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Research Article

Effect of Fibre Aspect-Ratio on the Fresh and Strength Properties of Steel Fibre Reinforced Self-Compacting Concrete

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This paper presents the findings of investigation, which was instigated to assess the effects of fibre aspect-ratio on the fresh and mechanical properties of SCC. The investigational parameters were aspect-ratio of the fibre and fibre addition rate. Two different aspect-ratios (64 and 73) of steel fibre were used and the fibre addition rate was between 0.2% and 1.0% with the increment of 0.2% and the fibres were added to the SCC in volume fraction. A series of tests were performed to determine the impact of fibre aspect-ratio and fibre inclusion rate on the engineering/mechanical properties of SCC. The presence of steel fibre in the SCC lessened the workability; furthermore, the upsurge in the inclusion rate of steel fibre abridged the workability further. The inclusion of fibre boosted the compressive strength of the SCC moderately, and conversely, an overwhelming increase in flexural and tensile strength was observed. The rise in the fibre aspect-ratio caused a 2.53% augmentation in the compressive strength of the SCC. Nevertheless, more than 11% improvement in tensile strength was observed, because of the bridging/anchorage established by the fibre. From the obtained results, it can be inferred that the impact of fibre aspect-ratio on the compressive strength of the SCC is not substantial; however, the tensile strength properties of the SCC can be enhanced moderately by increasing the fibre aspect-ratio.

1. Introduction

Over the past several decades, various types of special concrete have been used in the construction industry. Among the various conventional concretes, self-compacting concretes (SCCs) are the most widely used ones. SCC is a unique type of concrete and it can fill the formworks by its spread; further, it does not need any hand compaction or vibration [1]. Though the strength capacity of the SCC is comparatively similar to the conservative concrete, the cost allied with the compaction and vibration is relatively zero. Consequently, the SCC application has become extensive in the construction industry. As the event of frequent seismic happenings in recent years, researchers are showing more attention to enrich the energy absorption properties of the SCC [2]. For several years, different types of fibres (especially synthetic and steel fibres) were utilized in the construction industry to enrich the tensile capacity of traditional concrete. Among the various types of fibres, the influence of steel fibres (SF) on enriching the tensile capacity of the concrete was outperformed and it has been in practice for more than decades [3]. The addition of SF controlled the micro- and macrocracking behavior of the concrete matrix thus enhanced the mechanical properties of concrete. The test outcome of Yoo et al. [4] demonstrated that the effects of SF on the early level cracking of concrete were insignificant; nevertheless, the effects on controlling the postlevel cracking were highly significant. Accordingly, the ductile strain capacity of the SCC can be enhanced through the inclusion of steel fibre. The evolution of Fibre Reinforced Self-Compaction Concrete (FRSCC) extends its application in various high-end structural constructions, especially in densely reinforced elements [5].

Wijffels et al. [6] predicted that the presence of fibre significantly distressed the flow ability of the SCC; further, it is recognized that the uniformity in the distribution and the orientation of the fibre is very imperative to conquer the finest benefits of the fibre [7]. The flow characteristic of the SCC chiefly depends on the type of fibre, fibre geometry, and volume fraction [8]. Yehia et al. [18] recognized that the higher friction between the steel fibres and the concrete aggregates impaired the flow ability of the SCC.The augmentation in the strength and the modulus of elasticity of the SCC is much more significant with the inclusion of fibre [9]; however, the existence of fibre compensates for the shabby tensile strength of the concrete and boosts the crack resistance capacity of the concrete specimens.

Over the past few years, some of the research studies have been initiated to evaluate the impacts of steel fibre on the flow and strength characteristics of SCC. However, still more studies are desired to be executed to optimize the inclusion rate of fibres in SCC without compromising the strength and flow properties of SCC. In this focus, a study was started to assess the impacts of fibre aspect-ratio on the fresh and mechanical assets of SCC and also aimed to obtain the optimum inclusion rate of steel fibre content in the production of steel fibre reinforced SCC (SFSCC). The parameters of the present study were fibre aspect-ratio and fibre addition rate. Steel fibres having two aspect-ratios (64 and 73) were used in this study. The steel fibres were added to the SCC with the inclusion rate of 0.2%, 0.4%, 0.6%, 0.8%, and 1.0%, and the fibres were added to the SCC in volume fraction.

2. Experimental Study

2.1. Materials and Methods. Ordinary Portland cement was employed as a binding material to prepare the SCC. According to the procedure recommended in [10], the OPC was tested for specific gravity, and the determined specific gravity of the OPC was 3.11. The hydroxyl-propyl, methylcellulose, and poly-carboxylic based superplasticizer were utilized to increase flow characteristics. Regular sand with a grain size between 1 mm and 3 mm was used as fine aggregate. Two size of coarse aggregate, having an average size of 8 mm and 14 mm, were used to prepare SCC. A hooked type fibre having two dissimilar aspect-ratios was used to augment the tensile properties of SCC. Table 1 summarizes the properties of SF.

2.2. Mix Proportions. The SCC mixtures were designed to attain a mixture with reasonable/moderate cement content and the mixtures were designed to accomplish all the fresh concrete properties even with the addition of fibre. The water-cement ratio of 0.50 was employed throughout the study. Even with the inclusion of fibre, to obtain the required fresh concrete properties, the superplasticizer with a percentage of 1.50% to 2.0% was used in this study. To ascertain the most favorable distribution of the aggregates, dry packing density was acquired conferring to the procedure recommended in ASTM C29/29M-09 [11]. Fine aggregate and coarse aggregate distribution were considered as 50% and mixture details are provided in Table 2.

2.3. Mixture Fabrication and Testing Methods. A tabletop concrete mixer was used to prepare all the SCC mixtures, and the mixtures were prepared with the fibre addition rates of 0.2%, 0.4%, 0.6%, 0.8%, and 1.0%. All the concrete mixtures were prepared at room temperatures, and they were cured (water immersed curing) at a temperature of 28°C. In order to govern the compressive strength of all mixtures, cubes having a size of 150mm × 150mm × 150 mm were prepared and they were tested at the age of 7, 28, and 90 days using CTM with the capacity of 2000 kN. To determine the impact of steel fibre on the tensile behavior of concrete, concrete cylinders and prism having a size of 150 mm × 300 mm and 100 mm × 100 mm × 500 mm, respectively, were prepared and they were tested at the age of 7, 28, and 90 days. All the cylinders and cubes were prepared layer by layer, and every layer was vibrated perfectly.

3. Discussion on Results

3.1. Fresh State Properties. Slump flow and V-funnel tests were implemented to ascertain the fresh state stuffs of the SCC, and the fresh state stuffs of the SCC were tested conferring to the technique suggested in the EN: 12350-8 and [12], respectively. The test results revealed that the addition of SF into the fresh concrete caused a substantial diminution in the fresh properties; furthermore, a further decrease in workability was witnessed with the upsurge in the addition rate of fibre. Alberti et al. [5] anticipated that the flow properties of the SCC were significantly influenced by the steel fibres. However, the FRSCC fresh properties fulfilled the verge value endorsed in most shared standards and the recommended values were slump flow spread (d_f) should be between 500 mm and 850 mm and a slump patty flow should reach the diameter of 500 mm before eight seconds, further, the V-funnel emptying time must be lower than 25 seconds. Figures 1 and 2 present the impact of fibre on the fresh state stuffs of SCC.

The reference mixture exhibited a slump flow spread of 701 mm, whereas, the mixtures AR64-0.2%, AR64-0.4%, AR64-0.6%, AR64-0.8%, and AR64-1.0% reached a slump spread of 685 mm, 665 mm, 633 mm, 605 mm, and 581 mm, respectively, which are 2.33%, 5.41%, 10.74%, 15.86%, and 20.65%, respectively, lesser than the reference mixture. The presence of the steel fibre in the SCC created a fibre-binder network in which the distributed fibres were

Table 1: Physical and mechanical properties of fibres.

Fibre type	Diameter of the steel fibre (mm)	Length of fibre (mm)	Aspect-ratio of the fibre	Modulus of elasticity (N/mm^2)	Tensile strength (N/mm^2)	Anchorage	Surface texture
Steel fibre	0.55	35	64	210000	1150	Hooked	Smooth
	0.55	40	73		1150		

Table 2: Mixture proportions.

Material description	Quantity/M^3
Cement	247 kg
Fly ash	157 kg
Natural sand	856 kg
Coarse aggregate (5 mm to 9 mm)	452 kg
Coarse aggregate (10 mm to 14 mm)	452 kg
Water/binder ratio	0.50 Litre
Super plasticizer	1.5% to 2.0% of cement mass

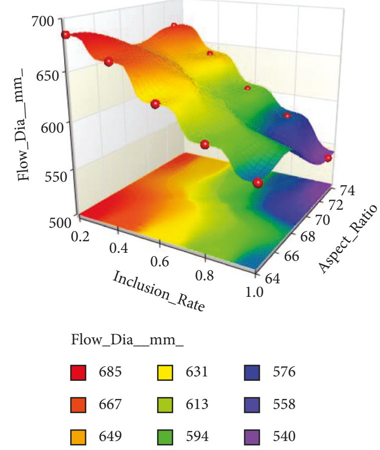

Figure 1: Effects of fibre inclusion and the increase in aspect-ratio on slump flow spread.

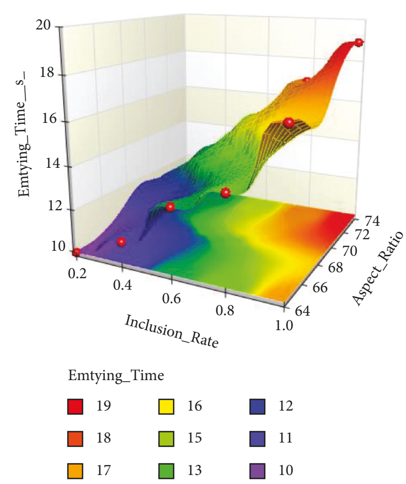

Figure 2: Effects of fibre inclusion and the increase in aspect-ratio on emptying time of the V-funnel test.

covered by the cement mortar of the SCC to form a fibre–binder interfacial attachment. That fibre-cement matrix network restricted the flow ability of the fresh concrete, which led to the reduction in the flow spread. In addition to that, the higher density of the steel fibre restricted the flow ability of the fresh concrete, leading to reduction in the fresh state stuffs of the SCC. Figure 2 shows the impacts of fibre addition on the discharging stretch of the V-funnel test. From Figure 2, it is understood that the SCC with steel fibre took more times for emptying; in addition, the higher inclusion of fibre content extended the clearing time further.

The effect of an increase in the fibre aspect-ratio on the fresh state stuffs of SCC is presented in Figures 1 and 2. The rise of the fibre aspect-ratio abridged the flow spread of the SCC; however, the lessening was within the optimum values and the reflections were agreed with the findings of Soon et al. [13]. The mixture AR64-1.0% attained a spread of 581 mm, while AR73-1.0% unveiled a spread of 540 mm, which is 7.59% lesser than the AR64-1.0%. The outcome of the V-funnel test also exposed the same (Figure 2). The upsurge in the fibre aspect-ratio decreased the emptying time of the test. When compared to mixture AR64-1.0%, the mixture AR73-1.0% revealed an 11.76% upper emptying time.

3.2. Compressive Strength (CS). The study outcomes regarding the CS development of SFRSCC combination for all ages with the insertion of steel fibre are presented in Figure 3. Since the inclusion of steel fibre was pretentious to the flow capacity of the SCC, it was expected that there may be a drop in the CT of the SCC. Contrariwise, the inclusion steel fibre in the SCC reasonably improved (approximately 5 to 6%) the CS of the SCC; furthermore, the upsurge in the steel fibre volume improved the compressive strength of the SCC further. It is well acknowledged that the addition of fibres does not enhance the CT of the SCC significantly, instead, will enhance the stretchy strength (Tensile) of the concrete. The findings of the current study also unveiled the same. From Figure 3, it can be agreed that the 28 days compressive strength values of the mixtures AR64-0.2%, AR64-0.4%, AR64-0.6%, AR64-0.8%, and AR64-1.0% were higher than those of the reference mixture (CM). At the age of 28 days, the SCC mixtures AR64-0.2%, AR64-0.2%, AR64-0.4%, AR64-0.6%, AR64-0.8%, and AR64-1.0% increased their compressive strength by 2.41%, 2.97%, 4.44%, 5.44%, and 5.74%, respectively, compared to the CM. The augmentation in the CS of the SFRSCC is exclusively credited to the presence of steel fibre. During an increase in the

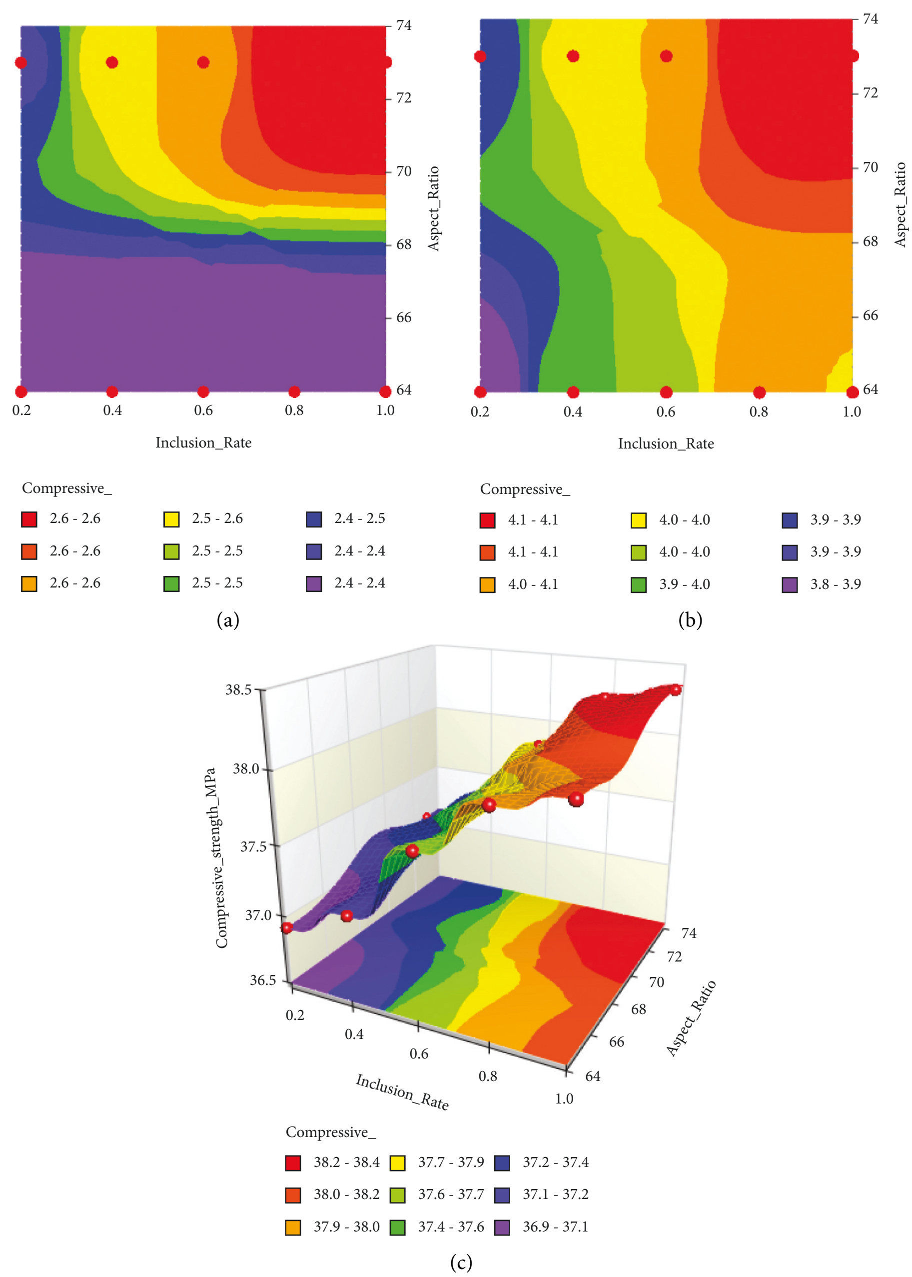

Figure 3: Effects of steel fibre inclusion rate and the increase in aspect-ratio on the compressive strength of SCC–comparison.

compression loading, cracks will be initiated in the concrete and progress. When the progressive crack reaches a fibre, the de-bonding at the fibre-mortar interface may initiates because of the tensile stresses upright to the anticipated path of the progressing crack. As the progressing crack reaches the interface, the crack tip stress attentiveness will be abridged, and the spread of cracks is soothed and blocked. This crack attractive ability or linking effect of the fibre led to the upsurge in the CS of the SFSCC. It was recognized that the increase in the inclusion rate of fibre may have an undesirable effect on the strength properties of the SCC and the observation of this study fairly coincide with the previous study. As shown in Figure 3, at all ages, the inclusion rate beyond 0.80% displayed an unarticulated effect on the CS enhancement. At the age of 28 days, compared to mixtures AR64-0.2%, AR64-0.4%, and AR64-0.6%, the mixture AR64-0.8% enhanced its compressive strength of 2.9%, 2.31% and 1.01%, respectively, whereas the mixture AR64-1.0% has shown only 0.31% enhancement in CS when compared to AR64-0.8%. As the rise in the fibre volume may generate the mortar demand to advance the fibre-cement network, there was an unarticulated consequence on the CS was observed. The further reason may have been deprived self-compaction of SCC due to the upper volume of fibre.

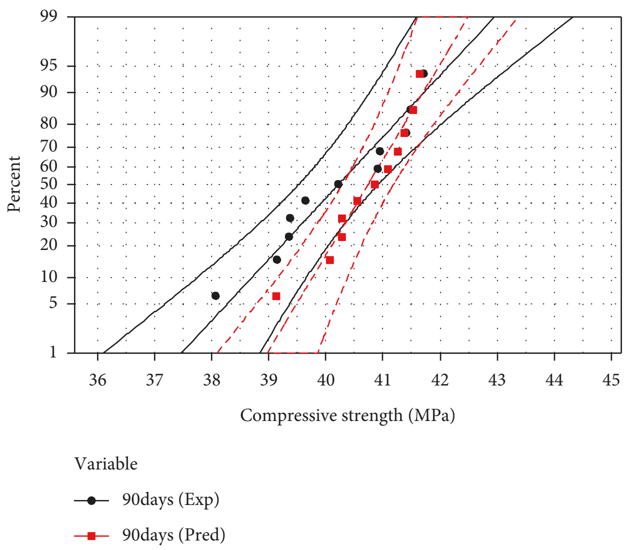

Figure 4: Comparison between measured and calculated 90 days compressive strength.

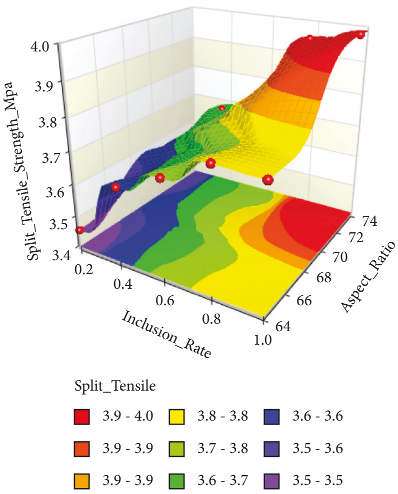

Figure 5: Effect of fibre inclusion rate and the increase in aspect-ratio on the 28-days split tensile strength of SCC–comparison.

It was expected that the the fibre aspect-ratio increases, the CS of the mixture may increase. Nevertheless, no significant enhancement in CS was observed, however, a small amount of increase in strength (ranges from 0.61% to 2.53% enhancement in CS was witnessed. At the time of 28 days, the specimen AR73-0.6% showed a compressive strength of 37.85 N/mm^2, which is 0.08% higher than the AR64-0.6%. As the aspect-ratio of the fibre was complete, the cubes were more intact and the ductile failure mode of the cubes was increased due to the enhancement in the strong bond (bridge effect) between the concrete and the fibre. From the reflection, it can be inferred that the CS properties of the concrete cannot be modified by as upsurge in the fibre aspect-ratio.

According to equation (1) commended in [14, 15] Type 1 the CS development of SFRSCC mixture upon aging was predicted.

$$f_{cm}(t) = f_{c28}\left(\frac{t}{4 + 0.85t}\right), \quad (1)$$

where f_{c28} is 28 days CS of the concrete, and t is time in days. As shown in Figure 4, the linear regression line prepared between the calculated and measured CS and the regression line made was also strong. Since the regression analysis is too strong, it can be implicit that the impact of fibre inclusion is not significant on the CS of the SCC.

3.3. Splitting Tensile Strength (STS). The vital property of the hardened SFRSCC is the STS. The STS of all combinations were governed at the age of 7, 28, and 90 days and presented in Figure 5. Unlike compressive strength, there was a significant enrichment in tensile strength was observed with the addition of fibre and the increase in the volume fraction of the steel fibre heightened the STS of the SCC further. The augmentation in STS of the SCC obtained with the addition of steel fibre may because of the linking results of the fibres and the upper elasticity modulus of the steel fibre. The discrete fibre in the SCC established a bridging between the fibre and concrete, thus enriching the STS of the toughened SCC. For instance, at the age of 28 days, the mixtures AR73-0.2%, AR73-0.4%, AR73-0.6%, AR73-0.8%, and AR73-1.0% improved their tensile strength by 8.38%, 11.51%, 13.21%, 16.13%, and 17.01%, respectively, than that of CM. From the results, it can be decided that the enhancement in the STS of the SCC with the inclusion of fibre is significant when compared to the enrichment of the CS. Like compressive strength, the mixtures AR64-0.8% and AR73-0.8% exhibited a more unpronounced increase in tensile strength due to the mortar demand and the poor self-compaction of SCC due to the upper volume of fibre.

The upsurge in the aspect-ratio was unveiled noticeable effect on the STS enhancement of the SCC (See Figure 5). At the time of 28 days, the specimen AR73-0.6% unveiled an STS of 3.75 N/mm^2, which is 2.73% higher than that of AR64-0.6%. Since the upsurge in the anchorage developed by the fibre enriched with the rise in the aspect-ratio, there was a significant augmentation in STS was observed with the rise in the aspect-ratio.

So it can be inferred that the STS of the concrete can be enhanced by increasing in the aspect-ratio of the fibre.

3.4. Flexural Strength (FS). The flexural strength of SFRSCC is determined at the stage of 7, 28, and 90 days is presented in Figure 6. Like STS, the FS of SCC was boosted with the addition of SCC. Moreover, more augmentations in strength were perceived with a rise in the addition rate. However, beyond the addition rate of 0.80%, no significant enhancement in the FS was observed. At the age of 28 days, the mixtures AR64-0.2%, AR64-0.4%, AR64-0.6%, AR64-0.8%, and AR64-1.0% achieved a flexural strength of 4.79 N/mm^2, 5.02 N/mm^2, 5.11 N/mm^2, 5.25 N/mm^2, and 5.29 N/mm^2, which are 7.69%, 12.89%,

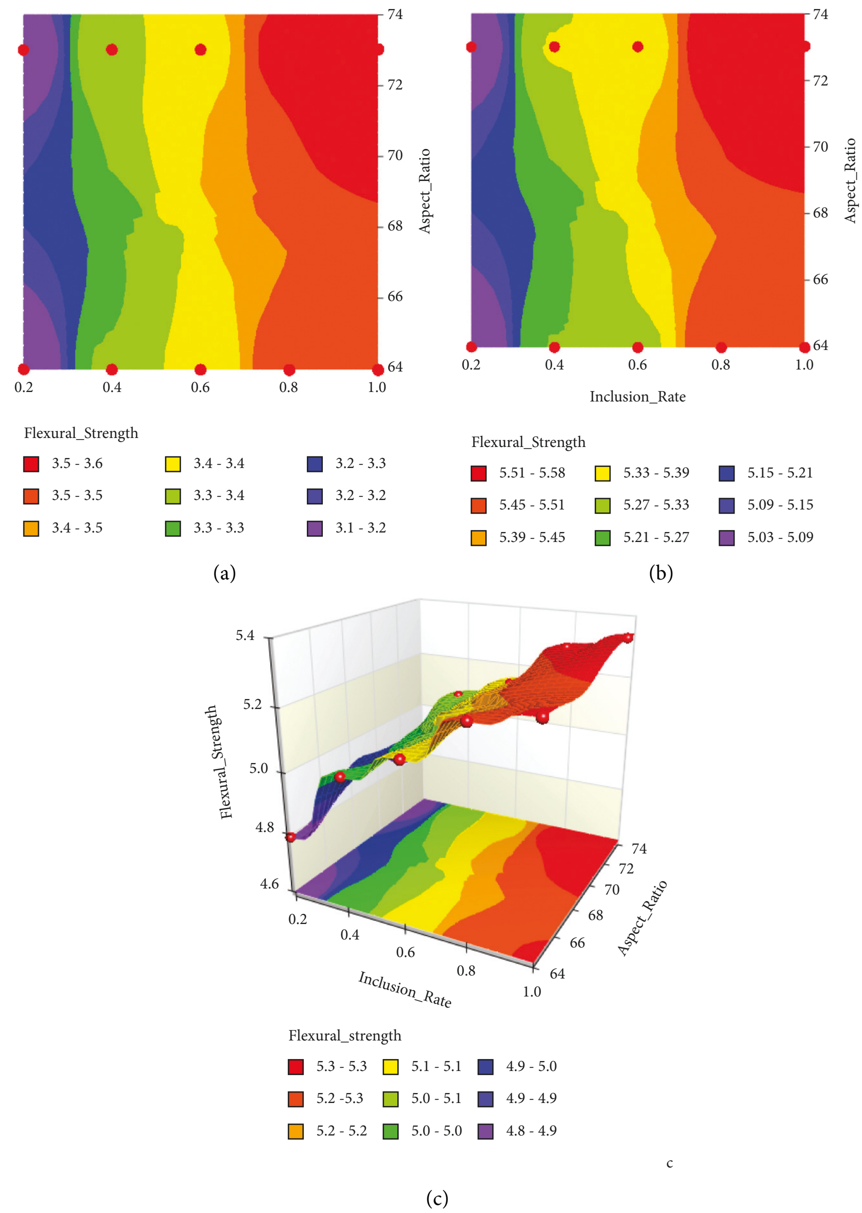

Figure 6: Effect of steel fibre inclusion rate and the increase in aspect-ratio on the flexural strength of SCC, comparison.

14.08%, 18.01%, and 17.43%, higher than that of the CM, which achieved a flexural strength of 4.67 N/mm^2. The reason for this enhancement in strength has been discussed in the earlier chapter. It was observed that at all ages, the upsurge in the steel fibre aspect-ratio boosted the flexural strength of the SCC further, and the mixture with the aspect-ratio of 73 has shown more enhancement in the strength when compared to the mixture with the aspect-ratio of 64. For instance, the FS of the specimen AR73-0.6% was 5.15 N/mm^2, which is 1.7% higher than the specimen AR64-0.6%. The above observation fairly coinciding with the STS.

The correlation between the CS and FS is provided in IS456-2000 and the following equitation is recommended to predict the FS of concrete from available CS results:

$$f_{ft} = 0.70 \times \sqrt{f_{ck}}, \quad (2)$$

where f_{ft} is the flexural strength of the concrete and f_{ck} is the compressive strength of the concrete. Based on equation (1), the FS of all mixtures was predicted and the relationship between the measured and calculated FS is presented in Figure 7. From Figure 7, it can be seen that the correlation was not good and the variation between the measured and calculated flexural strength was between 2% and 4%. Since the unpronounced effect of fibre addition on the compressive strength and the pronounced effect on the flexural strength, there was a significant variation in the measured and calculated flexural strength.

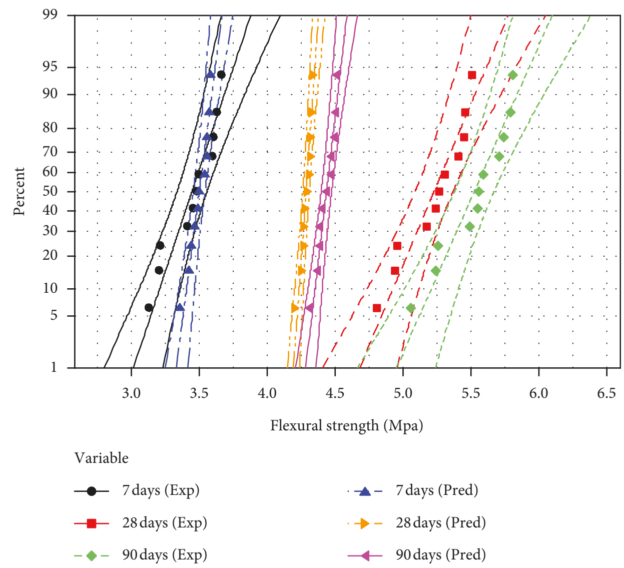

Figure 7: Comparison between measured and calculated flexural strength from compressive strength.

4. Conclusion

The consequence of fibre aspect-ratio on SCC was investigated through flow and engineering properties of the SCC. The formation of the fibre mortar matrix caused reduction in the flow ability of the SCC. Also, the rise of the fibre volume abridged the flow ability of the SCC. The inclusion of 1.0% of fibre resulted in a 20.65% reduction in the slump flow spread. Since the formation of the fibre mortar matrix and the density of the fibre is proportional to the fibre aspect-ratio, 14.01% reduction in flow properties was witnessed regarding the upsurge in the fibre aspect-ratio. The presence of steel fibre in the SCC moderately enhanced the CS of the SCC. Conversely, there was an overwhelming increase in STS and FS observed. The upsurge in the aspect-ratio of the fibre resulted in a 4.53% enrichment in the CS of the SCC. Nevertheless, more than 5% enhancement in STS and FS was observed, since the bridging/anchorage developed and the tensile stress advanced by the fibre is proportionate to the fibre aspect-ratio. It can be inferred that the CS properties of the concrete cannot be modified by an upsurge in the aspect-ratio of the fibre; however, the tensile and flexural strength properties of the SCC can be enhanced by an increasing in the aspect-ratio of the fibre.

Data Availability

The data used to support the findings of this study are included in the article.

Disclosure

This study was performed as a part of the employment of Samara University, Ethiopia and GMR Institute of Technology, Rajam, Andhra Pradesh, India.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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