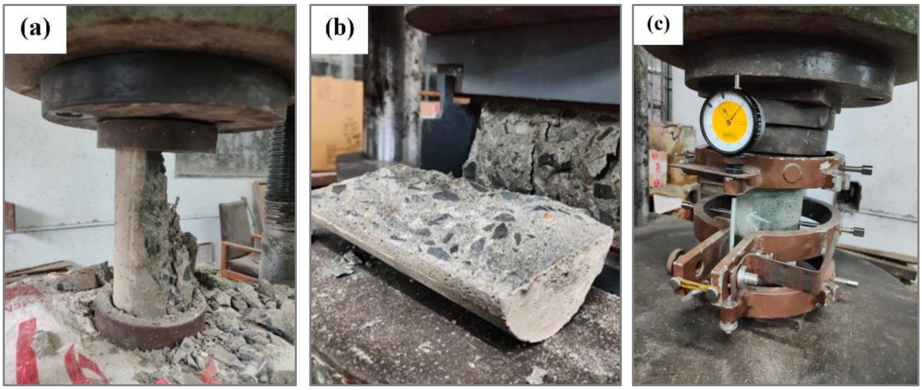

Fig. 3. Mechanical properties testing - (a) compressive strength (b) splitting tensile strength, and (c) modulus of elasticity

4 Results And Discussion

4.1 4.1 Fresh Properties of SCC

The fresh properties of different SCC samples were measured. These properties, which include filling ability (Slum flow), passing ability (L-Box), and viscosity (V-funnel) were evaluated, and the corresponding resulting data are represented in Figures 4, 5, and 6 respectively.

Slump flow. The slump flow results for various SCC mixtures are illustrated in Figure 4 and it is noteworthy that all SCC mixes, even the mixture of SCC containing synthetic fiber, met the required slump flow criteria. The slump flow measurements ranged from 550 mm to 850 mm according to EPG (2005) [10]. Figure 4 shows the highest slump flow result is 650 mm at 0% fibers, while the lowest slump flow value of 605 mm occurs for 1.5% fibers. Slum flow values decreased by 640, 625, and 605 mm with increasing fiber by 0.5, 1, and 1.5 percent respectively. The trend line shows the decrease in slump value as the percentage of fiber rises. Adding fiber to the SCC reduces its flowability and filling ability. [11] reported that the incorporation of the fibers reduced the diameter of the slump flow, and another study by [12] on SCC made with a stone aggregate stated that slum flow diameter decreased with increasing macro polypropylene.

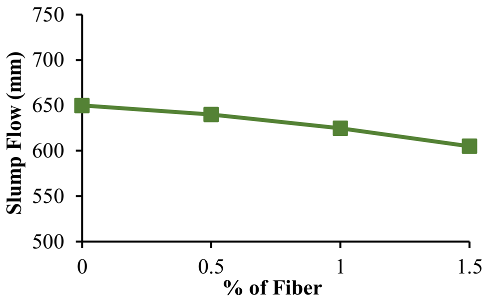

Fig. 4. Slum flow values for different fiber contents

L- Blocking Ratio. The passing ability of concrete, as indicated by the blocking ratio (H2/H1), is evaluated using the L-box flow test. A higher H2/H1 value signifies a better passing ability. Figure 5 shows all of the L-box ratios of the SSC within the acceptable range of 0.8 to 1 [10], [13]. As the percentage of fiber increases from 0 to 1.5%, the L-box ratio drops from 0.925 to 0.81. The trend shows that increasing the fiber content results in the reduction of the passing ability of SCC, at 1.5% fiber content, the ratio is just above the minimum acceptable value of 0.8 as shown in Figure 5. All mixtures exhibited good passing ability with a reduced tendency for segregation, suggesting that SCC has good flow characteristics in dense reinforcement. The use of fibers can significantly increase viscosity, affecting both passing ability and filling capacity because of the interaction between fibers and coarse aggregate, which leads to greater internal resistance to flow and L-box ratio decrease of 0.8 to 0.6 observed by [4]. Using various types of synthetic fiber [11] observed L-box ratio of control SCC 0.88 decreased non-uniformly by 0.86, 0.85, 0.81, and 0.86.

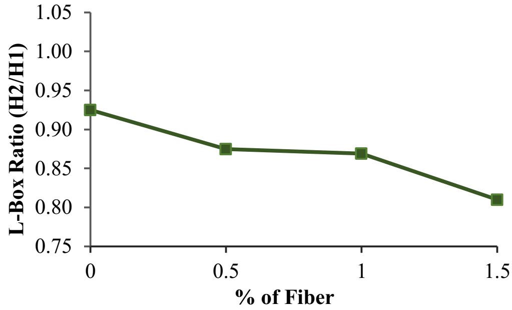

Fig. 5. L-box ratios for different fiber contents

V Funnel Test. A smaller flow time measured by V-funnel indicates improved segregation resistance and better filling ability. Based on the criteria set by EPG (2005) and EFNARC (2002), the acceptable duration for V-funnel flow time falls between 6 and 12 seconds. The flow time values observed in this research satisfied the required criteria. The flow time is approximately 7.3 sec for SCC with no fiber can be observed from Figure 6 and this value falls within the acceptable range. The data series exhibits an upward trend in flow time as the percentage of fiber increases, indicating that adding fibers to the SCC by 0.5%, 1% and 1.5% increases the flow time by 8.1 sec., 9 sec. and 11 sec., meaning the concrete becomes more viscous. [14] reported that the V-Funnel flow times for the various SCC samples were between 8-18 sec made with 10% limestone and natural fiber. [15] reported V-funnel test flow time values of SCC ranging from 9.4 to 20.6 seconds, with some mixture slightly below EFNARC limits.

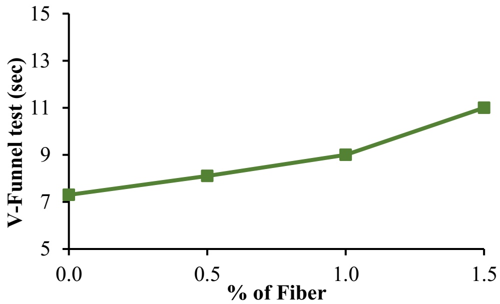

Fig. 6. V- Funnel test of SCC with different fiber contents

4.2 Mechanical Properties of SCC

The mechanical properties of SCC containing synthetic fiber are significant for evaluating its durability and sustainability. This study examined the mechanical properties of SCC through rigorous tests for compressive strength, modulus of elasticity, and splitting tensile strength of hardened concrete. This research results have been indicated in Figure 7, 8, and 9 for detailed analysis and interpretation. Noted that SCC samples produced with 0%, 0.5%, 1.0%, and 1.5% fibers are identified as SCC0%F, SCC0.5%F, SCC1%F, and SCC1.5%F respectively.

Compressive Strength. The compressive strengths of hardened SCC for 7, 28, and 56 days are shown in Figure 7 for the different fiber contents. The size of the cylindrical SCC specimen is around 100 mm in diameter and 200 mm in height. From Figure 7, the compressive strengths are 39.1 MPa at 7 days, 46.9 MPa at 28 days, and 47.73 MPa at 56 days for 0% fiber content. These strengths decrease to 35.81 MPa, 39.1 MPa, and 40.47 MPa for 7 days, 28 days, and 56 days respectively for the SCC containing 1.5% fiber. There is an increase in compressive strength during the early curing period, with an 18% rise from 7 to 28 days and a slight increase of 1.8% from 28 to 56 days, which is consistent across all specimens. As reported by [4], increasing the fiber volume to 0.25% and 0.50% slightly improved compressive strength, and the further increase in fiber contents caused a decline in the compressive strength of SCC. This decline is probably because of inadequate consolidation, as the concrete cylinders were prepared without additional external consolidation. The specimens without fiber exhibited sudden failure under compressive stress, while specimens containing synthetic fibers did not fail abruptly. The inclusion of synthetic fibers contributed to crack resistance and enhanced ductility.

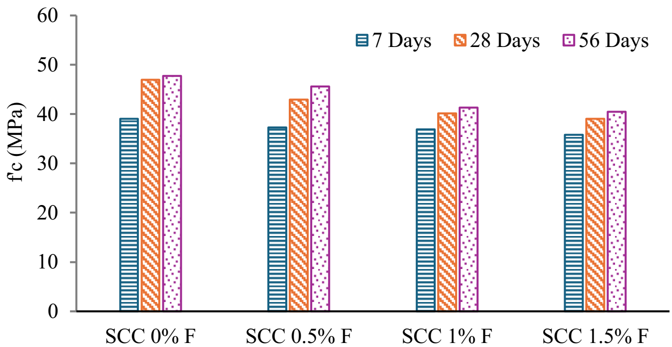

Fig. 7. Compressive strength of SCC at 7, 28, and 56 days for different fiber contents

Splitting tensile Strength. The splitting tensile strength of hardened concrete was assessed at 7, 28, and 56 days. Based on the data presented in Figure 8, the splitting tensile strength of the specimen (0% fibers) at 28 days is recorded at 4.07 MPa. This strength increases to 4.21 MPa, 4.28 MPa, and 4.34 MPa with the inclusion of fiber percentages of 0.5%, 1%, and 1.5%, respectively. Notably, at the 7-day mark, the increase in fiber content from 0% to 0.5% corresponds to a rise in splitting tensile strength. However, adding the fibers from 0.5% to 1% and 1.5% results in negligible enhancement, with some instances reflecting a slight decrease in strength. The concrete cylinder without fibers exhibited sudden failure, resulting in a complete split into two halves, whereas all fiber-reinforced cylinders maintained structural integrity after failure. The enhanced performance can be linked to the fiber's ability to obstruct the initiation and propagation of micro-cracks and control macro-crack development through a bridging mechanism, thereby contributing to the overall increase in splitting tensile strength. [15] observed an improvement in splitting tensile strength from 2.95 MPa to 5.84 MPa with rising monofilament polypropylene fiber from 3 to 9 kg/m^3 in the concrete.

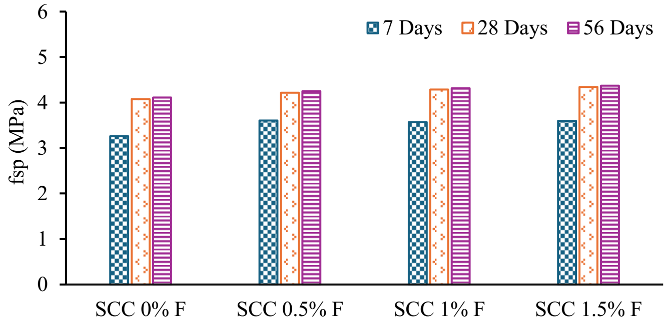

Fig. 8. Splitting tensile strength of SCC at 7, 28, and 56 days for different fiber contents

Modulus of Elasticity. The modulus of elasticity exhibits similar decreasing characteristics, such as compressive strength, with increasing fiber percentage, as illustrated in Figure 9. The incorporation of fiber in SCC results in greater deformation than in non-fiber SCC cylindrical specimens. As the fiber content increases, the modulus of elasticity decreases gradually from 27.72 GPa at 0% fiber to 25.87 GPa at 1.5% fiber. This indicates that adding fibers slightly reduces the stiffness of the concrete.

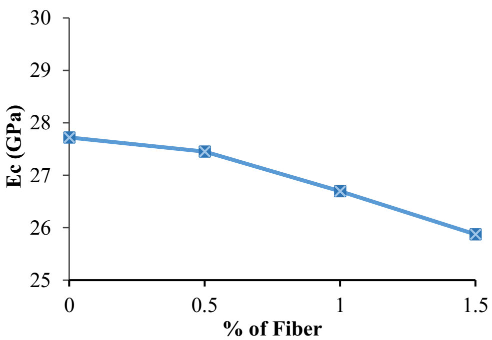

Fig. 9. Variation in the modulus of elasticity of SCC for different fiber contents

5 Conclusions

Reduction in slump flow from 650 mm to 605 mm was observed when the percentage of synthetic fibers increased from 0% to 1.5%. Similarly, the v-funnel flow time was increased from 7.3 seconds to 11 seconds, and the L-box blocking ratio was decreased from 0.925 to 0.81 due to the addition of fiber contents. These findings indicate that the fresh properties of self-compacting concrete, including filling ability, passing ability, and segregation resistance adversely affected due to the incorporation of fibers. Despite these changes, all measured fresh properties remained within the acceptable ranges specified by the EFNARC guidelines.

In terms of hardened properties, the overall compressive strength was reduced by 13% with increasing the fiber content from 0% to 1.5%. Conversely, the splitting tensile strength improved by approximately 8% within the same range of fiber addition. Also, the ratio of splitting tensile strength to compressive strength rose from 8.68% to 11.12% with higher fiber content. This suggests that fibers enhance the tensile strength of the concrete relative to its compressive strength and help control macro-crack propagation through a bridging effect. Additionally, the modulus of elasticity showed a declining trend as same as the compressive strength with increasing fiber percentages.

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