PASSING ABILITY, WATER AND CHLORIDE PENETRATION OF SELF-COMPACTING CONCRETE USING MICRO-SILICA AS CEMENTITIOUS REPLACEMENT MATERIAL

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The main constituent of concrete is cement which has a noteworthy negative ecological issue causing colossal CO_2 commitment amid the concrete creation. This cement content should be replaced with by-products like Micro-Silica (MS) in order to prevent the greenhouse effect to some extent. This study examines the penetrating response of Self-compacting concrete (SCC) made of micro-silica as partial cementitious replacement material. The utilization of micro-silica in varying percentage like 5%, 10% and 15% along with the appropriate dosage of chemical admixtures were experimentally investigated. This concrete proportion was tested for fresh properties like slump flow, J-ring test and U-Box test. The split tensile strength of SCC was determined at the age of 28 and 90 days. The water permeability properties like saturated water absorption, sorptivity, porosity were conducted on hardened concrete. The rapid chloride penetration test was conducted to evaluate the amount of charge passed in concrete. These results revealed that the replacement level of cement by optimized proportion of 10% MS improved the workability to 3.8%, the tensile strength to 22.82% and enhanced the durability properties.

Keywords: *micro-silica, flowing ability, strength, water absorption, sorptivity, chloride penetration.*

1. Introduction

In recent times, researchers have achieved a variety of diversification on concrete into special types and one such type of derivation was SCC found by Japanese in late 1980's. SCC required less labours, reduced noise at work sites and saved much concreting time [1]. This development of ease flowing capability of concrete under its own weight does not require any vibration during placing of concrete [2]. SCC has the ability to attain the level of high compaction and with good consistency. Properly designed SCC mix does not possess neither bleeding nor segregation, and it maintains its homogeneity [3].

The highly flowing nature of SCC can be adopted in the densely reinforced sections. Thus SCC act as a user-friendly concrete for the engineers and labours at the construction site for easy placing of concrete [4]. These flowability properties can be produced only by adding the chemical admixtures like Super plasticiser (SP) and Viscosity Modifying Agent (VMA). The role of SP and VMA can modify the viscous nature of concrete [5]. SCC basically consists of water, cement, aggregates, the use of mineral additives or chemical admixtures. The production of SCC led to the achievement of best workability and better strength compared to conventional concrete [6]. Wide area of research has been focused on cement replaced using those admixtures and river sand could also be replaced with effectively equivalent particles [7]. The SCC containing mineral admixture like fly ash in high volume can be adopted as a partial cement substitute material. This workability along with strength increased the durability and decreased the production cost [8].

The mineral admixtures include the by-products like fly ash, silica fume, rice husk ash, lime stone powder, etc., when used in self-compacting concrete as a cementitious materials enhanced the workability, rheological properties and strength performance characteristics of SCC [9]. Due to the necessity to prevail the sustainable development and to restrain the environmental issues like green house effects, there is a need to reduce the utilization of cement to some extent. As cement production contributes to a huge amount of CO_2 emission, gives a rise in the use of mineral admixtures [10]. In order to resolve this current issue the adoption of filler and by-products from numerous industries came into existence. Fly ash was the widely used cement replacement material in achieving good workable SCC [11]. Micro-silica derived as the by-product from the ferrosilicon industries was used as a substitute for cement. The

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need to achieve the flow criteria was satisfied and strength improvement was also investigated along with the appropriate dosage of SP and VMA [12]. The addition of micro-silica into SCC produced good workability as per limitations EFNARC [3] enhanced the durability and strength performed better [13].

The transport properties of self-consolidating concrete were determined and the influence of viscosity modifying agent in durability characteristics was discussed. It was found that SCC prepared with the addition of VMA possessed, increase in water permeability compared to SCC without VMA mixtures [14]. A detailed study was conducted on sorptivity of SCC with fly ash and micro-silica. The inclusion of fly ash and micro-silica in SCC as partial cement replacement decreased the amount of water absorption in concrete. When micro-silica was added, the sorptivity and surface water absorption decreased compared to other type and control concrete [15]. The investigation of sorptivity test on SCC containing mineral additives like fly ash, hydraulic lime and micro-silica was carried out. Though micro-silica is an expensive mineral additive, when added to concrete in the hardened state it absorbed less amount of water compared to hydraulic lime powder in SCC [16]. It was concluded that SCC with additional powder as fillers in concrete expressed least permeation properties like sorptivity, chloride diffusion and oxygen permeability compared to control SCC [17].

The target of the research presented here is to attain a suitable SCC containing micro-silica at 5%, 10% and 15% and to identify the optimum percentage replacement of micro-silica in cement. The effect of micro-silica was explored by investigating the fresh concrete properties like slump flow, L-Box, J-ring, Orimet and V-funnel tests. These tests were conducted to assess the workability characteristics of SCC. The strength properties like compressive, split tensile and flexure were determined and microstructural study at 28 days were carried out. The penetrability of water was determined by testing the water absorption of concrete and by conducting the sorptivity test of concrete specimens.

2. Experimental program

2.1 Materials and mix proportion

The cement used in this study was Ordinary Portland Cement of 53 grade corresponding to IS: 12269-1987 with a specific gravity of 3.1 g/cc. Naturally available river sand of specific gravity of 2.61 g/cc was used. The fineness modulus of sand was 2.9. The crushed and graded coarse aggregate of 12.5mm size and angular in shape with specific gravity of 2.7 g/cc was used. The micro-silica from Conriche India Pvt. Ltd, Mumbai was used as partial replacement of cement. The composition was about 92.8 percentage of SiO_2 content with average particle size of 150nm. The chemical constituents of cement and micro silica are represented in Table 1. The commercially available Super-plasticizer Master Glenium 8233 from BASF and viscosity modifying agent Auramix 200 from FOSROC was used. In order to achieve the required flow ability of concrete, the type of superplasticizer chosen was poly-carboxylic ether. Potable water was used for mixing of concrete. The four different SCC mixtures were designed with varying the percentage of micro silica as cement substitute from 0% to 15% of the mass of cement. The water-to-binder ratio was maintained at a constant of 0.44 for all mixtures. The mix proportions are given in Table 2.

2.2 Test methods

The concrete is said to be SCC only when it passes the workability tests. The flowability of

Table 1

Chemical and physical characteristics

Constituents	**CaO (%)**	**SiO_2 (%)**	**Al_2O_3 (%)**	**Fe_2O_3 (%)**	**MgO (%)**	**Na_2O (%)**	**LOI (%)**	**SO_3 (%)**	**Specific gravity**	**Blaine's Fineness m^2/kg**
Cement	55.71	22.35	10.88	5.87	1.15	0.34	1.23	1.59	3.1	-
Micro-silica	0.001	99.88	0.04	0.04	-	0.003	0.015	-	-	22

Table 2

Mix proportions of SCC with different percentage of micro-silica

Mix Proportions (kg/m^3)	**Mix ID**			
	Control	**5MS**	**10MS**	**15MS**
Cement	450	427.5	405	382.5
Micro-silica	-	22.5	45	67.5
Water	200	200	200	200
Fine aggregate	1000	1000	1000	1000
Coarse aggregate	750	750	750	750
SP (%)	1.2	1.5	1.8	2.0
VMA (%)	0.12	0.15	0.18	0.20

fresh concrete was tested using the Abrams (slump) cone. The flow of concrete through the slump cone examines the filling ability of the SCC. The J-Ring flow was tested by placing the slump cone inside the J-ring and concrete were tested for passing ability of the SCC. The horizontal flow diameter was measured at right angles and the average value was taken as the J-ring slump flow diameter. The slump flow diameter and the J-ring slump flow diameter was related directly to the passing ability index as interpreted by [18]. The passing ability index (PAI) was derived from

$$\text{PAI} = 1 - \frac{(d_{sf} - d_{jf})}{d_{sf}} = \frac{d_{jf}}{d_{sf}} \quad (1)$$

Where

d_{sf} – diameter of slump flow (mm)

d_{jf} – diameter of J-ring flow (mm)

The U-box test was conducted to check the filling ability of concrete with three rebar at the bottom junction. The fresh concrete was poured at one side of the U-box and the junction was closed with the sliding gate. The fresh SCC was allowed to fill the other side of the U-box. The difference in height of the concrete on both sides was measured. This difference should not be greater than 30mm [3].

Cylinders of size 100×200 mm were cast to evaluate the split tensile strength of SCC at 28 and 90 days respectively. A total of 24 cylinders was prepared. The SCC specimens were cast and demoulded after 24 hours and cured in water till the day of testing. On the day of testing like 28 and 90 days the specimens were taken and left for surface dry for about 6 hours and tested. The split tensile strength was tested according to ASTM C 496-11 [19]. SCC was prepared by varying micro silica from 0% to 15%.

The water permeability in concrete was tested using the two different methods. The saturated water absorption test was conducted for specimens of 100×100×100 mm. Three cubes were cast for each mix, water cured for 28 days and oven dried at 105°C for not less than 24 hours as per ASTM 642 [20]. Then the specimens were allowed to cool at room temperature and weighed. Again immersed in water and weighed on the day of testing. The percentage of water absorbed can be calculated by

$$\text{Water absorption } (\%) = [W2 - W1]/W1 * 100 \quad (2)$$

where

W_1 – mass of oven dried sample (g)

W_2 – mass of surface dried sample (g)

The sorptivity test (capillary rise of water) on concrete disc of 100×50 mm was prepared. Initially concrete cylinders of size 100×200 mm were cast and cut into the required size of three specimens for each mix and cured for 28 days. Then the specimens were oven dried and left to attain constant mass. Then epoxy was coated on the sides of the cylinder in order to prevent water penetration from external ways. Water was made to be in contact for a height of 5mm from the base height of concrete [21]. The weight at particular times of testing were noted by removing the specimen from water and then wiped with a dry cloth. The sorptivity can be determined using

$$i = St^{0.5} \quad (3)$$

where

i – increase in mass (g/mm^2)

t – time in minutes

S- sorptivity (mm/min$^{0.5}$)

The porosity is defined as the amount of pores present in the total volume of the concrete. It is expressed in terms of percentage. It can be said, evidently that a higher percentage of pores in concrete is directly related to the reduction in concrete strength. The pores present in concrete can be presented by

$$\text{Porosity } (\%) = [(W2 - W1)/V] * 100 \quad (4)$$

where

W_1 – mass of oven dried sample (g)

W_2 – mass of surface dried sample (g)

V – volume of the concrete sample.

The rapid chloride penetration was conducted on the SCC specimens at 90 days. This test was performed based on ASTM 1202 [22]. The concrete specimens of 100 mm diameter and 50 mm height were coated with epoxy on the sides of the specimens and left to dry. Three specimens for each mix were tested and the average value was taken. It was kept in the vacuum chamber and then placed in the test device. The test cell consists of 3% NaCl solution on the negative terminal and 0.3N NaOH solution on the positive terminal. This cell was connected to a constant power supply of 60V and tested for about 6 hours. The current was measured at every 30 minute interval. Finally, the amount of current passed through the specimen was calculated by the given formula

$$Q = 900 * [I_0 + 2I_{30} + 2I_{60} + \cdots + 2I_{330} + I_{360}] \quad (5)$$

where

Q represents the charge passed (coulombs)

I_0 represents the current (A) immediately after voltage is applied

I_t represents the current (A) at t minutes after voltage is applied.

3. Results and discussion

3.1 Relative slump

The horizontal flow of fresh concrete was measured. The relative slump is the slump flow values of the prepared SCC mix compared to the minimum slump flow as per European Guidelines [2]. The relative slump was calculated as an effective increase or decrease with compared to 650 mm. The effective slumps for SCC with and without micro-silica content are shown in Figure 1. The slump value increased with increase in percentage of Micro-silica by further addition of chemical admixtures. The control concrete had a 1.53% increase in slump value compared to the minimum value of 650 mm. The value of the slump was little higher for 5% Micro-silica mix which had an increase of 1.83% of 650 mm. For 10% Micro-silica mix, the increment in variation of the slump was 3.8% with respect to standard minimum value. The slump was higher for 15% replacement mix, which gained a rise in slump value of 4.5% also showed mild segregation. SCC with 10% micro-silica had a better workability and did not exhibit any segregation or bleeding.

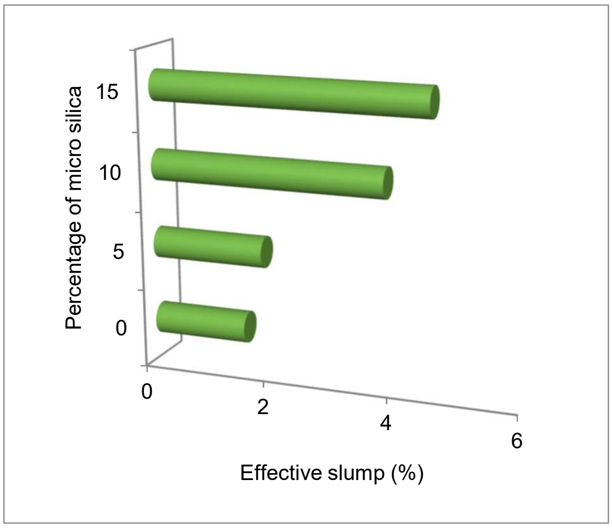

Fig. 1- Percentage increase in slump compared to [3].

3.2 U-box

From Figure 2, it was noticed that the increase in Micro-silica and chemical admixtures content provides a better flow of concrete through the reinforcing bars. The height of the concrete on both sides of the U-box was measured. The difference in height was calculated for different types of concrete. The height of difference was observed to be 26 mm, 25 mm, 23 mm and 21 mm for control concrete, 5%, 10% and 15% replacement mixes. The U-box test results were within the acceptable criteria compared with [2]. With the addition of 10% micro-silica there was a better flow, which improves the passing ability of concrete.

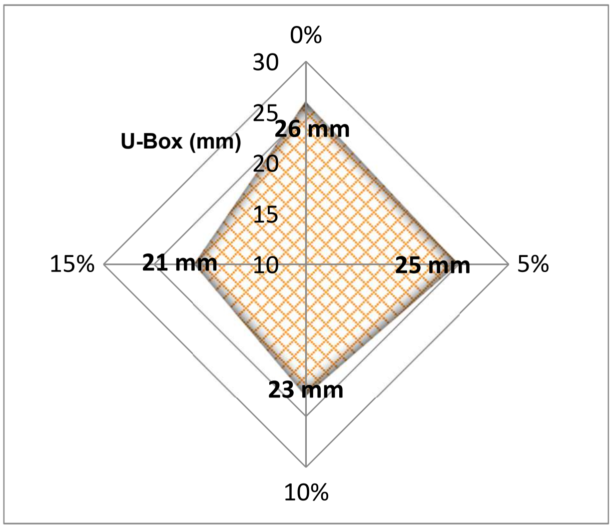

Fig. 2 - U-Box test results of SCC with micro-silica.

3.3 Passing Ability Index

PAI is defined as the ratio of reduced flow diameter by the J-ring apparatus to the slump flow diameter measured by Abrams cone (slump cone). The passing ability indexes of various types of the fresh SCC are presented in Figure 3. The slump flow of fresh concrete was directly related to PAI. For decrease in the slump flow type of mix, the passing ability index increases. For control concrete of slump flow, the PAI value was about 0.97 and for 5% micro-silica of 662mm slump the PAI value slightly greater than control concrete. The PAI is the important parameter for predicting the ability of concrete to fill the areas of congested reinforced. By further addition of micro-silica in SCC, the slump flow increased by increasing the PAI of fresh concrete. Figure 3 shows that the regression equation can be able to predict the passing ability index for the SCC mixes of slump ranges from 660 mm to 680 mm. The regression coefficient is 97.71%, which shows that the current equation's precision for M40 grade of SCC.

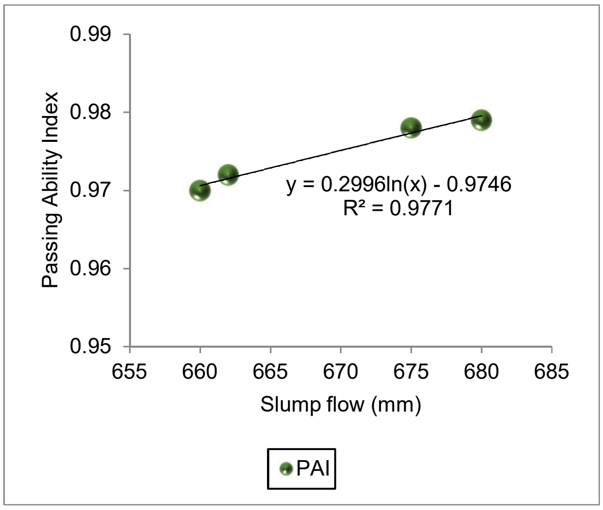

Fig. 3 - Passing ability Index for SCC.

3.4 Split tensile strength

The splitting tensile strength of the SCC for 28 days and 90 days are shown in Figure 4. All of the mixes with Micro-silica had an increase in strength compared to control mix. As the percentage of Micro-silica increases, the strength gets gradually increased except for 15% replacement mix which had a decrease in strength of 16.17% and 15.67% for 28 and 90 days respectively, compared to 10% Micro-silica mix. The percentage increments in split tensile strength of 5%, 10% and 15% Micro-silica mix were 5.07%, 22.91% and 3.02% for 28 days and 6.85%, 22.82% and 3.57% for 90 days compared to control concrete mix. From the recent studies, it was reported that addition of silica particles enhanced the conversion of calcium hydroxide crystals into calcium silicate hydrates (CSH) by improving the tensile strength [23, 24]. The higher amount of fine content and superplasticizer directly affect the strength thereby creating larger calcium hydroxide crystals which weakened the aggregate – cement paste transition zone [25]. In the current study, it was noticed that the split tensile strength increased by increasing the percentage of micro-silica up to 10%. However, there was a decrease in strength of 15% MS which was due to the weaker interfacial transition zone (ITZ) between the aggregate and cement paste.

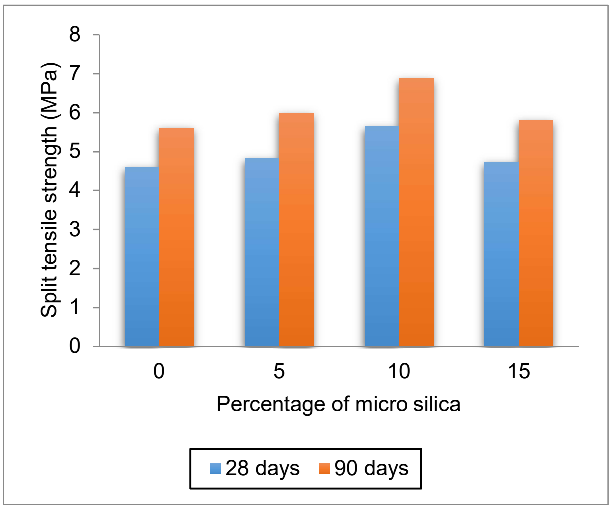

Fig. 4 - Split tensile strength results at 28 and 90 days.

3.5 Saturated water absorption

From the Figure 5, it was observed that the range of water absorption values varied between 1.6% to 3.03%. It has been verified from the results [26] that the percentage of water absorption would be less than 10% for an SCC type of concrete turning it to be categorized under "good concrete". With the addition of micro-silica in SCC, it was noticed that the water absorption decreases. In control SCC, due to the hydration the CSH gel was formed less than compared to micro-silica concrete. The greater the value of saturated water absorption indicates the amount of pores is more and that activates the movement of water, resulting in higher volume. In case of SCC containing micro-silica, the CSH gel was formed interconnected throughout the specimen thus by covering the capillary pores absorbs less amount of water.

3.6 Porosity

The porosity was determined in order to calculate the amount of pores present in the concrete specimens. The porosity values decreased from 5.2% to 4.5% for all types of mixes as shown in Figure 5. For increase in amount of micro-silica gradually the pores were reduced. This was related to the decrease in percentage of porosity. In accordance with control SCC, the 5% micro-silica showed a decrease of 3.92%. For 10% and 15% micro-silica as a cementitious replacement in concrete the porosity was reduced by about 5.94% and 14.43% respectively.

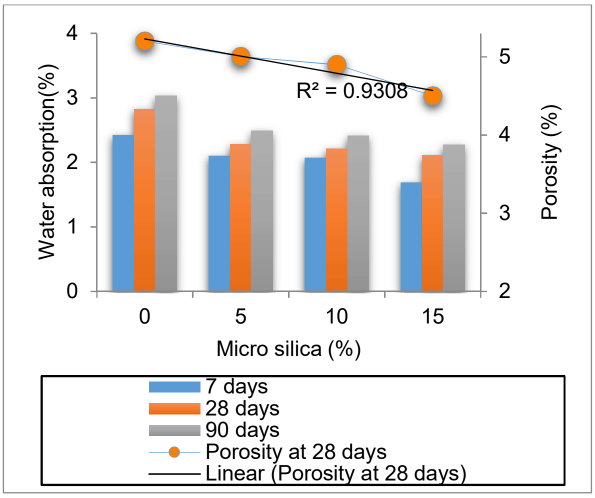

Fig. 5 - Water absorption and Porosity for various mix proportions.

3.7 Sorptivity

The results of sorptivity of the concrete specimens with various micro silica content are shown in Figure 6. It was inferred that the sorptivity values decreased for all types of concrete from 1day to 28 days. For control concrete the values decreased from 0.042 to 0.014 (10^{-4}mm/min$^{0.5}$) and for 10% micro-silica content in SCC the sorptivity values reduced from 0.033 to 0.012 (10^{-4}mm/min$^{0.5}$) from 1 day to 28 days. Compared to control concrete 10% MS exhibited some 24% decrease in 1 day sorptivity. By the end of 28 days the amount of capillary water absorbed was 15.38% less for 10% MS in comparison with control concrete. The increase in micro-silica content decreased the capillary rise of water in concrete maintained at a constant water height of 5mm throughout the experiment. For SCC with 15% MS, there was an increase in the capillary absorption of 6.89% compared to control concrete.

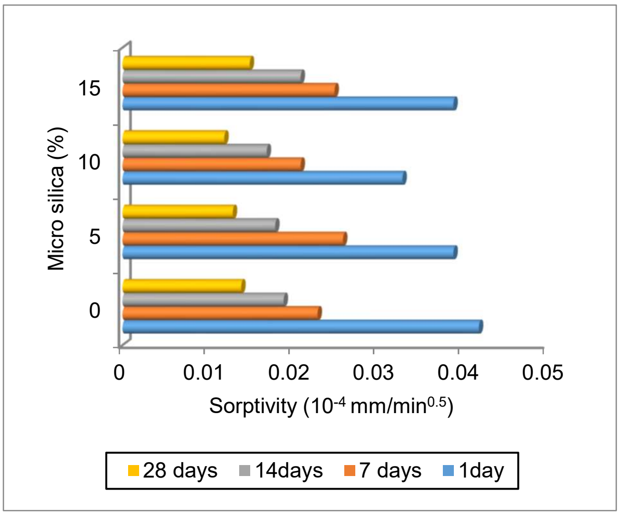

Fig. 6 - Sorptivity for various mix proportions.

This is due to the presence of more reactive silica, which readily reacted with cement paste. The unreacted silica particle leads to the formation of pore on the cement- aggregate interface. Finally, this led to the rise in sorptivity values as water was absorbed through the pore network.

3.8 Rapid chloride penetration

The chloride penetration was determined for all mix proportions for about six hours testing. This test was conducted at the age of 90 days. As per ASTM 1202-12 [20], the chloride ion penetration is based on the total charge passed onto the concrete measured in coulombs. The standard categorization for chloride penetration and the experimental investigations are shown in Table 3. The Table 3 shows that for increase in MS content the chloride penetration is less. It can be concluded that the use of a byproduct like micro-silica in concrete performs well and reduced porosity. The penetration of chloride ion is reduced in SCC with micro-silica thus preventing corrosion activity. Micro-silica when added as a cement replacement in SCC, it reacted with the Calcium hydroxide crystals and formed a dense CSH gel compound which helped to reduce the permeability and improved the durability of the concrete in long term aspects.

Table 3

Chloride ion penetration

Standard values		Experimental investigations	
Charge passed (coulombs)	Chloride ion penetration	Mix ID	Charge passed (coulombs)
>4000	High	Control	1420 (Low)
2000-4000	Moderate	5MS	782 (Very low)
1000-2000	Low	10MS	613 (Very low)
100-1000	Very low	15MS	484 (Very low)
<100	Negligible	-	-

4. Conclusion

The experimental investigations on SCC using micro-silica on strength and durability tests were carried over and the following conclusions are made.

1. The addition of micro-silica in SCC along with the usage of chemical admixtures activated the flowing ability of fresh concrete compared to the control concrete.
2. The U-box interpreted the passing ability of the fresh concrete with micro-silica. The 10% micro-silica in SCC exhibited a better workability without any segregation or bleeding.
3. The passing ability index found to increase for increase in micro-silica content by improving the horizontal flow through the slump cone.
4. For SCC with 10% micro-silica expressed high split tensile strength of about 22.82% higher compared to control mix at the age of 90 days.
5. The amount of water absorbed through SCC was less compared to conventional concrete because the SCC has more powder content, thus it possesses pore filling capacity of concrete. Furthermore the addition of micro-silica decreased the saturated water absorption.
6. Micro-silica as cement replacement improved the particle packing density by forming a complex gel formation by reducing the voids present.
7. The capillary rise of water absorption was also less for addition of micro-silica in SCC. This gel formation broke the capillary chain of pores and decreased the sorptivity.
8. The RCPT values were 15.38% less permeable to chloride for 10% MS concrete. The results of RCPT showed that the chloride ion penetration was very low for micro-silica type of mix which can be preferred for coastal areas.

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