Experimental and Microstructure Study on Ternary Blended SCC Using RHA, SF and MK as a Partial Cement Replacement

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Abstract. Self-compacting concrete (SCC) is compacted by its weight without the need for a vibrator, and so this fills the formwork quickly. The application of by-products or industrial waste materials as cementitious material could improve the mechanical properties. The mineral admixtures obtained from industrial by-products, namely, rice husk ash (RHA), silica fume (SF) and metakaolin (MK), could be used as partial cement replacement. In this research paper, the mechanical properties of SCC were studied by partially replacing cement by RHA with 10%, 20%, 30% and 40% in binary form. The optimum RHA was 10% in binary form from the compressive strength results and was blended with SF from 5% to 20% and MK from 5% to 20% as ternary blended SCC mixes. Totally 14 mixes were cast and tested, including four binary RHA mixes, eight ternary mixes containing optimum RHA with SF+MK, and two control mixes of conventional & SCC of the same grade. For experimental investigations on prepared SCC mixes, the tests on fresh properties and mechanical properties were conducted. For sustainable development in concrete materials, the binary and ternary blended greener SCC mixes were prepared to reduce the hydration rate. Under the Matlab environment, an artificial neural network (ANN) tool has been used to simulate the strength characteristics of SCC. A better correlation has been exhibited between the experimental and analytical results, validated. The microstructure study was carried out through SEM examination for the optimum binary and ternary SCC mixes to justify the experimental results.

Keywords: SCC · RHA · SF · MK · Mechanical properties

1 Introduction

In the current scenario, the innovations in concrete technology would have an impact on the construction industry. At the research level, many different types of concrete could be prepared and tested. But only a few types could be adopted practically in the construction site without any difficulties. Such type of concrete used worldwide is self-compacting concrete (SCC). SCC had wide field applications, namely beam-column joints in seismic

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regions, pile locations, bridge piers, etc. If the mix design of SCC was prepared with the utmost care, then the problems like segregation and bleeding could be curtailed. For conducting the rheological properties tests and mix design on SCC, the provisions given in EFNARC (2002 & 2005) and IS: 10262-2019 shall be followed. SCC production cost would be 10% higher than conventional concrete of the same grade, but it would be long lasting with less maintenance cost. SCC could also be prepared using industrial wastes and supplementary cementitious materials. SCC mixes were prepared in binary, ternary, quaternary and poly-blended forms.

RHA based SCC mixes were prepared to study the rheological and strength properties. The rheological properties got decreased by incrementing the percentage of RHA in SCC. Hence, authors were concluded that 10% rice husk ash would be the optimum mix based on the strength characteristics (Elias et al. 2018). In concrete, the cement was replaced up to 35% of rice husk ash and 100% by RCA to study the strength properties. The authors concluded that the mix containing 15% RHA and 100% RCA had shown better strength characteristics when tested at early and later ages (Rupali et al. 2018). The experimental investigation on HSC mixes using RHA up to 25% with 10% micro-silica (constant) as a ternary blended mix was conducted. It was inferred that 25% RHA and 20% RHA mix had better resistance against water absorption and strength characteristics respectively (Seyed et al. 2017). The experimental study was performed on the cement mortar by replacing cement up to 10% RHA and 20% by waste glass powder in ternary form. The authors inferred that the mix prepared with 5% rice husk ash had shown improved strength and less water absorption characteristics (Younes et al. 2018). The behaviour of blended Portland cement in ternary form by partially replacing cement with residual RHA up to 35% along with 5% limestone filler kept constant for all mixes. The authors inferred that the mix containing 5% RHA and 5% LSF was the optimum mix obtained in respect to strength characteristics (Gemma and Iliana 2018). The behaviour of SCC was studied using rice husk, fly ash and blended fine aggregate. The authors concluded that the strength reduction took place by higher percentages of cement replacement by rice husk ash and fly ash in SCC mixes. Further, authors inferred that rice husk ash-based SCC mixes' strength gain was higher than fly ash-based SCC mixes (Rahman et al. 2014). The authors reported that the strength obtained had a better correlation between experimental results and the simulation using soft computing tools (Chithra et al. 2016). High-performance concrete using ultra-fine residual RHA and sugar cane bagasse ash in binary and ternary blended concrete forms was conducted as an experimental study. It was inferred that the strength obtained from RHA-based concrete mixes had better performance when compared to sugarcane bagasse ash based concrete mixes (Cordeiro et al. 2012). SCC was prepared using fly ash from 25% to 50% as cement replacement was investigated. The authors suggested that cement replaced by 40% fly ash had obtained better fresh and mechanical properties (Vivek and Perumal 2013). The behaviour of SCC based Silica fume mixes were studied by cement replacement from 5% to 20%. The authors revealed that 10% silica fume had shown better fresh and strength characteristics (Vivek and Dhinakaran 2015). MK based SCC mixes were prepared up to 20% by replacement of cement. It was inferred that 20% metakaolin as cement replacement had improved fresh and mechanical properties (Vivek and Dhinakaran 2017a, b, c). A comparative experimental study on composite short column structural behaviour subjected to axial load using self-compacting concrete and conventional control concrete was reported. The authors concluded that the short composite column's load-carrying capacity was higher than the conventional composite short column (Vivek et al. 2016). SCC using binary blended mixes, namely GGBFS, SF, MK, as substitute to cement was prepared and tested. The authors suggested that cement replacement with 50% GGBFS, 10% SF, and 20% MK in SCC had enhanced the rheological properties and improved the mechanical behaviour (Vivek and Dhinakaran 2017a, b, c). SCC using quarry dust and brick dust as a partial replacement to the fine aggregate was researched and concluded that 20% quarry dust and 10% brick dust had shown increased strength characteristics (Govandan and Vivek 2014). Flexure study on beams using SCC ternary mixes were tested and reported. The cement was partially replaced by SF and MK with 25% and 30% in ternary SCC combinations. The authors inferred that the ductility nature was better attributed in ternary SCC beams when compared with conventional RCC beam (Marshaline Seles et al. 2017). The study on durability properties of SCC using GGBFS from 25% to 75%, MK from 10% to 30% and SF from 5% to 15%, a partial substitute to the cement was experimentally investigated. After conducting durability tests on SCC, the authors concluded that the cement replaced by 10% SF, 20% MK, and 50% GGBFS had better resistance against the durability characteristics (Vivek and Dhinakaran 2017a, b, c). Research on self-compacting (SC) mortar cubes using mineral admixtures, namely SF up to 20%, MK up to 30% and GGBS up to 75%, partial substitute to the cement was prepared and tested. The authors reported that by the electric oven curing method, the SC mortar mix containing 15% silica fume, 20% metakaolin and 25% by GGBS had shown the highest compressive strength (Prasanna Venkatesh et al. 2017). SCC was prepared by partially substituting cement with two mineral admixtures, namely metakaolin & GGBS by 40% and silica fume & GGBS by 35% in ternary blended forms. The authors concluded that ternary blended SCC beams had better flexural behaviour than control SCC and conventional RCC beams of the same grade (Vivek et al. 2017). SCC behaviour was studied by adding coconut fibres up to 1% with different treatments, namely soaked fibres, boiled fibres, and chemically treated fibres. The authors concluded that the chemically treated fibres in SCC of about 1% had shown improved strength characteristics among the other treatment methods given to coconut fibres. The microstructure study on fibres was also discussed to examine why the increase or decrease of strength values (Vivek and Prabalini 2021). The experimental investigation was carried out on SCC by partially replacing cement in ternary combinations using MK & GGBS by 30%, GGBS & SF by 40% and MK&SF by 25%. The rheological and flexural behaviour was performed for the above ternary SCC mixes and compared with control mixes of CVC & SCC. The obtained experimental results were validated using ANSYS (Lakman Prabu and Vivek 2020). SCC was prepared by adding stainless steel scrap and steel fibres in hybrid fibre combinations. The slump flow and J-ring tests were conducted for SCC in hybrid fibre combinations, and the fresh properties had shown reduced values. The authors concluded that the addition of fibres in SCC had shown improved mechanical properties (Lakman Prabu et al. 2020).

In the present research, the rice husk ash, a locally available material, has been blended with cement from 0% to 40% with 10% to prepare binary blended SCC mixes. Other industrial wastes like silica fume and metakaolin were blended from 0% to 20% to prepare the ternary blended SCC mixes from the optimum percentage of rice husk ash. The microstructure study using a scanning electron microscope has been carried out for the optimum binary, ternary and control mixes. Using an artificial neural network tool (ANN), the simulated results were correlated with the obtained experimental results.

2 Materials and MIX Proportions Used

2.1 Materials Used

OPC of 53 grade was adopted, and the specific gravity was found as 3.14. Fine aggregate adopted was river sand with a FM of 2.75 and SG of 2.6. The coarse aggregate passing through 12.5 mm sieve was adopted. To increase the fresh properties in SCC, a superplasticizer, namely Tec Mix 640, was used as high range water reducing admixture. During flow, there could be a possibility of segregation and bleeding of SCC. To overcome the above problem, the viscosity modifying agent is a white coloured of high viscosity nature and purchased from ASTRRA chemicals. Effects due to variation in moisture content, grain size distribution were minimized by using VMA.

The XRD tests were conducted for the mineral admixtures used in the experimental programme is shown in Table 1.

Table 1. XRF results

Formula	RHA (%)	Metakaolin (%)	Silica fume (%)
SiO_2	89.18	53.67	97.36
P_2O_5	3.32	0.12	0.09
Al_2O_5	2.42	43.34	0.53
K_2O	1.80	0.17	0.29
MgO	1.65	0.09	0.79
CaO	1.14	0.37	0.14
Fe_2O_3	0.46	0.46	0.15
SO_3	0.41	0.27	0.51
Na_2O	0.27	0.12	0.06
TiO_2	0.08	0.19	0.01

2.2 Mix Proportions

The conventional concrete (CC) was prepared using mix proportions of 1: 0.66: 1.79 according to IS: 10262-2019 code of practice. To obtain the optimum water-cement ratio, the workability test namely the slump test was conducted using an Abrams cone. While casting the conventional concrete, the segregation and bleeding of concrete have been restricted in terms of the w/c ratio of 0.40. Hence the optimum w/c ratio of 0.4 has been maintained in CC mixes to prevent the segregation and bleeding effects.

SCC mixes were prepared by conducting slump flow and T500 test trials in the laboratory. The optimum SCC mixes were prepared by adjusting the fine aggregate and coarse aggregate proportions along with the dosages of superplasticizer having kept constant water to binder ratio. The significance in SCC mix was in total aggregate the fine aggregate proportion was higher than the coarse aggregate to generate the flowability. The fresh properties test trials were carried out by slump flow and T500 tests until the desired range of slump flow spread diameter and T500 time in seconds (s) has been obtained according to EFNARC guidelines. Thus control SCC was tested for fresh properties and later cement was replaced by RHA, SF & MK in binary and ternary blended combinations.

Rice husk ash (RHA) is the locally available material in the region of Thanjavur, Tamilnadu. The objective of the current research is to prepare SCC as a green building material by partial cement replacement using pozzolanic materials and to maintain sustainable development in the concrete production by reducing CO_2 emission in the atmosphere has been studied in two stages. In the first stage, the effective use of incinerated RHA as a partial substitute to the cement to study the behaviour of binary SCC in terms of fresh and mechanical properties. From the first stage, the optimum RHA has been concluded based on strength characteristics. In the second stage, the optimum RHA has been blended with SF and MK to study the fresh and mechanical properties of ternary blended SCC combinations.

Binary blended SCC mixes were designed with partial replacement of cement by RHA from 0% to 40% with an increment of 10%. The first series of ternary blended SCC mixes were prepared by blending optimum RHA% and MK from 0% to 20% with 5%. The second series of ternary blended SCC mixes were designed by combining optimum RHA% and SF from 0% to 20% with 5%. The SCC binary and ternary SCC mix proportions are shown in Table 2, 3 and 4, respectively.

Table 2. Mix proportion of SCC binary blend using RHA

Mix proportions	Mix ID	W/B	SP (%)	VMA (%)	Cement (kg/m^3)	RHA (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)
Conventional concrete	CC	0.40	–	–	600	–	397	1074
Control SCC	SCC	0.40	2.0	0.2	600	–	810	660
10% RHA	R1	0.40	2.6	0.3	555.73	44.27	810	660
20% RHA	R2	0.40	2.8	0.3	511.45	88.55	810	660
30% RHA	R3	0.40	3.0	0.3	467.18	132.82	810	660
40% RHA	R4	0.40	3.0	0.3	422.90	177.10	810	660

Table 3. Mix proportion of SCC ternary blend using RHA & SF

Mix proportions	Mix ID	W/B	SP (%)	VMA (%)	Cement (kg/m^3)	RHA (kg/m^3)	SF (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)
5%SF+10%RHA	SF1R1	0.40	2.6	0.3	531.94	44.27	23.79	810	660
10%SF+10%RHA	SF2R1	0.40	2.6	0.3	508.15	44.27	47.58	810	660
15%SF+10%RHA	SF3R1	0.40	2.6	0.3	484.36	44.27	71.37	810	660
20%SF+10%RHA	SF4R1	0.40	2.8	0.3	460.57	44.27	95.16	810	660

Table 4. Mix proportion of SCC ternary blend using RHA & MK

Mix proportions	Mix ID	W/B	SP (%)	VMA (%)	Cement (kg/m^3)	RHA (kg/m^3)	MK (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)
5%MK+10%RHA	MK1R1	0.40	2.6	0.3	532.98	44.27	22.75	810	660
10%MK+10%RHA	MK2R1	0.40	2.6	0.3	510.22	44.27	45.51	810	660
15%MK+10%RHA	MK3R1	0.40	2.8	0.3	487.46	44.27	68.27	810	660
20%MK+10%RHA	MK4R1	0.40	2.8	0.3	464.70	44.27	91.03	810	660

Before casting specimens into the desired moulds, the fresh property tests were conducted and met EFNARC guidelines' requirements.

3 Results and Discussion

3.1 Fresh Properties of Binary and Ternary SCC Mixes

The prepared SCC mixes should have basic fresh properties like flowability, passing ability, filling ability and viscosity ability. The fresh properties test on prepared SCC binary and ternary mixes, namely, the slump flow and T500 tests were performed according to EFNARC (2002 & 2005) guidelines. The slump flow test was conducted in the laboratory is shown in Fig. 1.

The fresh properties test was conducted in the laboratory with different test trials by modifying the proportions of fine & coarse aggregates, adjusting water to binder ratio, adjusting the dosages of superplasticizers and viscosity modifying agent. Once the required flow range was obtained, the optimum control SCC mix was chosen. From the satisfied control SCC mix, the partial substitution of cement by RHA in binary and SF & MK in ternary along with optimum RHA was prepared by modifying the dosages of SP and VMA only. Simultaneously, the fine and coarse aggregate mix proportions and water-binder ratio were kept constant for all the prepared SCC binary and ternary type 1, type 2 and type 3 mixes. The results shown that the W/B ratio adopted were between 0.40, the SP dosages had a range between 2% and 3% by weight of cement; the VMA percentage adopted was 0.2% and 0.3% by weight of cement.

Fig. 1. Slump flow test

RHA in SCC from 0% to 40% has reduced the flow properties in binary SCC mixes in slump flow test. It was observed that due to the increase in water demand by the replacement of cement by RHA. The particle size of RHA could also have an impact on flow properties in SCC. This was in agreement with the findings made by (Elias et al. 2018). When the RHA content increased in SCC mixes, the fresh property test results had a descending trend. Though the other mineral admixtures like SF and MK blended with RHA, the fresh property values decreased from the binary SCC slump flow values. The reason could be the highest water demand and higher specific area required for the ternary blended SCC mixes. Hence, similar flow behaviour was exhibited among binary SCC mixes of type 1; ternary SCC mixes of type 2 and types 3 when subjected to slump flow test. The obtained slump flow values for all the three SCC mix types were well within the guidelines laid by EFNARC (2002 & 2005).

In the T_{500} test, the time taken to reach the 50 cm diameter was measured in a slump flow test using the stop clock. This test would measure the flow rate in second (s) for the prepared SCC mixes. The increase in powder content like rice husk ash, silica fume, and metakaolin would affect all SCC mixes' flow rate. From Table 5, 6 and 7, the flow rate in binary and SCC mixes has exceeded the time values beyond 5 s; the reason could be the increase in water demand and higher specific surface area. SCC binary and ternary mixes were made workable by the dosages of SP, and VMA added higher percentages to cater to the water demand.

Hence, an increase in powder material like RHA, SF and MK has increased the slump flow time and decreased the slump flow diameter values were inferred from the fresh property test results of binary and ternary blended SCC mixes. However, the slump flow time (T500) was more significant than 2 s, and the slump flow spread diameter values range between 550mm-650mm, which satisfied the EFNARC guidelines.

The compression and tensile test conducted on cube and cylinder specimens are shown in Fig. 2, 3, 4 and 5.

3.2 Hardened Properties of Binary and Ternary SCC Mixes

3.2.1 Compressive Strength of Binary and Ternary SCC Mixes

From Table 8, the compressive strength of cube specimens with the size 100 mm × 100 mm × 100 mm and cylinder specimens of size 75 mm diameter and 150 mm height

Table 5. Fresh state property of SCC binary blend using RHA

Fresh property tests	Conventional concrete	Control SCC	R1 10% RHA	R2 20% RHA	R3 30% RHA	R4 40% RHA
T500 (s)	–	3.54	4.42	5.27	5.62	6.32
Slump Flow(mm)	85	620	617	595	580	575

Table 6. Fresh state property of SCC ternary blend using RHA & SF

Fresh property tests	Conventional concrete	Control SCC	SF1R1 5% SF+10% RHA	SF2R1 10% SF+10% RHA	SF3R1 15% SF+10% RHA	SF4R1 20% SF+10% RHA
T500 (s)	–	3.54	4.39	5.30	5.58	6.40
Slump Flow (mm)	85	620	610	592	587	571

Table 7. Fresh state property of SCC ternary blend using RHA & MK

Fresh property tests	Conventional concrete	Control SCC	MK1R1 5% MK+10% RHA	MK2R1 10% MK+10% RHA	MK3R1 15% MK+10% RHA	MK4R1 20% MK+10% RHA
T500 (s)	–	3.54	4.48	5.16	5.55	6.28
Slump Flow(mm)	85	620	615	586	577	562

Fig. 2. Compression test on cube specimen

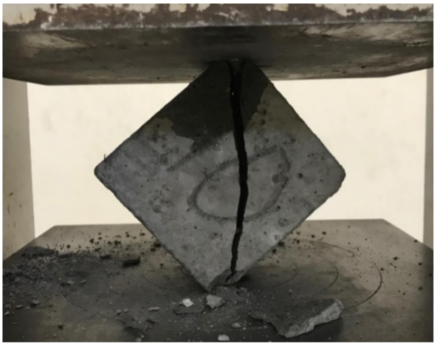

Fig. 3. Tensile test on cube specimen

Fig. 4. Compression test on cylinder specimen

Fig. 5. Tensile test on cylinder specimen

were investigated under uniaxial compressive strength at the age of 28 days. From Table 8 in binary SCC mixes using RHA, it is inferred that the replacement of cement by 10% RHA has increased the strength of about 8.18% and 14.82% in respect to control CC and SCC mixes of cube specimens. In axial compressive strength of cylinder specimens, the compressive strength of 10% RHA as cement replacement is increased by 1.55% and 17.17% in respect to control CC and SCC mixes. The partial substitution of cement beyond 10% RHA has shown a reduction in compressive strength values of both cube and cylinder specimens when tested at the age of 28 days. The results obtained from the experimental investigation on binary blended RHA based SCC mixes were in agreement with (Elias et al. 2018). As mentioned in Table 1, the presence of a higher percentage of SiO_2 was the reason behind the strength enhancement in binary RHA based SCC mixes. When the compressive strength of cube and cylinder specimens was compared, the cube compressive strength was higher than the cylinder compressive strength for RHA binary SCC mixes. Whereas in ternary SCC mixes, the cylinder compressive strength has dominated the cube strength. The compressive strength ratios had shown an increasing trend when cement was replaced by RHA from 10% to 40% because of the gradual reduction in their strength values. The lesser percentage of RHA as partial cement replacement in concrete has obtained the highest strength agreed with (Younes et al. 2018).

The ternary blended SCC mixes were prepared by partially replacing cement with 10% RHA was being kept constant and blended with SF ranging from 5% to 20%. From Table 8, it is observed that the mix consisting of 5%SF with 10% RHA has obtained the highest compressive strength amongst all SCC binary, ternary and control mixes. The reason could be silica presence in a higher percentage in SF and RHA, as shown in XRD Table 1. The compressive strength of cylinder specimens was higher than the cube specimens when tested at 28 days. It was observed that the effect of size ratios between cube (1:1) and cylinder (1:2) specimens had influenced the compressive strength values.

Hence the mix ID SF1R1 has shown a 3.35% and 19.85% increase concerning control CC mixes of cube and cylinder strength, as shown in Fig. 6 and 7. In ternary SCC mixes, the compressive strength has shown an increasing trend of 15% MK with a constant 10% RHA as cement replacement. It was observed that the addition of 5% SF along with a constant 10% RHA as cement replacement had shown the highest compressive strength results among ternary SCC mixes.

Table 8. Compressive strength of cube and cylinder specimens at 28 days

Sl. no.	Mix combinations	Mix ID	Cube compressive strength (fc1) in MPa	Cylinder compressive strength (fc2) in MPa	fc1/fc2 ratio
I	Control Mixes				
1	Conventional concrete	CC	32.51	32.85	**0.99**
2	Control SCC	SCC	30.63	28.47	**1.08**
II	Binary RHA Mixes				
3	10% RHA	R1	35.17	33.36	**1.05**
4	20% RHA	R2	30.12	27.35	**1.10**
5	30% RHA	R3	27.37	23.34	**1.17**
6	40% RHA	R4	16.7	13.49	**1.24**
III	Ternary RHA+SF Mixes				
7	5% SF+10% RHA	SF1R1	33.6	39.37	**0.85**
8	10%SF+10%RHA	SF2R1	28	33.02	**0.85**
9	15%SF+10%RHA	SF3R1	25.51	27.52	**0.93**
10	20%SF+10%RHA	SF4R1	18.94	24.56	**0.77**
IV	Ternary RHA+MK Mixes				
11	5%MK+10%RHA	MK1R1	27.42	25.41	**1.08**
12	10%MK+10%RHA	MK2R1	30.19	33.15	**0.91**
13	15%MK+10%RHA	MK3R1	35.88	38.28	**0.94**
14	20%MK+10%RHA	MK4R1	27.18	36.25	**0.75**

Figure 8 a better correlation between the compressive strength of cube and cylinder specimens with the R^2 value of 0.81. The size effect and the lateral restraint of the rigid platens used for the testing could also explain the above R^2 value.

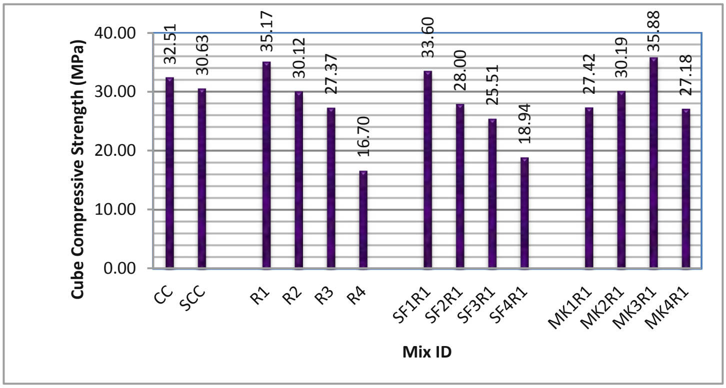

Fig. 6. Compressive strength of cube specimens at 28 days

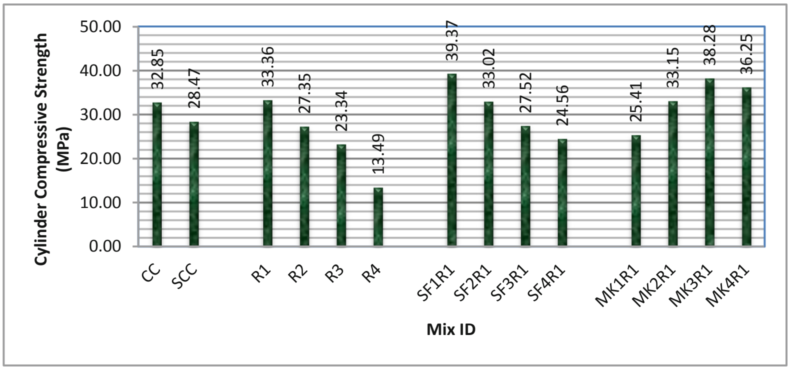

Fig. 7. Compressive strength of cylinder specimens at 28 days

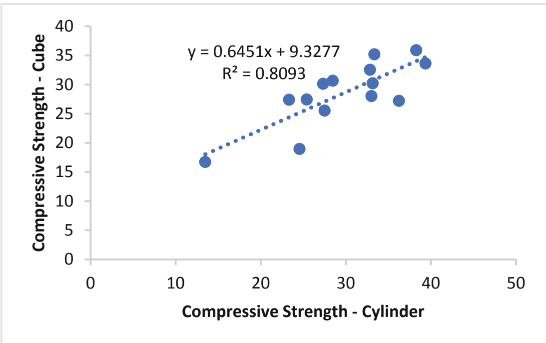

Fig. 8. Relation between compressive strength of cube and cylinder specimens

3.2.2 Split Tensile Strength of Binary and Ternary SCC Mixes

As the compressive strength increases, the tensile strength also increases proportionately, observed from the experimental results. By comparing Table 8 and 9, 10% of the compressive strength would be the obtained tensile strength values. In binary SCC mixes, 10% RHA has obtained the highest compressive strength values than control CC and SCC mixes. The mixes, namely SF1R1 and MK3R1, have shown the highest tensile strength in ternary SCC mixes, similar to the compressive strength results reported. Hence the optimum percentage of cement replacement could be 5% SF and 15% MK with 10% RHA had kept constant in SCC ternary mixes, as shown in Fig. 9 and 10. In all 14 mixes, it was observed that the tensile strength values of cylinder specimens were higher than the cube specimens.

Table 9. Tensile strength of cube and cylinder specimens at 28 days

Sl. no	Mix combinations	Mix ID	Cube split tensile strength (ft1) in MPa	Cylinder split tensile strength (ft2) in MPa	ft1/ft2 ratio
I	Control Mixes				
1	Conventional concrete	CC	3.23	3.78	**0.86**
2	Control SCC	SCC	2.64	3.54	**0.75**
II	Binary RHA Mixes				
3	10% RHA	R1	3.48	3.83	**0.91**
4	20% RHA	R2	2.86	2.83	**1.01**
5	30% RHA	R3	2.25	2.53	**0.89**
6	40% RHA	R4	1.76	1.68	**1.05**
III	Ternary RHA+SF Mixes				
7	5% SF+10% RHA	SF1R1	3.71	4.72	**0.79**
8	10%SF+10%RHA	SF2R1	3.40	3.97	**0.86**
9	15%SF+10%RHA	SF3R1	2.80	3.69	**0.76**
10	20%SF+10%RHA	SF4R1	2.28	3.06	**0.75**
IV	Ternary RHA+MK Mixes				
11	5%MK+10%RHA	MK1R1	3.38	3.86	**0.88**
12	10%MK+10%RHA	MK2R1	3.86	4.37	**0.88**
13	15%MK+10%RHA	MK3R1	4.38	4.84	**0.90**
14	20%MK+10%RHA	MK4R1	3.29	4.08	**0.81**

Figure 11, it was inferred that a better correlation obtained between the tensile strength of cube and cylinder specimens with the R^2 value of 0.86. The correlation was well pronounced in the tensile strength compared with the compressive strength

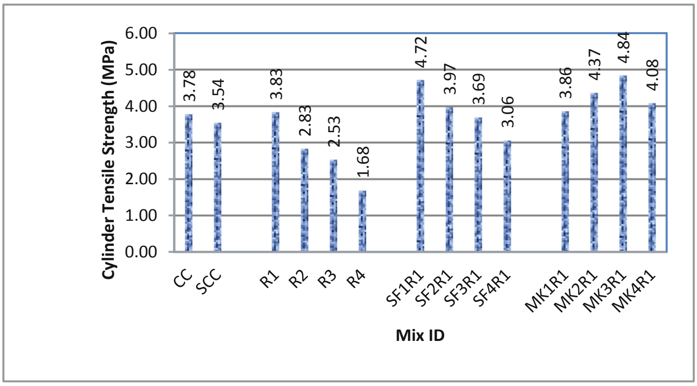

Fig. 9. Split tensile test on cylinder specimens at 28 days

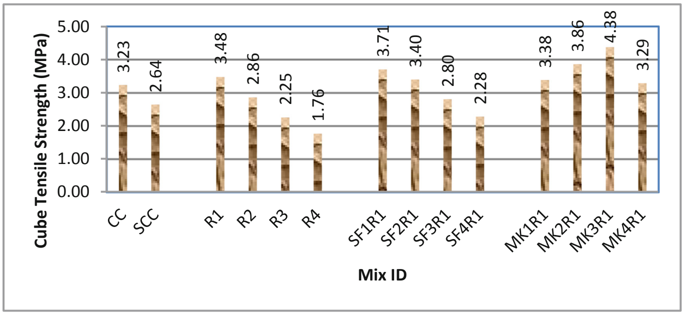

Fig. 10. Split tensile test on cube specimens at 28 days

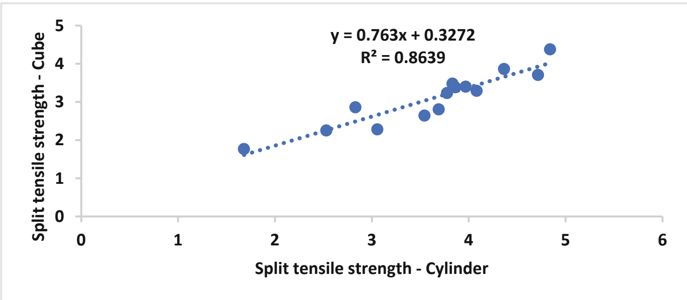

Fig. 11. Relation between the split tensile strength of cube and cylinder specimens

observed through an increase in R^2 value. The cube specimen position for tensile testing remains the same as the cylinder inscribing the square with a circle.

3.2.3 Modulus of Rupture

The modulus of rupture test was conducted using the prism specimens of size 500 × 100 × 100 mm. The experimental test set-up comprises two-point loading, as shown in Fig. 12.

The mode of failure obtained was flexure. The optimum binary and ternary SCC mixes were subjected to the rupture test's modulus as shown in Table 10. Hence, ternary SCC mixes had better behaviour compared with binary SCC and control mixes. Using IS: 456-2000 code, the flexural tensile strength is given by $fcr = 0.7\sqrt{fck}$. If we adopt the equation mentioned above in ternary SCC mixes, namely SF1R1 and MK3R1, theoretical values are 4.39 MPa and 4.33 MPa, respectively. But the obtained experimental values were 5.50 MPa was greater than the calculated theoretical flexural tensile strength values. Comparing the cylinder and flexural tensile strength values of mixes SF1R1 and MK3R1, the flexural tensile strength values were higher than cylinder tensile strength by 16.52%, 13.63%, respectively.

Table 10. Modulus of rupture for control and optimum mixes

Mix combinations	Mix ID	Modulus of rupture (MPa)
Control Mixes		
Conventional concrete	CC	4.00
Control SCC	SCC	4.00
Binary RHA Mixes		
10% RHA	R1	4.50
Ternary RHA+SF Mixes		
5% SF+10% RHA	SF1R1	5.50
Ternary RHA+MK Mixes		
15%MK+10%RHA	MK3R1	5.50

3.3 Microstructure Analysis Using Scanning Electron Microscope (SEM)

From Fig. 13, it was inferred from the SEM examination of control SCC that the presence of more void spaces could be the reason for the decrease in their strength properties.

The clusters of void spaces in control SCC had caused the brittle failure when the loading was applied gradually.

From Fig. 14, it was inferred from the SEM examination of 10% RHA in SCC that the larger platelets of calcium hydroxide, Calcium-Silicate-Hydrate gel formation with flowery appearance and tiny needles of ettringite formation. Hence it could be the reason

Fig. 12. Modulus of rupture test set up

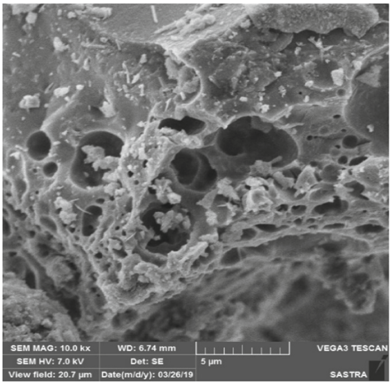

Fig.13. Microstructure of SCC

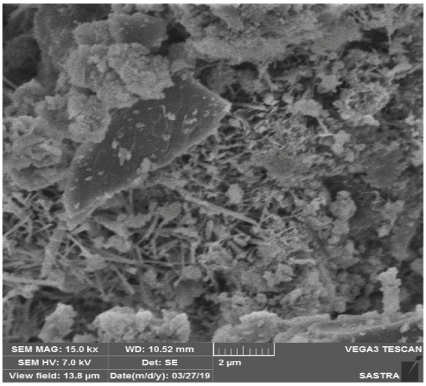

Fig. 14. Microstructure of R1

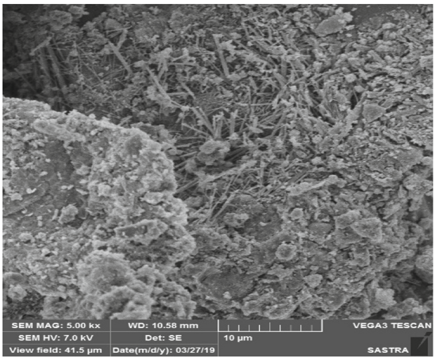

Fig. 15. Microstructure of MK3R1

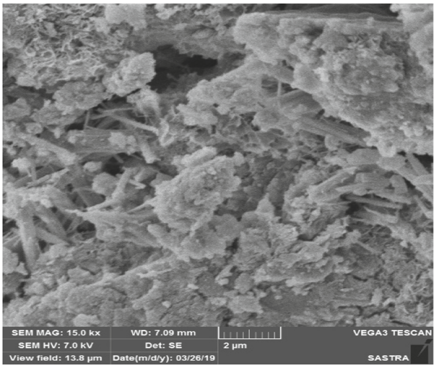

Fig. 16. Microstructure of SF1R1

for the highest strength because of the fewer number of void spaces in RHA based SCC mix.

From Fig. 15, the SEM image of the ternary mix with ID MK3R1 was noticed. It was reported from the image that tiny platelets of calcium hydroxide, C-S-H gel formation, small needles of ettringite formation, and fewer void spaces. C-S-H gel's presence with the supplementary crystalline products could be the reason for the highest tensile strength among other CC and SCC mixes. The creamy texture was inferred due to the presence of MK along with RHA in the SCC mix.

From Fig. 16, the SEM image of ternary mix with ID SF1R1 has shown the dense formation of C-S-H gel with fewer void spaces could be the reason for the highest compressive strength among other CC and SCC mixes. Since the particle size of silica fume is less than 1 μm could have filled the pores during hydrated phases and has shown the highest strength.

3.4 Simulation of Experimental Results Using Artificial Neural Network (ANN) Tool

In this present research, a two-layered feed-forward mechanism trained with a backpropagation algorithm is used in ANN. The network architecture used is shown in Fig. 17. The network layout comprises eight input parameters, ten neurons, two hidden layers and one output layer. The ANN architecture was formulated with a hidden layer using a sigmoid function and an output layer with a linear function. The input parameters used were aggregate size, cement content, water/cement ratio, RHA content, SF content, MK content, Slump value, and superplasticizer dosage, similar to the experimental investigation parameters. The output layer of the ANN was compressive and split tensile strength. A data set including 48 data samples was obtained from other references' experimental results (Elias et al. 2018; Rahman et al. 2014; Chithra et al. 2016). Thirty-four samples were used for training, seven samples are used for validation, and seven samples are used for testing. The three different algorithms, namely Lavenberg Marquardt, Bayesian Regularization, and Scaled Conjugate Gradient, were used to train the network. Table 11 and 12 show the compressive strength's simulated results and split tensile strength performed by the three algorithms. The best algorithm was found to be Lavenberg Marquardt. Figure 18, 19, 20, 21, 22 and 23 shows the R^2 values of various algorithms used for simulation of strength.

Table 11. ANN results for compressive strength

Types of algorithm	R^2	No of epochs	MSE
Lavenberg Marquardt	0.7969	17	71.1
Bayesian Regularization	0.7801	1000	76.70
Scaled Conjugate Gradient	0.7704	18	57.92

Table 12. ANN results for split tensile strength

Types of algorithm	R^2	No of epochs	MSE
Lavenberg Marquardt	0.8386	7	0.09
Bayesian Regularization	0.7937	190	0.27
Scaled Conjugate Gradient	0.7930	21	0.19

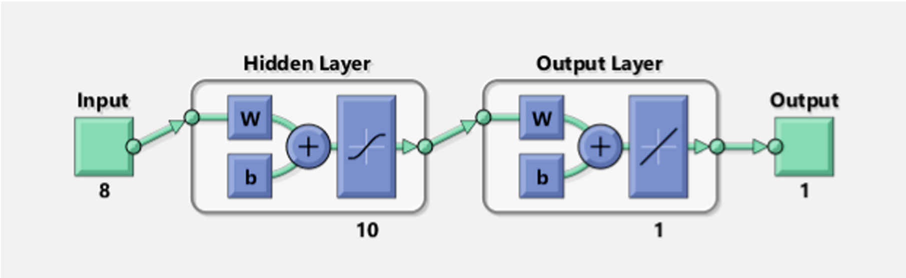

Fig. 17. ANN architecture

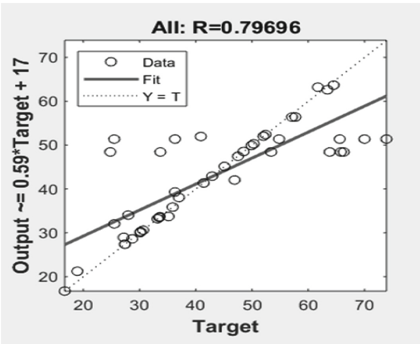

Fig. 18. Lavenberg Marquardt algorithm of compressive strength

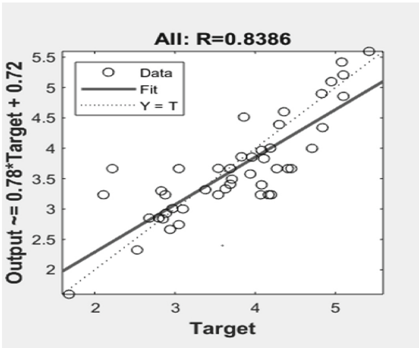

Fig. 19. Lavenberg Marquardt algorithm of split tensile strength

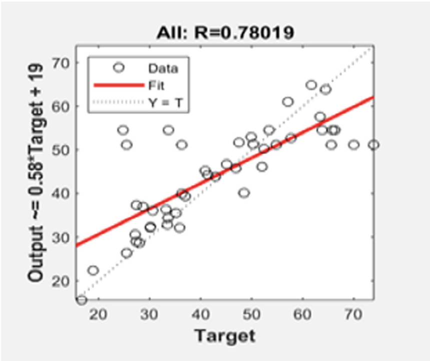

Fig. 20. Bayesian Regularization algorithm of compressive strength

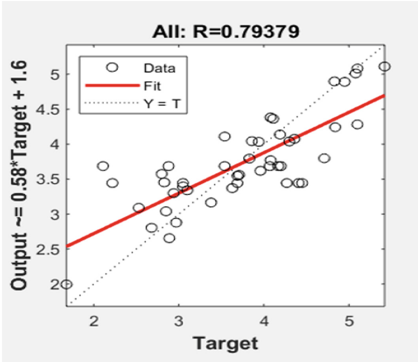

Fig. 21. Bayesian Regularization algorithm of split tensile strength

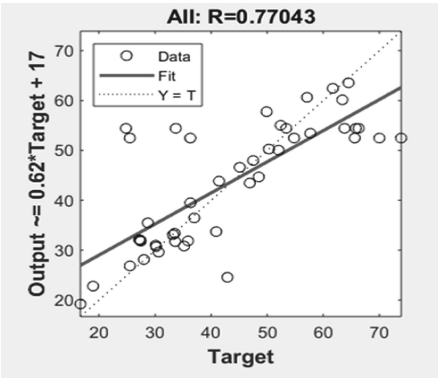

Fig. 22. Scaled Conjugate Gradient algorithm of compressive strength

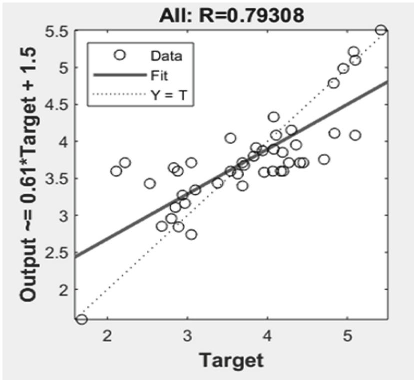

Fig. 23. Scaled Conjugate Gradient algorithm of split tensile strength

4 Conclusions

Based on the experimental investigation, microstructure and analytical study performed on binary and ternary SCC mixes, the following important conclusions are drawn as follows:

- The fresh property of SCC has decreased with an increased percentage of RHA. The slump flow time (T_{500}) was more significant than 2 s, and the slump value range between 550 mm–650 mm and these ranges satisfied the EFNARC guidelines.
- In binary blended RHA based SCC mixes, for 10% RHA, the compressive strength was increased by 8.18% and 14.82% in respect to control and SCC mixes; split tensile strength was increased by 1.49% and 8.14% in respect to control CC and SCC mixes.
- In ternary blended RHA+SF based SCC mixes, for 5% SF+10% RHA the compressive strength was increased by 3.35% and 9.69% in respect to control and SCC mixes; split

tensile strength was increased by 24.88% and 33.06% concerning control CC and SCC mixes.

- In ternary blended RHA+MK-based SCC mixes, for 15% MK+10% RHA, the compressive strength and split tensile strength was increased by 10.3% and 17.1% 28.18% and 36.58% in respect to control and SCC mixes.
- A better correlation was exhibited between cube tensile strength and cylinder tensile strength with an R^2 value of 0.8639.
- It was inferred that cube compressive strength was 25% higher than cylinder axial compressive strength.
- It was inferred through SEM examination; the pore size refinement took place and the formation of C-S-H gel in the form of crystalline products.
- Based on the analytical modelling using ANN, the experimental and analytical values were better correlated with an R^2 value of 0.7969 and 0.8386 for compressive strength and split tensile strength, respectively.
- Hence, the cement replacement by 15%MK+10% RHA was suggested as an optimum mix for sustainable development.

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