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ANALYSIS OF THE ALIGNMENT OF MICRO-STEEL FIBERS IN ADMIXTURE-BASED SELF-COMPACTING CONCRETE (MSFR-SCC) USING NDT AND EVALUATION OF ITS EFFECT ON THE MODULUS OF RUPTURE

Athiyamaan V.[1], G. Mohan Ganesh[1*]

[1]*School of Civil Engineering, Vellore Institute of Technology, Vellore 632014, Tamilnadu, India*

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ABSTRACT

Self-compacting concrete (SCC) is a particular type of concrete that flows and becomes consolidated under its own weight. Various have been conducted to enhance its performance. Key developments have been the addition of fibers and replacement of the mineral admixtures; several studies have focused on varying these factors in different proportions to produce a high performance concrete. However, there is no standard mix design for self-compacting concrete containing admixtures. Therefore, optimization of the mix design is very important in order to save time and to develop an economical SCC, but there has been no detailed study of mix design and optimization of materials, and no research into the alignment and orientation of the steel fibers. Along with the uniform dispersion of fibers, few steps have been taken to optimally align the micro steel fibers, with ultrasonic pulse velocity used to justify their distribution and alignment. These factors were taken into consideration in this study. The results show that the addition of steel fibers reduces the rheological properties of the concrete by 40%-55% compared to the control mix (MC1), although all the mixtures (MC1-MX4) justified the guidelines set by EFNARC (European Federation of National Association Representing for Concrete). All the specimens failed under shear. The addition of hooked-end micro steel increased the flexural strength compared to the control mixture and a 60% increase in MX4 and 75% increase in MA7 were observed compared to MC1. The fibers were aligned along the direction of flow and the alignment properties was justified by flexural strength and UPV. A regression equation was finally developed between flexural strength and UPV for future development, which predicts the behavior of micro steel fiber reinforced self-compacting concrete (MSFRSCC).

Keywords: Flexural strength; Micro steel fiber; Orienting; Self-compacting concrete; UPV

1. INTRODUCTION

1.1. General

Self-compacting concrete is a special concrete that has been desired as wide ranging development in concrete construction for several decades. The concept of SCC was first introduced by Okamura in 1986 (Okamura & Ouchi, 2003) as a concrete that was able to fill the formwork without any vibration. But the design procedure and the limitations were missing. In February 2002, EFNARC published guidelines and specifications on testing the fresh concrete properties of self-compacting concrete, but there were no specific guidelines on the definition of either the mechanical properties or mix design procedure. In 2001, Nan Su et al. developed a

*Corresponding author's email: gmohanganesh@vit.ac.in, Tel. +91-416-2202850/1/2, Fax. +91-416-2243092
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mix design procedure for self-compacting concrete, which incorporated the idea of filling voids to the maximum extent by calculating the packing factor of the aggregates. This mix design method helps to fix the required target strength and design accordingly, as well as helping to reduce the cost, time and energy that are wasted during the trialling of mixes and to define the target strength. Concrete has high compressive strength and stiffness, low combustibility and toxicity, and low thermal and electrical conductivity, although brittleness and tension are the two main characteristics that limit its uses (Bhalchandra & Pawase, 2012). However, the improvements in fiber-reinforced composites (FRC) have contributed to enhancing the inadequacies of concrete. The addition of steel fibers improves its ductility properties (Antonius, 2015) and helps to enhance different mechanical properties, such as resistance to fire and reduced plastic shrinkage, in addition to improving the sustainability of SCC (Mazaheripour et al., 2011; Sideris & Manita, 2013). The incorporation of macro steel fibers affects the workability of fresh concrete, making the matrix stiffer. Figure 1 shows the influencing factors of SCC containing fibers. It is important to be aware of the factors that influence the flow ability of self-compacting concrete with fibers (fiber-reinforced self-compacting concrete - FRSCC) in order to select the exact material for achieving optimal performance. In this study, the mix proportions were obtained using the Nan Su method by fixing the required target strength, where the traditional method was lagging behind. An attempt was made to study the impact of mineral admixtures and steel fibers over fresh and hardened properties of micro steel fiber with SCC (MSFRSCC).

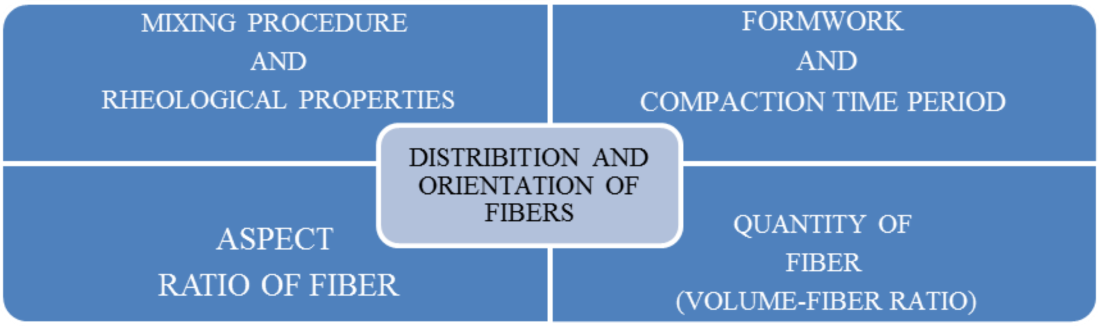


Figure 1 Factors influencing the orientation and dispersion of fiber-reinforced concrete

Despite the fact that higher proportions of fibers gave better flexural quality, the workability of SFRC (steel-fibre reinforced concrete) was observed to be negatively influenced by the aspect ratios and proportions. Therefore, the aspect ratio is the most important constraint to accomplishing ideal workability and quality. In addition, the density of steel fibers is higher in the composite materials; because of this fibers could become isolated at the base of the mold during vibration, causing uneven scattering and affecting the homogeneity of the blend (Gettu et al., 2005). Hence, by taking advantage of the rheological properties of SCC in a fresh state, which fills formwork without vibration, the steel fibers can be added to the mix to produce micro steel fiber-reinforced self-compacting concrete (MSFRSCC), with a more uniform fiber dispersion in a highly workable mixture. Since the aspect ratio of steel fibers is directly proportional to their tensile strength and elastic modulus, hooked-ended micro steel fibers were used in this study (Won et al., 2013; Lee et al., 2015). SCC requires more cementitious material, which can be counterbalanced by using mineral admixtures such as fly ash and micro silica fume. Fly ash enhances workability because of its spherical-shaped particles, while micro silica fume helps in early strength (Eddhie, 2017). No study has been conducted on aligning or orienting the fibers. Hence in this study, along with the uniform dispersion of fibers, few steps were taken to align the micro steel fibers. Flexural strength and ultrasonic pulse velocity were used to justify the distribution and alignment of fibers. Initially, the mix design of self-compacting concrete was developed using the Nan Su method.

1.2. Application of Non-Destructive Testing (NDT) to Fiber-Reinforced SCC (FRSCC)

European standard EN 14721 characterizes various testing methods for the metallic fiber content of concrete. However, these methods are insufficient for evaluating current study. Numerous other NDT and destructive logical techniques have been proposed. Non-destructive testing plays an essential role in distinguishing and recognizing deformities and cracks in numerous modern applications; for example, concrete structures, asphalts and metal testing (Wankhade & Landage, 2013). Non-destructive testing methods are used to classify and make detailed studies of the existing structure without disturbing it, so these techniques play a vital role in evaluating the mechanical characteristics of concrete structures (Tsioulou et al, 2017). The mechanical properties and stress pattern of FRC mainly depend on the alignment and dispersion of fibers in the matrix during the mixing and placing of the concrete. The introduction of self-compacting concrete into the market increased interest in studying and optimizing the distribution and orientation of fibers using the improved rheological properties of SCC. The commonly used NDT methods include CT scan - X-ray computed tomography (Pujadas et al., 2014), which provides detailed photographic images of the different composite materials present in concrete and helps to study their orientation and alignment. However, this method consumes more time and is economically inefficient. Electrical resistance tomography (ERT) is based on the injection of a current and fluctuation in the voltage received from object boundaries. The microwave non-destructive testing technique - ultrasonic and acoustic -is used to gauge the time required for the ultrasonic wave to go through the testing sample. By knowing the time and distance travelled, the wave speed through the material can be calculated, which helps to validate the sample accordingly (Gebretsadik, 2013). Table 1 shows the main advantages of fiber-reinforced self-compacting concrete over fiber-reinforced normally vibrated concrete.

Table 1 Advantages of FR-SCC over FR-Normally Vibrated Concrete (FR-NVC)

FR-NVC (Fiber-Reinforced-Normally Vibrated Concrete)	FR-SCC (Fiber-Reinforced Self Compacting Concrete)
Chance of the accumulation of fibers forming ball shapes due to inadequate workability.	Distribution and suspension of fibers is even throughout the matrix.
Poor compaction leads to the settlement of fibers due to the variation in densities (steel > concrete).	This effect is prevented due to its natural self-compacting effect and the suspended fibers are not disturbed further.
Alignment and distribution of fibers along the required direction is impossible.	Due to its flowability and optimized rheological properties, fibers can be aligned along the direction of flow.
There is only the technical advantage of the discrete distribution of fibers over conventional concrete.	By aligning the fibers along the direction perpendicular to the direction of the load, its flexural properties can be further enhanced.

2. EXPERIMENTAL PROGRAM

2.1. Material Properties

Cement, fly ash, micro silica fume, fine aggregate, course aggregate, super plasticizer and micro-steel fibers were the materials employed for experimenting the fresh properties and hardened properties. The properties of the materials used are discussed below.

2.1.1. Cement

Cement is a binding material used in concrete, which sets, hardens and adheres to fine and coarse aggregate, binding them together. The commonly used cement is Ordinary Portland Cement (OPC); OPC conforming to IS 12269:1987 for 53 grade cement was used in this study.

2.1.2. Fly ash

Fly ash is a residue obtained from the combustion of powdered coal. The flue gases from the chimneys are collected by an electrostatic precipitator. In most countries it is known as pulverized fuel ash (PFA). It is most commonly used as a pozzolanic material in various parts of the world and is made up of the noncombustible mineral constituent of coal. It is mostly glassy in texture, spherical in shape like a ball bearing, and finer than cement. The size of the particles ranges from 0.1μm to 150μm. This pozzolanic material reacts with free lime in the presence of water, forming calcium silicate hydrate (C-S-H), which contributes to the strength and durability of concrete. Table 2 shows the properties of fly ash acquired from the Neyveli Thermal Power Plant, conforming to IS 3812:2003. This plant is situated in Neyveli Tamil Nadu, India. The specific gravity of the fly ash used in this study was 2.18.

Table 2 Chemical properties of fly ash

Chemical Component	Percentage
Silica (SiO_2)	58.65
Alumina (Al_2O_3)	15.65
Iron-oxide (Fe_2O_3)	6.08
Calcium-oxide (CaO)	3.50
Magnesium-oxide(MgO)	0.28
Trioxide (SO_3)	0.16

2.1.3. Micro silica fume

Silica fume is a fine, dust-like siliceous material with pozzolanic properties; it is spherical in shape, with a diameter of 50nm-100nm. Its texture can be advantageous ingredient in developing optimized self-compacting concrete. The micro silica, including its properties, was obtained from Elkem Microsilica grade 920, which had a specific gravity of 2.2.

2.1.4. Aggregate

Fine aggregates can be obtained from natural sources or manufactured artificially; those used in this study were sieved with a 4.75mm sieve and the particles retained on a 2.36mm sieve. They conformed to IS 383-1987. The moisture content and water absorption of the fine aggregates were closely observed. The sand employed was procured from the Palar river, Vellore, Tamil Nadu. Coarse aggregates passing through 12.5mm sieve and retained in 10mm sieve, conforming to IS 383:1987 were used for the study. The aggregates were crushed and were angular in shape.

2.1.5. Steel fibers

dataset - sise of dataset – Methodology text – sise of dataset - sise of dataset - sise of dataset - One of the greatest advantages of the steel fiber reinforcement of concrete is the enhancement in flexural toughness (the total energy absorbed by the composite concrete in flexure) (Selvamani, et al., 2016). A discrete hooked-end steel fiber with an aspect ratio (l/d) of 60 was used for the study.

2.1.6. Super Plasticizer (SP)

Master Glenium SKY 8233 was used as a high-range water reducing super plasticizer, being a modified polycarboxylic ether based super plasticizer. The specific gravity of the SP used was 1.08.

2.2. Mix Design and Mix ID

The initial mix design was calculated based on the Nan Su method and an optimized mix design was derived with the help of design of experiments (DOE); five variables and two responses are clearly shown in Table 3. The procedure and optimization was explained in detail by (Athiyamaan & Ganesh, 2018).

Table 3 Mix proportion

Total Binder kg/m^3	Fine Aggregate kg/m^3	Coarse Aggregate kg/m^3	Water kg/m^3	HRWR kg/m^3	S/A	Packing Factor	Slump Flow	Compressive Strength MPa	Density kg/m^3
525	935	710	231	8.925	0.56	1.10	720	60.8	2409.9

The initial proportions were computed using the Nan Su method of mix design, and the derived mix proportion was further optimized using the DOE approach. Seven concrete mixtures were designed in order to study the rheological properties, the alignment of steel fibers and the mechanical properties by varying the proportions of the fibers in the self-compacting concrete. The first mixture was the control mix of self-compacting concrete, denoted as MC1. In the second, third and fourth mixtures, hook-ended micro steel fibers with an aspect ratio of 60 were added in proportions of 0.25%, 0.50% and 0.75%, to the total volume of concrete and were denoted by MX2, MX3 and MX4, respectively. All seven mixes contained identical quantities of mix proportions, with 40% replacement of the total binder content (FA-30% & micro silica fume of 10%), as shown in Table 3. The fifth, sixth and seventh mixtures contained the same percentage of micro steel fibers as MX2, MX3 and MX4; in addition, an attempt was made to align the fibers along the direction of the concrete flow. These mixtures were denoted as MA5, MA6 and MA7. The mix proportions followed in this work are given in Table 4.

Table 4 Replacement of Binder Content and Mix Proportions

Mix	MC1	MX2	MX3	MX4	MA5	MA6	MA7
Steel fiber weight(kg/m^3)	0	19.5	39	58.5	19.5	39	58.5
Alignment	-	discrete	discrete	discrete	unidirectional	unidirectional	unidirectional

2.3. Methodology

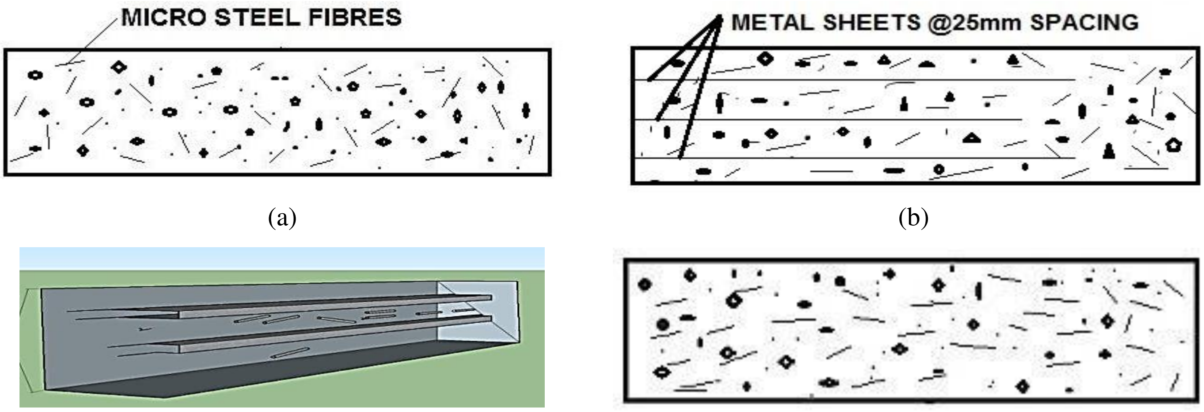
2.3.1. Mix procedure

The concrete mixtures were made with the help of a drum mixer. The mixer made 25 to 30 revolutions per minute and was run until the desired quantities of the materials were mixed together and formed uniform concrete. After mixing, the self-compacting concrete containing steel fibers and mineral admixtures was taken to test the rheological and mechanical properties (fresh stage and hardened stage), in which the fiber orientation was random due to the natural flow of SCC. In total, seven concrete mixes were designed; nine beams for each mix design were cast after experimenting the rheological properties to analyze the mechanical behavior of MSFRSCC in three different curing periods (7 days, 28 days and 56 days). A total of 63 prisms (7 mixes × 9 prisms/mix) were cast.

2.3.2. Procedure for aligning the fibers

Apart from studying the distribution of the fibers, several steps were taken to align the micro steel fiber Reinforced self compacting concrete (MSFRSCC) artificially, as detailed below.

1) Initially the mix containing fine aggregate, coarse aggregate, water, superplastizicer and binder was replaced with 30% fly ash and 10% micro silica fume, and micro steel fibers of three different percentages (0.25%, 0.50% and 0.75%) were devised.
2) The metal sheet was then placed perpendicularly inside the mold (formwork) with dimensions of 500×100×100 mm, with spacing of 25mm with a shortened middle sheet to avoid blockage, as shown in Figure 2b. A 3-D view of the metal sheet is shown in Figure 2c.
3) The mold was kept at a slope of 1 in 3 and the prepared concrete mixture was poured from one end until the mold was filled completely.
4) The metal sheets were then removed and the concrete kept for curing. A virutual representation of the aligned fibers after removing the metal sheet is represented in Figure 2d.
5) Later, the concrete was cured to estimate the mechanical properties and NDT to classify the MSFRSCC according to the fibers orientation.
6) Conforming that he concrete flows according to the Bingham model (Feys et al., 2007); i.e., $\tau = \tau_o + \mu\gamma$, where τ is the yield stress, (Pa), μ is the plastic viscosity (Pa.s), and γ is the shear strain rate (1/s). The first property (τ_o) provides a measure of the shear stress required to initiate the flow and the second (μ) a measure of the resistance to the flow of materials. When the concrete was poured, as the sheets were kept perpendicular to the direction of the flow, the fibers tended to align along the axial direction of the load.



(a) (b)

(c) (d)

Figure 2 Thematic representation of the fiber alignment mechanism

3. MECHANICAL PROPERTIES OF MSFRSCC

3.1. Rheological Properties

The fresh properties tests were conducted according to EFNARC for each mix because this procedure remains the protocol for finding the exact ratios of material contents (aggregates, W/C ratio, admixtures and steel fibers) for structural applications. L-Box and J-Ring are eminent tests for validating the passing and filling ability of self-compacting concrete containing steel fibers. Since the fibers in the mixtures need to flow fluidly in between densely reinforced structure as normal SCC without fibers, slump flow and T_{500} for filling ability, V-Funnel for viscosity and filling ability tests were conducted respectively in order to confirm that the mix proportions satisfied the guidelines provided by EFNARC.

3.2. Hardened Properties – Modulus of Rupture

The key application of adding fibers to concrete is to enhance the flexural properties. From the literature study, the efficiency of the concrete increased by between 100%-200% by the addition of 0.25%-2% of steel fibers. Flexural behavior is considered as one the measuring tool to assess the alignment and orientation of steel fibres in self-compacting concrete (Alberti et al., 2017). Assumptions had been made that the aligned fibers and uniformly distributed ones performed well, rather than randomly distributed fibers in the flexural behavior of concrete. Aspect ratio plays a vital role in orienting the fibres. Hence, micro steel fiber with an aspect ratio of 60 was chosen. Although the quantity of steel fiber is directly proportional to flexural strength, the rheological properties are affected, so optimized volume percentages of steel fiber were used. With increased aspect ratio and quantity of fiber, the matrix has the tendency to form balls during the mix, which affects the homogeneity of the composite material.

3.3. UPV Testing

UPV (Ultrasonic Pulse Velocity) testing is an NDT (Non-Destructive Testing) technique, which helps to validate the existing structure, and to determine the homogeneity of the composite concrete. To find flaws, such as voids or cracks, in the structure, Lee et al. (2015) studied the changes which occurred during the hydration process to evaluate the dynamic elastic modulus of concrete. The applications of using UPV techniques helps usto validate concrete based on the orientation of composite materials present in it. The ultrasonic pulse velocity is created by an electro-acoustical transducer. At the point when the pulse is passed through the concrete from a transducer, it experiences various reflections at the limits of the various material phases inside the composite concrete. Since the velocity of the pulse is relatively unique to the geometry of the material through which it passes and depends on its elastic properties, the pulse velocity method is a helpful system for researching structural composite materials.

(a) (b)

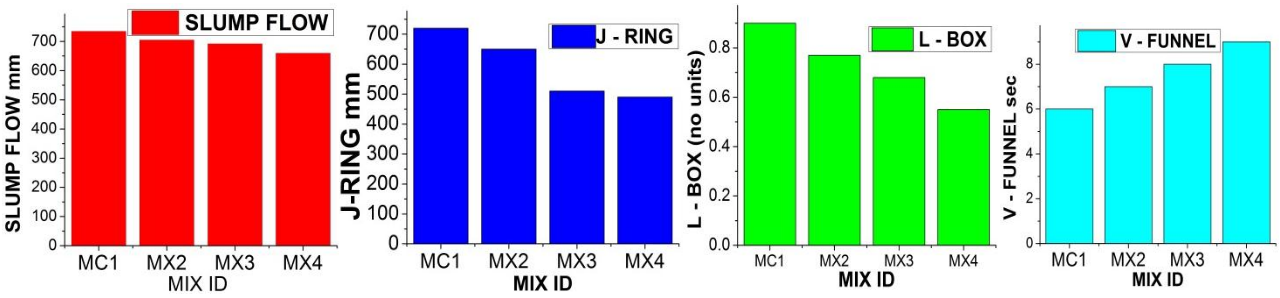
Figure 3 Specimen testing and UPV testing machine

Figures 3a and 3b show the UPV testing machine and tested specimens. The quality of the concrete was validated according to IS 13311(Part 2): 1992.

4. RESULTS AND DISCUSSION

4.1. Rheological Properties

The fresh concrete properties for mixes MC1, MX2, MX3 and MX4 were analyzed according to EFNARC guidelines. Figure 4 shows the results obtained from testing the fresh concrete properties with various proportions of steel fibers. Although there were fluctuations in the readings, it was clearly observed that all the mixes satisfied the minimum limit of 600 mm for slump, 6 secs for V-Funnel, 2 secs for T_{500mm} and 0.8 for L- Box, as per EFNARC guidelines. From Figure 4a it can be seen that the addition of steel fibers affects the flowability (slump flow). Having a control mix as a benchmark, and adding 0.25% of steel fibers, reduced the flow ability by 30 mm, i.e. 4.08%. Similarly, adding 0.5% and 0.75% of steel fibers reduced the flow by 5.85% and 10.2% respectively. Passing ability was evaluated by J-Ring; from Figure 4b it can be seen that the addition of fibers reduces this by up to 230 mm (31.94%). A further increase in steel fibers may lead to blockage and poor flow ability. From figure 4(c), the efficiency of L-Box was reduced by 38.89%; similarly, from Figure 4d, with the V-Funnel there is an increase in time by 3 seconds, which is a 50% reduction in efficiency. Therefore, the addition of steel fibers shows the linear reduction in performance of fresh concrete properties.

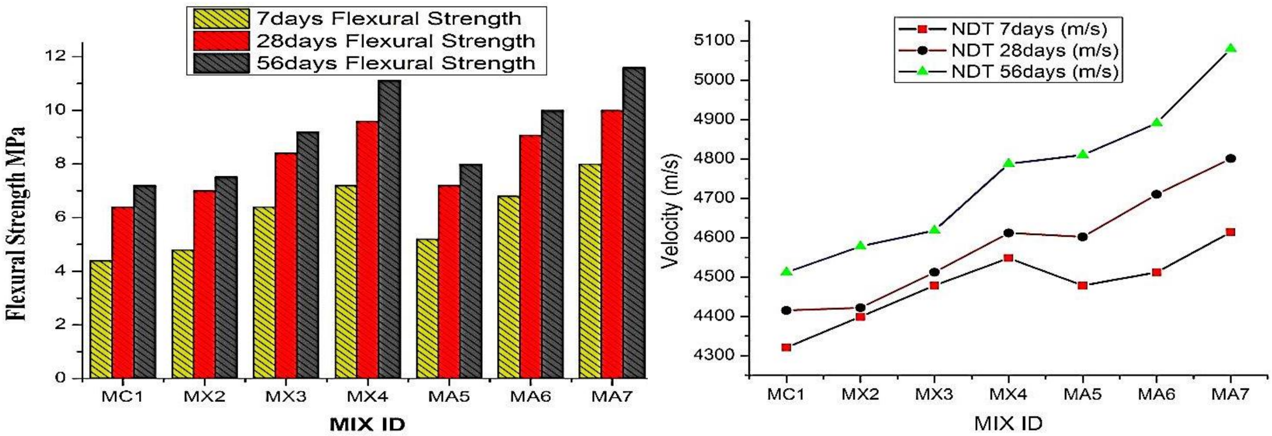


(a) Slump Flow (b) J-Ring (c) L-Box (d) V-Funnel

Figure 4 Rheological properties

4.2. Behavior of Beams under Flexural Loading and UPV

After curing periods of 7, 28 and 56 days, three beams with dimensions of 100×100×500 mm (W×D×L) from each mixture were taken out of the curing tank and tested under surface dried conditions. The ultimate strength and velocity values obtained from the flexural testing machine and UPV testing machine are presented in Figures 5a and 5b, respectively.



(a) Flexural strength (b) Velocity

Figure 5 Mix ID vs Responses

These figures show the flexural strength and UPV of different mix IDs of 7, 28 and 56 days. When the flexural strength of the concrete mix containing steel fibers (i.e. mixtures MX2 – MA7) was compared with the control mix (MC1), there was a linear increase in strength at all stages because of the presence of the micro steel fibers. A 12%-16% linear gain in strength was observed even after 28 days, since the mineral admixtures of fly ash and micro-silica fume were replaced by up to 40% of total binder content, showing the continuity of the hydration process. From Figure 5a, it can be seen that the MA5, MA6 and MA7 mixtures showed average increases in strength of 2%, 8% and 4.17% compared to mixtures MX2, MX3 and MX4 respectively, with same quantity of steel fibers. This proves that the steel fibers were aligned along the perpendicular to the loading direction. The addition of steel fibers increases the strength by up to 81% when MC1 is compared with MA7.

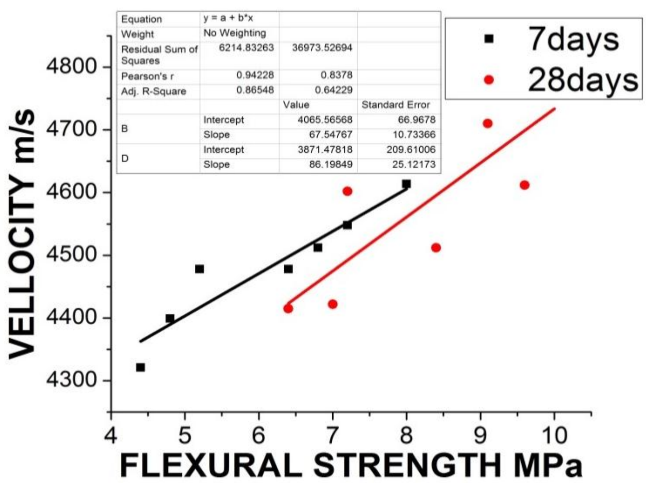
From Figure 5b, it can be seen that all mixtures possess excellent concrete conditions according to IS 13311:1992 Part I. Compared to MC1, the other mixtures show higher velocity, since the addition of steel fibers makes the concrete more compacted and denser, thus reducing shrinkage, internal voids and also increasing the surface area, allowing the waves to propagate faster. It was observed that the quantities of steel fibers and the curing days were directly proportional to velocity. There was a linear 2%-5% increase in velocity with the increase in curing days, showing the reduction in inner moisture content because of the hydration process. A similar rate of increase was found by increasing the percentage of steel fibers in MX2, MX3 and MX4. Apart from the quantities, from Figure 5a, it is clearly shown that the MA5, MA6 and MA7 mixtures showed 8.33%, 6.25% and 11% higher flexural strength than MX2, MX3 and MX4 respectively after 7 days. As shown in Figure 5b, when MA5, MA6 and MA7 are compared with MX2, MX3 and MX4 after 56 days the velocity shows increases of 6.09%, 5.911%, and 5.06%, respectively. This shows that apart from the densely packed, fibers were arranged unidirectionally along the direction of flow and perpendicular to the ultra-sonic wave passing from the transducer.

4.3. Regression Equation

For the development of better knowledge on concrete and to predict exact value of strength and quality of concrete, the linear regression equation has been developed between flexural strength and the velocity for 7 days and 28 days. Which is considered as a typical days for gaining strength (Zain & Abd, 2009). From Figure 6 the linear equation;

- For 7 days is $\mathbf{Y_{7D} = 4065.5656 + 67.57X_{7D}}$, **Pearson's r** = 0.94 $\mathbf{r^2_{7D} = 0.87}$, and**;**
- For 28 days is $\mathbf{Y_{28D} = 3871.4664 + 86.2298\ X_{28D}}$, **Pearson's r =** 0.88, $\mathbf{r^2_{28D} = 0.65}$ where, Y_{xx}, X_{xx}, B_{xx} and A_{xx} represents the velocity, flexural strength, slope and intercept of the respective days

The values of slope and the co-efficient are clearly shown in the Figure 6. The r-square shows how close it splits the match line. Since the sample size was low the accuracy level was restricted. The r-square values for 7 days and 28 days shows the points are falling along the fitting curve.



Equation	$Y_{xx} = B_{xx} \times X_{xx} + A_{xx}$	
Pearson's r	0.94_{7D}	0.88_{28D}
Adj. R-Square	0.87_{7D}	0.65_{7D}
7days	A_{7D}	4065.56
	B_{7D}	67.54
28days	A_{28D}	3871.47
	B_{28D}	86.19

Figure 6 Multiple linear fitting curves and values

5. CONCLUSION

The following conclusion has been derived in this study: (1) Increase in steel fires affects the flow, filling and passing ability of MSFRSCC. Addition of steel fibres increases the flexural strength of the concrete and resists the development of micro cracks that prevents the concrete from brittle failure and increases the strain hardening property; (2) The average flexural strength the contribution of SCC with aligned steel fibres (MA5, MA6 and MA7) was 8.5% more when compared with MX2, MX3 and MX4 for same quantities of fibre content, since of the fibres were aligned and they were artificially placed axial to loading direction; (3) From UPV results it was clearly seen that the inclusion of steel makes the concrete denser which makes the propagation of waves through the concrete easier in MX2, MX3 and MX4 when compared to MC1. The values of UPV were 4%-6% predominant in MA5, MA6 and MA7 when compared to MX2, MX3 and MX4 for the same quantities of steel fibres because of the uniform orientation of steel fibres; (4) Hence, the attempt made to align the steel fibres is successful. This is validated with the help of UPV testing and by flexural strength; and (5) The linear regression equations that were developed will help to predict the behavior of Micro Steel-Fibre Reinforced Self Compacting Concrete (MSFRSCC) according to their flexural strength and velocity.

Hence by making the use of rheological properties, using 0.25% of fibres for densely reinforced structure and using 0.5% and 0.75% for normally reinforced structure with mineral admixtures can make the construction highly efficient towards feasibility and strength criteria.

6. ACKNOWLEDGEMENT

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