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Recycled coarse aggregate and silica fume used in sustainable self-compacting concrete

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Abstract

When used in conjunction with cementitious mortar, recycled coarse aggregates (RCA) from demolition and rubble debris have numerous financial and environmental advantages by reducing carbon dioxide (CO_2) emissions, minimising wasteful resource consumption, and assisting in a cleaner concrete manufacturing process. This paper evaluates fresh properties, durability properties and compressive strength (CSs) of self-compacting concrete (SCC) using RCA and silica fume (SF). Therefore, in this study, the effects of partial replacements of natural coarse aggregate (NCA) by RCA and ordinary Portland cement (OPC) by SF in the SCC mixes, cured in normal tap-water and also, in the presence of sodium sulphate (Na_2SO_4) solutions (2.0 g/l) for the exposure period of 28, 180 and 270 days, are investigated. Three different SCC mixes – control mix (CM) [OPC (100%) +NCA (100%)] whereas the other mixes have been designated as Mix-SF10 [OPC (90%) + SF (10%) + NCA (100%)] and Mix-SF10RCA25 [OPC (90%) + SF (10%) + NCA (75%) + RCA (25%)]. The fresh and hardened properties of the mixes, along with their microstructural properties were determined. The change in microstructure of the SCC mixes due to sulphate attack were investigated by X-ray diffraction (XRD). It is concluded that fresh properties are increased up to an optimum level of SF content (SF-10%) and in case of RCA, the trend reverses; the gain in CSs of different SCC in normal tap-water is lies between 6.76-25.00%, and reductions in CSs of SCC mixes exposed to Na_2SO_4 solution is in the range of 0.75-7.01 % in comparison to the SCC mixes's strength in normal tap-water. In contrast to the CM, the Na_2SO_4 attack had a smaller impact on the SCC mix, which contained SF viz., SF10 and SF10RCA25.

Keywords

Recycled coarse aggregate, Silica fume, Self-compacting concrete and Sodium sulphate.

1.Introduction

Due to its many advantageous characteristics, concrete is the material most commonly used in construction, which includes good compressive strength (CSs) high moldability, plasticity etc., and impermeability, fire resistance, durability, etc. It is used in different structures like buildings, bridges etc. However, there is a need to enhance the attributes of concrete because it has some unwanted qualities, such as tensile weakness, brittleness, low crack resistance, low impact resistance, weight etc. The most expensive component in concrete is the binder ordinary Portland cement (OPC), which serves as the traditional binding agent.

The production of OPC is a highly energy-intensive process that consumes a lot of fuel to make clinker and leads to significant emissions of carbon dioxide (CO_2) etc., which leads to global warming [1].

As a result, numerous research projects are focused on finding ways to partially or completely replace OPC in the manufacturing of concrete with other materials, like industrial, agricultural, and agro-industrial by-products, without sacrificing the quality of the concrete. Utilizing such materials not only helps in protecting the environment, but also in reduction of the cost of the structures metakaolin (MK), sugarcane bagasse ash (SBA), and silica fume (SF) are a few examples of pozzolanic materials that can be used to partially replace.

OPC in the production of concrete. These are either wastes or industrial by-products that have been added

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to cement during the concrete-making process. These are frequently added to the concrete mixtures to improve durability and the strength through pozzolanic or hydraulic activity, minimize the amount of cement, and improve the workability [2, 3]. A unique form of concrete known as self-compacting concrete (SCC) slows through choked reinforced, seals each gap of the formwork, and compacts under its own weight. The SCC exhibits an excellent passing ability, filling ability and segregation resistance. The SCC in general is made by use of different pozzolanic materials such as fly ash (FA), ground granulated blast-furnace slag (GGBS), MK, SF etc. The SF is regarded as one of the most efficient and mineral admixtures that significantly enhances concrete strength and reduces permeability. Due to the difficulties in achieving the requisite SCC workability, the use of SF in the SCC is limited. The demolition wastes obtained from different structures are useless and dumped; however, the waste concrete aggregate can be used for recycling in concrete. The resulting concrete mixes environment friendly and makes the construction “greener”. The use of recycled coarse aggregates (RCA) in concrete is one of the steps for sustainable development [4].

This paper is organized as follows. Literature review has been discussed in section 2. Methods and results have been elaborated and investigated in section 3 and section 4 respectively. Finally, it is concluded in section 5.

2.Literature reviews

Sustainable waste management and recycling are critical for ensuring a long-term prospect. Worldwide, the construction sector generates an enormous amount of waste that must be properly disposed of. Construction and demolition rubbish is made up of miscellaneous materials like metal, concrete, mineral, and wood wastes in unsorted mixed fractions. The subcategory of masonry rubbish, the most common, and hence the most problematic garbage that winds up in landfills is bricks, tiles, and concrete. The disposal of masonry waste is miserable because it has the potential to be recycled in concrete [5]. Thermal power plants and ferro-silicon industries generate several types of wastes which pose many environmental problems, if not disposed of properly. By incorporating these products into concrete, several issues can be resolved. For the creation of SSCs, FA, micro-silica (MS), and nano-silica (NS) etc. can be used. After 90 days, the SCC mixes with NS (2%) and the MS (10%) +NS (2%) showed an improvement in CSs by 9.28% and 10.84%, respectively. Less water is needed for the addition of NS. Also, it significantly reduces the chloride penetration depth [6]. When FA greater than 30% is incorporated into SCC, its strength drops at earlier ages but increases at a later age. At all curing durations, the concrete that contains MK and SF possesses a developed CSs. The CSs of SCC using high-volume FA (HVFA) has been found to decline significantly with additions of RCA and coal bottom ash (CBA). HVFA-based SCC has a similar tensile strength pattern to natural coarse aggregates (NCA) based blends, according to the tests on CBA and NCA/RCA based concrete [7]. When GGBS percentage is increased by 10, 20, and 30% in geopolymer concrete based on FA, the CSs is increased by 17, 31, and 41%, respectively. X-ray diffraction (XRD) analysis of these samples showed a decrease in crystallinity with an increasing percentage of GGBS, and a corresponding increase in calcium-silicate hydrate (C-S-H) gel that had better reactivity than FA [8]. By reducing the greenhouse gas emissions and saving natural resources, the green concrete made with RCA and recycled powder can perform well. The RCA and powder mixed concrete's CSs increase by about 11% over NCA concrete, and its cost parameters are also lower [9]. All mixes' CSs are reduced when RCA is used, whereas, the influence on tensile strength is negligible. The incorporation of RCA, had a negative impact on the measured durability attributes of recycled aggregate concrete, such as water absorption and permeable void volume, and these properties increased as the RCA level increased. The substitution of 25% NCA by RCA had no influence on the durability characteristics of SCC, such as chloride ion resistance and electrical resistivity; however, increasing the fine aggregates and RCA content decreased these parameters [10]. The CSs of the SCC mixes is improved by the addition of steel fibres and RCA for partial replacement of coarse particles. At 28 days, the CSs of M30 grade concrete increased by 22.7% when NCA (0 to 50%) was substituted with RCA; the tensile strength increased by 16.5%. All concrete blends improved their splitting tensile strength as the amount of RCA and steel fibre increased [11]. When concrete is submerged in water for 7, 28 and 56 days, and thereafter vulnerable to magnesium sulphate ($MgSO_4$) solution (40 g/l), the CSs of mixes with 10% RCA are more advanced than the standard mix. With a rise in RCA, RCA concrete loses CSs. The strength loss would be significantly worse, if the concrete were exposed to the sulphate solution for a longer period. According to the results of experiments, 10% of RCA is ideal in terms of sulphate resistance [12]. The hardened properties of the SCC can be greatly improved by replacing the NCA with RCA, and the OPC with SF [13]. The mortar that is affixed to RCA's surface responds to ambient and produces CO_2, which improves RCA's microstructure and compactness significantly. Fibers and RCA can be used to improve the microstructure and performance of interfacial transition zone (ITZ) in concrete, and it enhances the mechanical characteristics and durability [14]. Numerous studies have been conducted to investigate how SCC performs when different mineral additives are used. In addition to greatly increasing CSs, binary and ternary sand-based self-compacting mortars (SCMs) meets the requirements for slump flow and V-funnel time [15]. High FA content slightly decreases workability, whereas high rice husk ash (RHA) content reduces both the workability and segregation. Up to 25% RHA can be used which provides adequate workability [16]. However, there hasn't been much research on using RCA to create SCC, especially for recovered fine aggregates. Typically, fine materials from demolition sites or gravel quarries are dumped; however, if the characteristics of the recycled fine aggregates are considered in the plan, it could be used in place of natural fine aggregates [17]. Coarse (20%) and fine recycled aggregates (FRA) in SCC mixes weren't enough to meet EFNARC SCC specifications [18]. Under cyclic environmental situations along with exposure to Na_2SO_4, the durability of mixtures with RCA outperformed mixtures with NCA and pozzolans [19]. The use of recycled fine material as inert extracts in SCC develops its mechanical, physical, and durability-related characteristics with respect to the CM with the same cement content [20, 21].

In the research work, the SCCs were made using the optimum quantities of SF (10%) and RCA (25%), and these were exposed to both the normal tap-water and Na_2SO_4 solution for 28, 180 and 270 days. The fresh properties, CSs and microstructure of the different SCC mixes viz., CM, SF10 and SF10RCA25 were determined.

3.Materials and methods

3.1Materials and mix proportioning

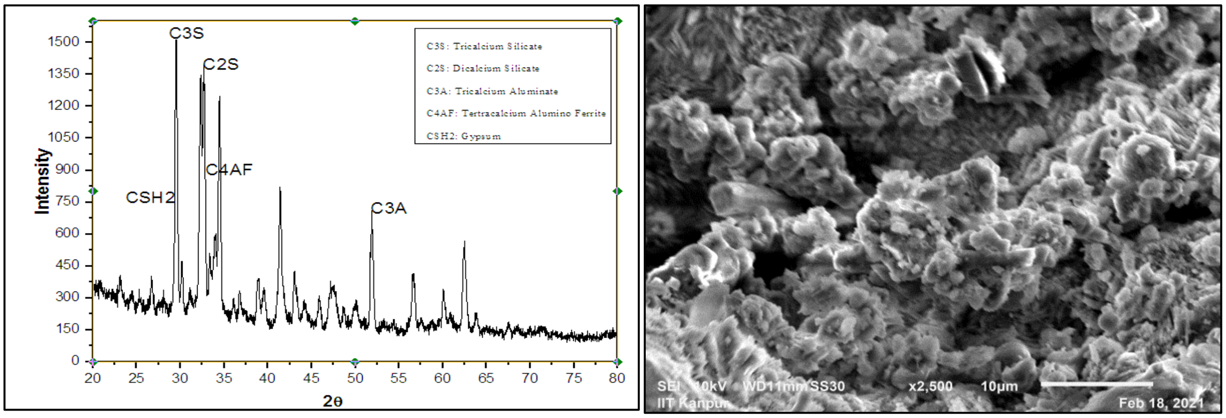
All the SCC mixes in this investigation were made with 43 Grade Jaypee OPC, which complied with the requirements of IS: 8112-1989 [22]. The SF is a very fine, non-crystalline silica, which complied with the standards of IS: 15388 -2003 [23] and was purchased from M/S-Jalyan-Trading, Bhaleja, G.I.D.C., District: Anand, Gujarat. In *Table 1*, the physical and chemical properties of both the OPC and the SF are listed. *Figures 1* and *2* display the XRD and SEM photographs of the OPC and SF, respectively. The natural river sand (maximum particle size-4.75 mm) was used as fine aggregate. Coarse aggregates of 10 and 20 mm sizes were used. Natural fine and coarse aggregates complied with IS: 383-1987 [24] criteria, and *Table 2* lists their physical characteristics. *Figure 3* displays the photographs of NCA and RCA. A Polycarboxylic based super-plasticizer Master-Rheobuild-817RL was used. The SCC mixtures were cured in normal tap-water and were exposed to Na_2SO_4 solution. Na_2SO_4 salt was dissolved in distilled water to make the solutions. All the SCC mixes (CM, SF10 and SF10RCA25) were exposed to both the tap water and Na_2SO_4 solution (2.0 g/l). The mixes were exposed to the Na_2SO_4 solution after 28 days normal tap-water curing to simulate the precast concrete conditions, and the number of days includes the initial 28 days tap-water curing. The sodium sulphate solutions were not replaced during the trials, resulting in a static testing circumstance; nevertheless, the pH of the solutions was kept constant. *Figure 4* and *Table 3* show both the pictures and physical properties of sodium sulphate salt.

Table 1 Physical and chemical properties of OPC and SF

Compositions	**OPC**	**SF**
SiO_2	20.4	96.10
Fe_2O_3	3.09	3.09
Na_2O	0.50	0.80
CaO	63.90	0.31
Al_2O_3	6.20	6.20
K_2O	0.49	0.35
MgO	1.50	0.45
Specific Surface Area (m^2/g)	2930	30000
Specific Gravity	3.15	2.20
Loss of ignition	3.10	2.43
Density (kg/m^3)	3150	2930

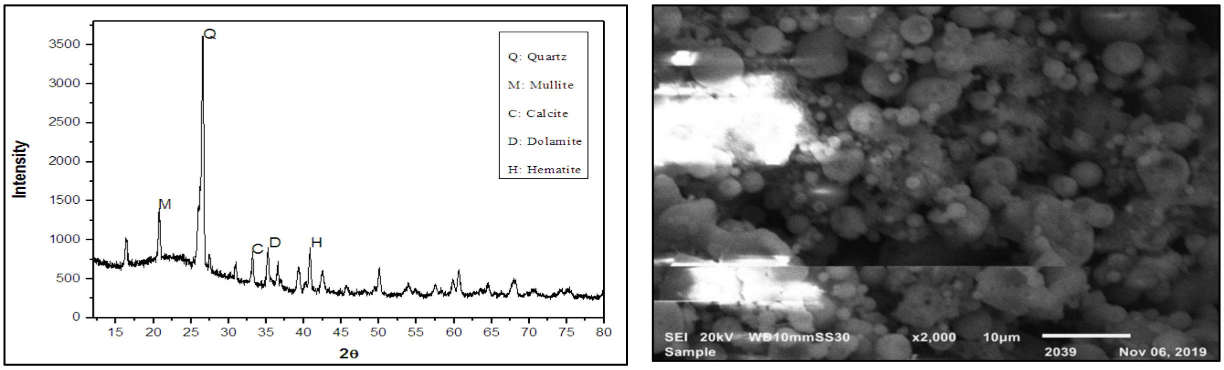
Table 2 Physical characteristics of NCA and RCA

Characteristics	NCA		RCA	
	10 mm	**20 mm**	**10 mm**	**20 mm**
Water Absorption (%)	1.0	0.9	2.0	1.0
Specific Gravity	2.66	2.70	2.60	2.65
Impact Value (%)	15	16	16	17
Crushing Value (%)	25	23	24	26
Bulk Density (kg/m^3)	1590	1560	1600	1590
Fineness Modulus	6.7	7.2	6.5	7.0



(a) (b)

Figure 1 XRD photographs of OPC, (b) SEM image of OPC



(a) (b)

Figure 2 (a) XRD photographs of SF, (b) SEM image of SF

NCA (10 mm) **NCA (20 mm)** **RCA (10 mm)** **RCA (20 mm)**

Figure 3 Photographs of NCA and RCA

Figure 4 Pictures of sodium sulphate salt

Table 3 Physical properties of sodium sulphate salt

Appearance	White crystalline solid
Boiling Point	1429C (Anhydrous)
Melting Point	884C (Anhydrous)
Refractive Index	1.468
Solubility	Insoluble in ethanol; Soluble in water, Glycerol and hydrogen iodide
Odour	Odourless
Density	2.664 g/ml

3.2Methods

3.2.1Optimisation of the SCC mixes

For finding the optimum doses of SF and RCA in the SCC mixes, in isolation and in combination, different SCC mixes were prepared considering different replacement levels of the OPC by SF content, and NCA by RCA. This investigation is divided into three following parts. In the first part, OPC was used in the SCC mixes, designated as CM; OPC was in part substituted (0-25%) by the SF, and the optimum was 10%, the mix prepared using optimum SF and NCA is designated as mix-SF10; third-OPC was in part substituted by the optimum SF content (10%), and also, the NCA was in part substituted (0-100%) by RCA, and the optimum replacement level was 25%, the mix prepared using the optimum contents of the above materials is designated as Mix-SF10RCA25. The SCC cubes of different trial mixes were cast and cured in normal tap-water for 28 days, and their CSs were found at 7 and 28 days for determining the optimum doses of SF and RCA. All the above concrete mixtures were prepared with total binder content = 465 kg/m^3, and at a constant w/b ratio of 0.43 using OPC, SF, NCA and RCA. The final mix ratio (Binder: Fine aggregate: Coarse aggregate; w/c) was 1:2.01:1.58; 0.43. The CSs of various mixes are included in *Table 4*. The details of mix proportions of trial mixes are presented in *Table 5*. The block diagram of the present study is shown in *Figure 5*.

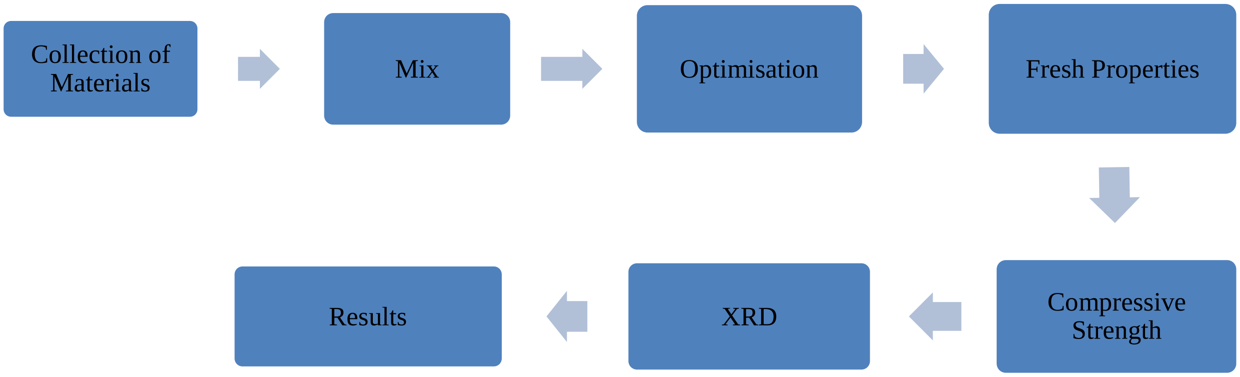


Figure 5 Block diagram of work

Table 4 Compressive strength of the SCC mixes

	Compressive strength (MPa)	
Mix	**7 days**	**28 days**
SF00	26.00	39.34
SF05	29.34	42.00
SF10	**34.67**	**44.00**
SF15	32.00	41.67
SF20	30.00	39.00

	Compressive strength (MPa)	
Mix	**7 days**	**28 days**
SF25	28.34	37.34
SF10RCA00	34.67	44.00
SF10RCA25	**33.00**	**42.00**
SF10RCA50	32.34	41.34
SF10RCA75	32.00	40.00
SF10RCA100	31.67	39.67

Table 5 Mix proportions of the mixes (Kg/m^3)

Sample	OPC (Kg)	SF (Kg)	Fine Aggregate (Kg)	NCA (Kg)	RCA (Kg)	W/C ratio	Super plasticizer dose (Litre)	Water (Litre)
SF00	465.00	0.00	937.50	737.00	-	0.43	3.72	200.00
SF05	441.75	23.25	937.50	737.00	-	0.43	3.72	200.00
SF10	**418.50**	**46.50**	**937.50**	**737.00**	**-**	**0.43**	**3.72**	**200.00**
SF15	395.25	69.75	937.50	737.00	-	0.43	3.72	200.00
SF20	372.00	93.00	937.50	737.00	-	0.43	3.72	200.00
SF25	348.75	116.25	937.50	737.00	-	0.43	3.72	200.00
SF10RCA00	418.50	46.50	937.50	737.00	0.00	0.43	3.72	200.00
SF10RCA25	**418.50**	**46.50**	**937.50**	**552.75**	**184.25**	**0.43**	**3.72**	**200.00**
SF10RCA50	418.50	46.50	937.50	368.25	368.25	0.43	3.72	200.00
SF10RCA75	418.50	46.50	937.50	184.25	552.75	0.43	3.72	200.00
SF10RCA100	418.50	46.50	937.50	0.00	737.00	0.43	3.72	200.00

3.2.2Fresh properties of the SCC mixes

SCC may exhibit greater plastic shrinkage or creep than the regular concrete mix because of the high powder content. Therefore, these factors ought to be taken into account when designing and defining the SCC. However, there isn't much information about these aspects, so more research is needed in this area. Additionally, it is important to take special care to cure the concrete as soon as feasible. The workability test equipment's are displayed in *Figure 6*. The workability/fresh properties of SCC are reflected through the following characteristics:

- Filling ability-slump flow test, T-50 time and V funnel test.
- Passing ability- L-box test, U-box test and J-ring test.

Slump flow test and T-50 time: The slump flow test is used to evaluate SCC's flowability (ability to fill all parts of formwork). For this test, the SCC circle's diameter is measured in two transverse directions in accordance with EFNARC-2005 [25]. The time required for concrete to attain a 500 mm diameter is known as the T-50 time.

V-funnel test: The V-funnel time is the time that a specific volume of the SCC takes to pass through a small opening, and it indicates the SCC's capacity to fill the cavities, provided obstructive and segregation does not occur. The flow time of the V-Funnel Test is somewhat correlated with the plastic viscosity.

L-box, U-box and J-ring test: The L-box test which indicates the concrete's flow as well as the degree to which it is blocked by the reinforcements; U Box test evaluates the SCC's filing capacity; J-Ring Test is employed to determine a reliable indicator of the SCC mixture's capacity to pass.

3.2.3Compressive strength of the mixes

A 2000 KN Compression Testing Machine (Loading rate 140 kg/cm^2/min, IS: 516-1959) [26] was used to find the CSs of 100 mm size SCCs cubes produced using different materials at 28, 180, and 270 days. Compression Testing Machine is shown in *Figure 7*, and *Figure 8* shows the concrete samples in the curing tank.

Slump flow test V-funnel test

L-box Test U-box Test J-ring Test

Figure 6 Workability test apparatus

Figure 7 Compressive testing machine

Figure 8 SCC cubes exposed to sodium sulphate solution

3.2.4Microstructural analysis

The purpose of the microstructural examination is to understand in a better way the shape and complexity of the SCCs prepared in this work. In comparison to other petrographic techniques, the XRD analysis is one of the most reliable techniques. This technique provides a good qualitative and relative quantitative assessment of the hydrated products, and thus it was used in this study.

3.2.4.1 X-Ray diffraction analysis

The XRD is a non-destructive material which discloses precise details of the physical characteristics, chemical compositions, and crystallographic structure of a material. It works on the principle of interference with monochromatic X-rays and crystalline samples. The material is illuminated by collimated X-rays in an XRD. The sample and X-rays interact to create a diffracted beam that is captured. Plotting the intensity of the diffracted rays that are dispersed throughout the material at different angles will reveal a diffraction pattern. Each phase of the substance produces a unique diffraction pattern because of the atomic and chemical structure of the substance. The SCC mixes' samples were prepared for the XRD, and X-Ray transmission micrographs were obtained (Xpert pro, Panalytical, USA). The mineralogical composition or phase identification of SCC mixtures was determined at 2ϴ in the range of 0-100 degree, and each element's XRD is shown graphically, with distinct peaks for each element. C_2S, C_3S, C_3A, and C_4AF are the main compounds of the cement/concrete that go through the hydration procedure. CH, C-S-H, and ettringite are the most common hydrated products. XRD peaks can be used to identify these compounds/elements. The XRD setup is shown in *Figure 9*.

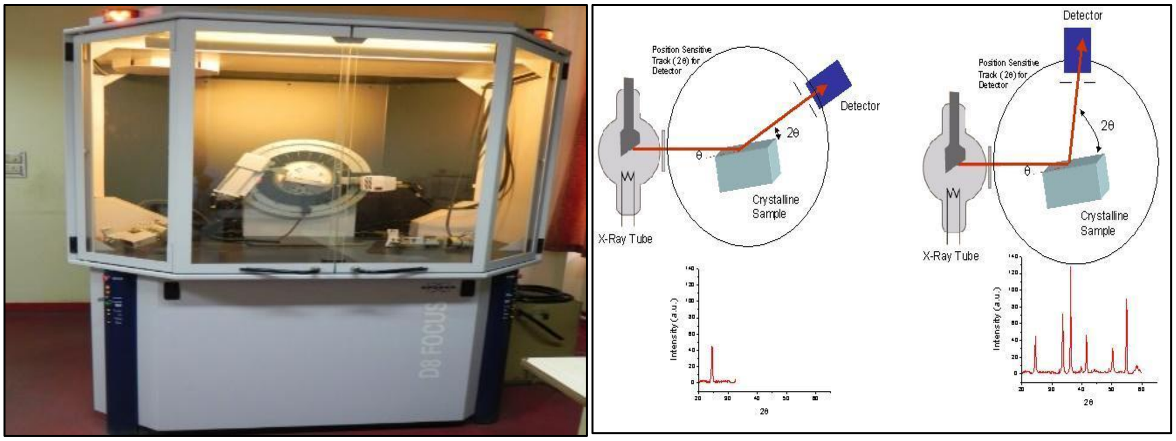


Figure 9 XRD setup

4.Results and discussion

4.1Fresh Properties of the mixes

For finding the optimum doses of SF and RCA in the SCC mixes, in isolation or in combination, the different SCC mixes were decided at the optimum levels of the OPC replacement by SF, and NCA by the RCA, and their effects on the workability parameters were investigated. The workability results are graphically represented in *Figures 9-11*. *Figure 10* shows that the slump flow lies between 540-600 mm, and the maximum slump flow (600mm) was found when the OPC was replaced by 10% SF in the SCC mix i.e., Mix-SF10. The T-50 Time lies between 5.5-6.0 sec (*Figure 10*). The Slump Flow (mm) value as well as T-50 Time (sec) increases up to the optimum level of the SF content (10%) and after that these decreases. The SF has smaller particles than the OPC, so it requires more water for the hydration process. The V-Funnel values of the different SCC mixes lie between 12.5-13.3 sec (*Figure 11*). The L-Box values (h_2/h_1) was lying between 0.92-9.8 (*Figure 10*), and the values of the U- Box (28.5-30 mm) and J-ring (8.2-8.8mm) were also within the required limits of EFNARC-2005 **[**21] (*Figure 12*). All the SCC mixes satisfied the requirements of EFNARC-2005 limits [25]. It is clear from the experimental results that the Slump Flow (mm) is increased up to the optimum level of SF content (10%), while the V-Funnel, U-Box, T-50 Time, L-Box and J-Ring values decreased; however, the trend reversed when NCA was substituted by RCA at optimum level (25%).

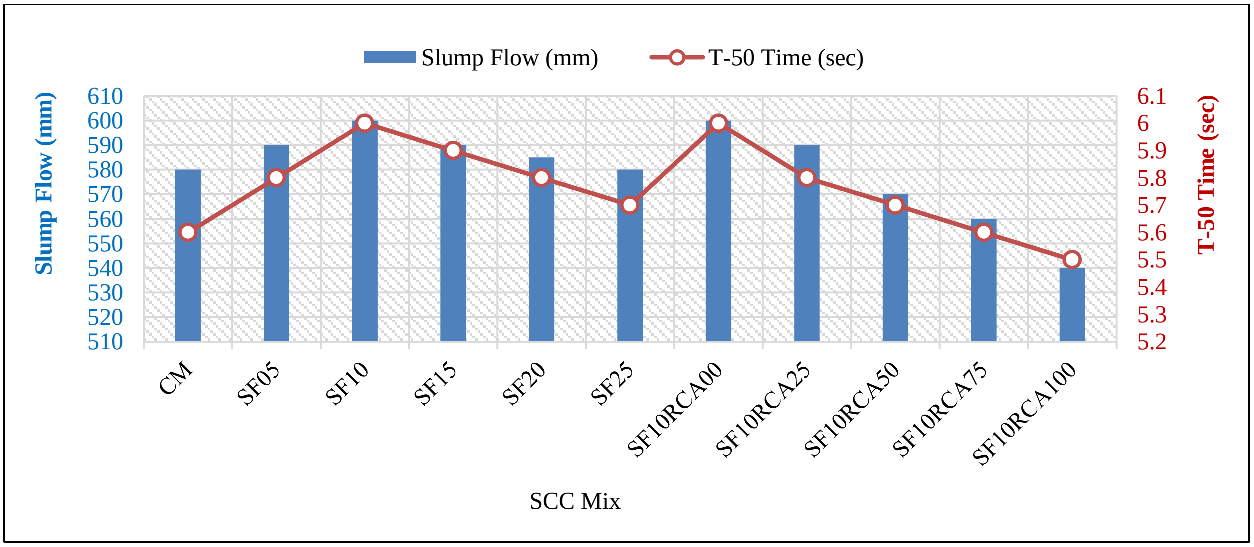


Figure 10 T-50 time and slump flow tests of the mixes

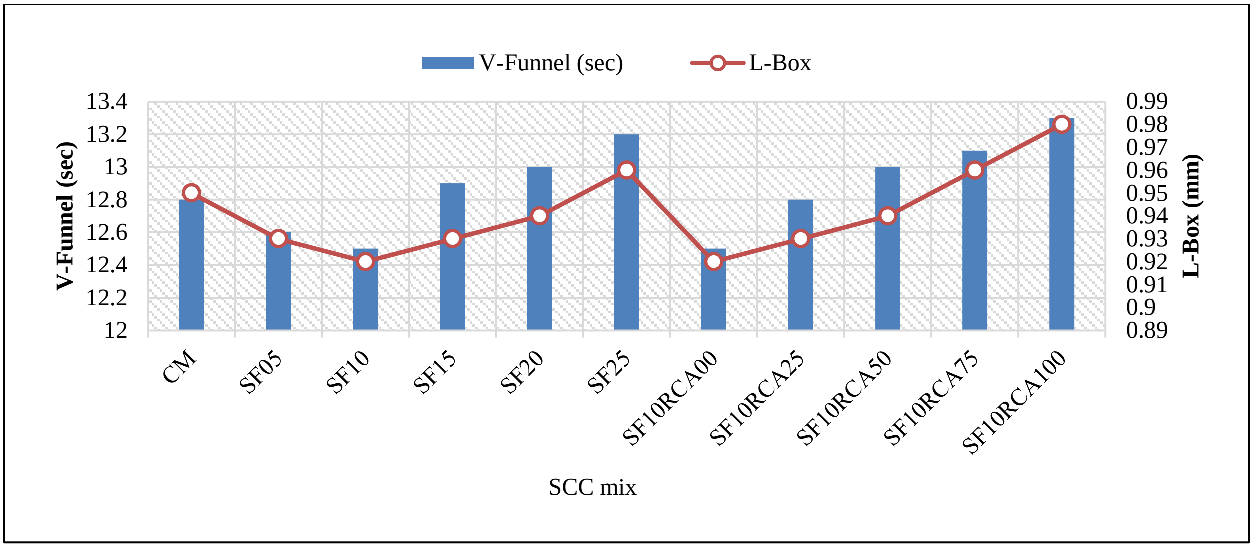


Figure 11 L-box and V-funnel tests of the mixes

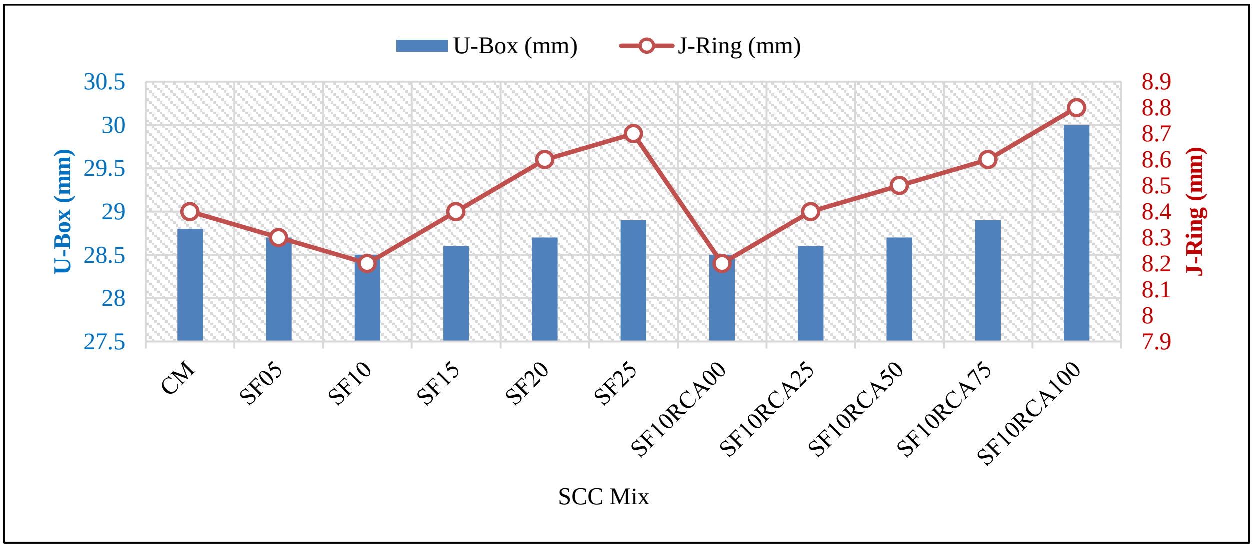


Figure 12 J-ring and U-box tests of the mixes

The decrease in workability may have been caused due to the ultrafine particles present in FRA. Nel and Fowler [27] identified this tendency and discovered that raising the w/b ratio is necessary to keep a consistent slump. This behaviour is brought on by the larger specific surface area that these particles display, which indicates a greater need for water. The slight variance seen in mixes including 100% RCA might be brought about by the RCA' coarser surface, which increases friction in the cementitious paste [28]. It is reported that concrete containing 10% SF needed a higher w/b ratio in comparison to the mixes containing 0% and 5% SF to maintain a constant workability. The higher specific surface area of SF particles may also be related to higher water demand [29]. The Slump Flow for natural pozzolana mixed SCC and natural pozzolana plus recycled aggregate mixed SCC is comparable to that of control concrete containing these materials up to 15% and 20%, respectively, and is within the range (650-800 mm), as proposed by EFNARC [25]. However, the natural pozzolana reduces the slump flow of SCC slightly below the EFNARC guidelines (625 mm) at its 20% level, and for 25% pozzolana with RCA (630 mm). The V-Funnel Flow time rises with natural pozzolana content. All mixes had V-Funnel Flow times between 5–12 sec, with the exception of those with replacement levels more than 15% for natural pozzolana mixed SCC, and 20% for recycled mixed SCC. With the exception of greater replacement rates

(15% for natural pozzolana mixed SCC and 20% for recycled mixed SCC), J-Ring diameters were found between 650-750 mm for all the mixes. Apart from replacement levels of 15% or advanced for natural pozzolana mixed SCC and over 20% for recycled mixed SCC, height ratios (L-Box) of more than 80% for all the mixtures. All mixtures' segregation resistance fell within the range of 0-15%, making them all compliant with EFNARC's standards [25].

4.2Compressive strength of the mixes

One of the quickest and most severe mechanisms for the deterioration of concrete structures is sulphate attack. Utilizing additional cementitious materials is one of the most popular methods for enhancing concrete's resistance to sulphate attack. However, even with additional cementitious ingredients, physical salt attack can still harm concrete. Additionally, some supplemental cementitious elements, according to some literature, may even lessen resistance to physical salt attack. The current study examines how additional cementitious elements, such as SF and RCA, affect a structure's ability to withstand sulphate salt attack over the course of 28, 180, and 270 days. SCC specimens with 10% replacement of OPC by SF and 25% replacement of NCA by RCA were exposed to physical sulphate attack. Under the provisions of IS: 516-1959 [26], the SCCs manufactured with OPC, SF, NCA, and RCA content in various proportions is determined, and its variation at 28, 180, and 270 is shown in *Figures 13-15.*

The CSs of the CM increases by 15.25 and 16.92% at 180 and 270 days, respectively, when compared to the CM at 28 days in normal tap-water. When exposed to sodium sulphate solution (2.0 g/l), the CM loses CSs after 28, 180, and 270 days, by 1.70, 5.16, and 7.23%, respectively in comparison to the CM cured in normal tap-water (*Figures 13*). This variance is mostly caused by the salt's ongoing crystallisation as well as the production of ettringite and gypsum in the pores and microcracks of the concrete. In the early stage, crystallization-induced expansion and additional materials (such as gypsum and ettringite) can fill the pores and microcracks and improve the compression resistance, compactness of the concrete and enhance its strength. The pores or microcracks in the concrete, however, are unable to tolerate further expansion at this point due to increased salt crystallisation, the creation of ettringite and gypsum, and other processes.

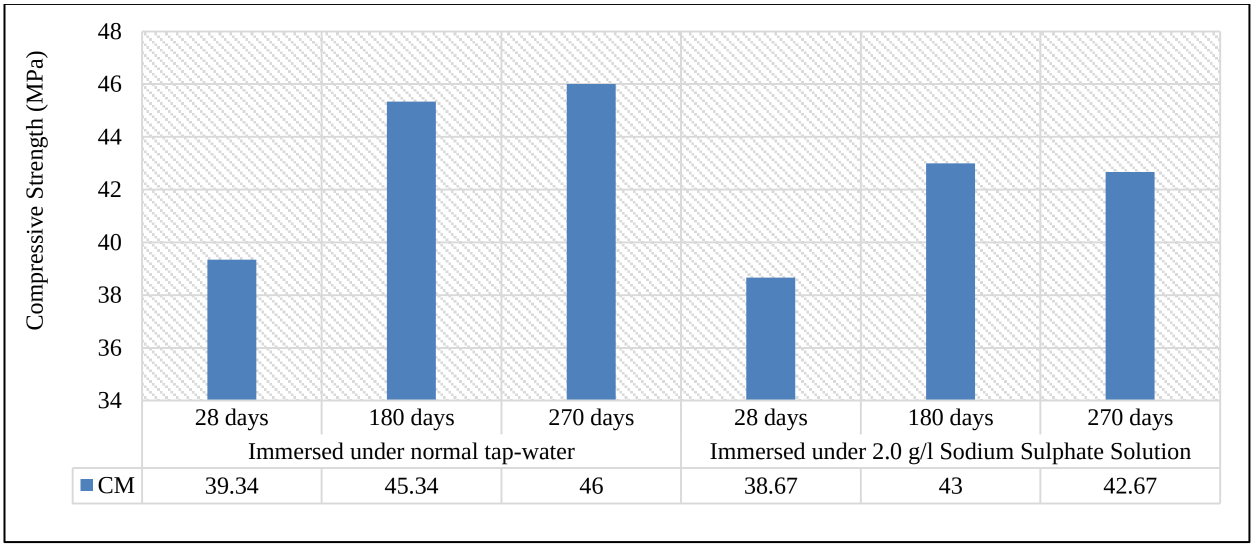


Figure 13 Compressive strength of CM

The rise in CSs of the Mix-SF10 at 180 and 270 days is 22.72 and 25.00%, respectively, with respect to its CSs at 28 days in normal tap-water. Also, the rise in CSs of Mix-SF10 is 11.84, 19.10 and 19.56% in 28, 180 and 270 days, respectively, with respect to the CM at respective days. Compared to the CSs of Mix-SF10 in normal tap-water, the strength of Mix-SF10 is reduced by 0.75, 4.31, and 6.65% after 28, 180, and 270 days of exposure to Na_2SO_4 solution (2.0 g/l) as plotted in *Figure 14.*

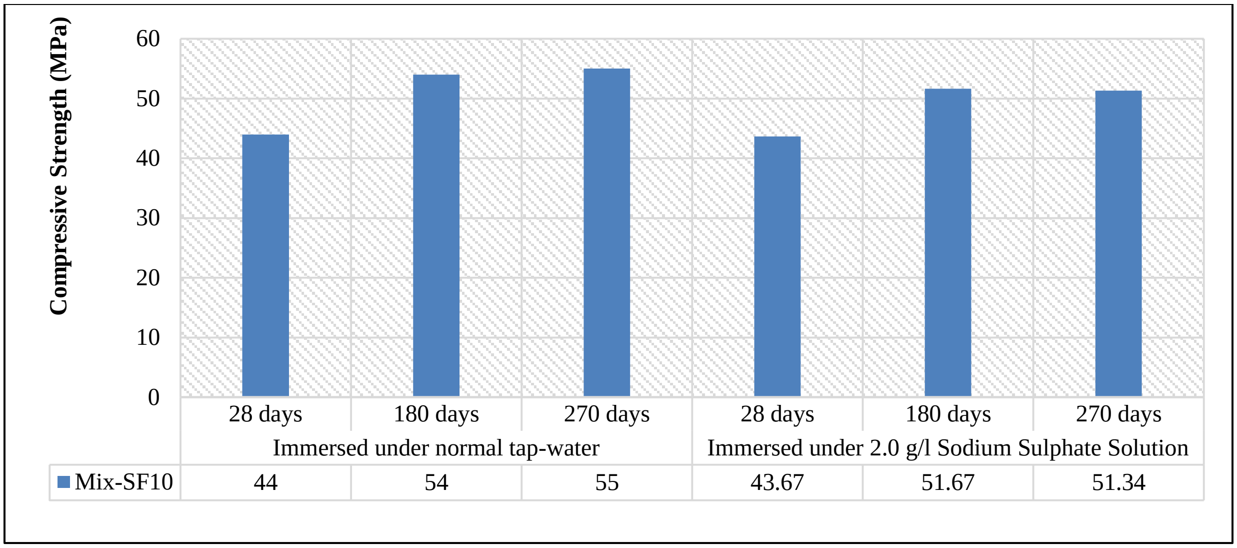


Figure 14 Compressive strength of Mix-SF10

When (25%) NCA is substituted by RCA in the SCC mix (Mix-SF10RCA25), the CSs increases by 6.76, 13.96, and 13.78% at 28, 180 and 270 days, respectively, with respect to the CM. But, the CSs of Mix-SF10RCA25 decreases by 4.54, 4.31, and 4.83% at 28, 180, and 270 days, respectively, with respect to the Mix-SF10, immersed in normal tap-water. The increase in CSs of Mix-SF10RCA25 at 180 and 270 days is 23.02 and 24.61%, respectively, with respect to the Mix-SF10RCA25 at 28 days in normal tap-water. With respect to the Mix-SF10RCA25 in normal tap water, the CSs of the Mix-SF10RCA25 are reduced by 0.78, 5.16, and 7.01% after 28, 180, and 270 days of exposure to Na_2SO_4 solution (2.0 g/l) (*Figures 15*). Sulphate solution exposure causes the creation of ettringite and gypsum, which causes deterioration of concrete, internal stresses and cracking and due to the restricted space available. This demonstrates the advantages of RCA over NCA. Because of its enhanced porosity and plastic-like microstructure, RCA mixed concrete can withstand the extreme expansion without breaking, which reduces pressure, especially as it ages.

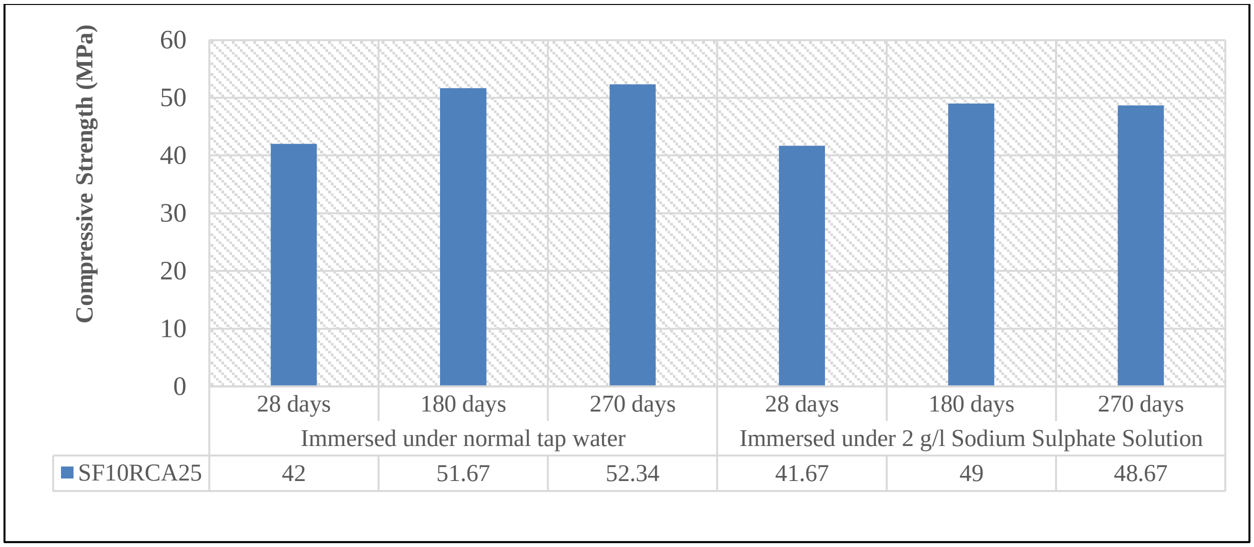


Figure 15 Compressive strength of Mix-SF10RCA25

Following exposure to sodium sulphate solution (2.0 g/l), all SCC mixes, CM, SF10, and SF10RCA25, see an increase in CSs in the first 180 days, thereafter, the values start to decrease. This is due to the presence of two compensatory processes: hardening and softening. Sulphate ions have been found to react and break down C-S-H gel and CH and in concrete, causing softening and expansion. Simultaneously, the continued hydration of the matrix and the pozzolanic reaction, as well as the filling of voids with reactive products result in an increase in the strength. The durability properties are improved when 50% of NCA is replaced with RCA and 10% of OPC is replaced with SF or MK [30, 31]. Replacement of 20% of fine aggregate with recycled sand provided the best durability [32]. For workability, mechanical characteristics, and durability, 30% OPC substitution level with FA may be the best option. Water absorption is reported to decrease when FA content increases [33]. As compared to the SCC made with only OPC, the SCC made with binary, ternary, and quaternary cements demonstrated reduced sulphate expansion, lower chloride ion penetrability, and resistance to de-icing salt surface scaling [34]. The SCC made with RCA performed better in sulphate solution than the SCC made with NCA [35].

The following are some of the study's limitations:

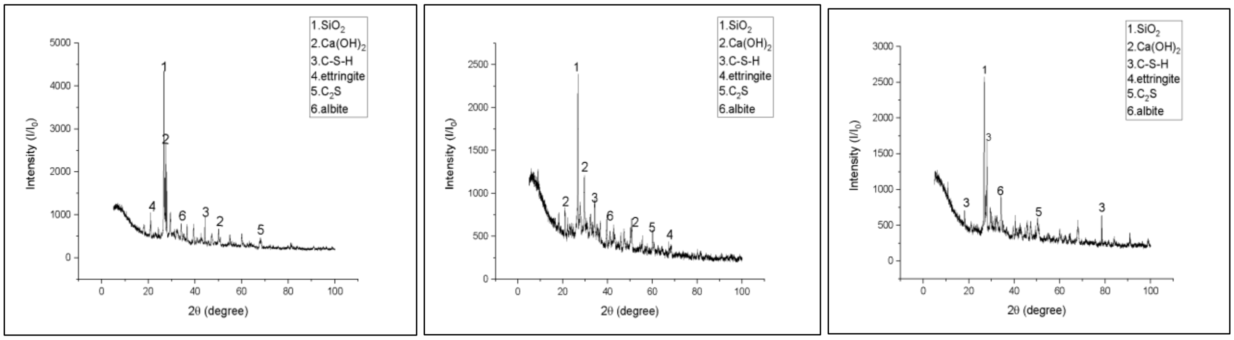
- The results may vary depending upon the properties of the materials used in other investigations.
- Overall, the experimental programme found that using SF (0-25%) and RCA (0-100%) had not much detrimental impact on the CSs of SCC.

4.3Microstructural analysis

4.3.1XRD analysis

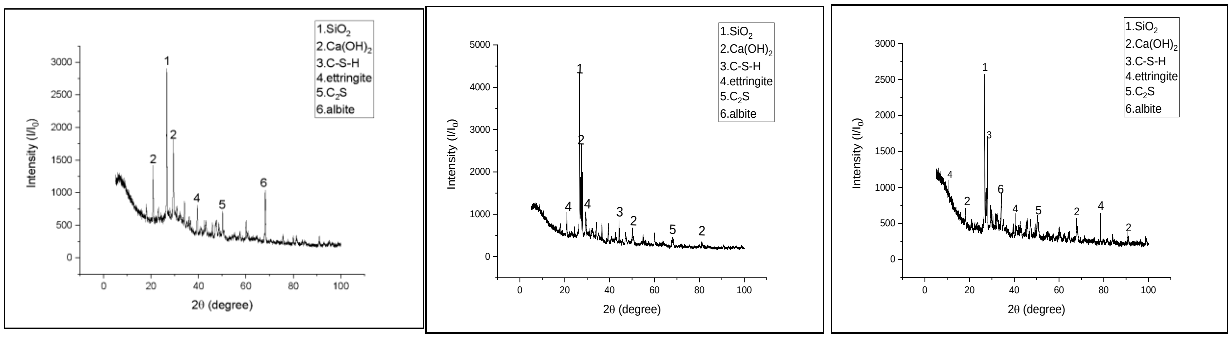
The mineralogical composition of SCC mixtures at 2ϴ in the range of 0-100^0, is determined via XRD analysis. *Figures 16-21* show the findings of XRD analysis of CM, Mix-SF10, and Mix-SF10RCA25 at 28, 180, and 270 days curing in normal tap-water and sodium sulphate solution. The following were generally discovered: SiO_2, CH, C-S-H gel, ettringite, albite, and C_2S. Because of the pozzolanic reaction of SF, the CH chemically interacted to create additional hydration products with siliceous or aluminous phases. When OPC is replaced with SF, the clinker phases (C_3S and C_2S) are frequently reduced, resulting in less CH production. The concrete matrix's mechanical properties are mainly dominated by the production of C-S-H gel. Unhydrated cement phase (C_2S) was discovered in concrete samples after 28 days curing. However, at 180 and 270 days of curing, the C_2S peaks disappeared, which could be attributable to the constant hydration activity as the curing progressed. According to the findings, SF blended mixtures (Mix-SF10) had higher intensity peaks for the C-S-H gel than the CM and Mix-SF10RCA25. The increased mechanical performance of such combinations is attributed to an increase in C-S-H gel in the Mix-SF10 (*Figures 15-20*). The CH combines with the sulphate during the hydration phase to generate Gypsum. The amount of Gypsum in the SCC mixes increased as the duration of exposure in the sulphate solution increased. Ettringite is formed when sulphate reacts with C_3A, and monosulpho-aluminate reacts with the excess sulphate in solution. Ettringite is the substance that causes expansion, cracking, surface degeneration, and strength loss. The SCC mixes (CM, SF10, and SF10RCA25) immersed in sodium sulphate solution (2.0 g/l) have more ettringite; however, Mix-SF10 has less ettringite than the Mix-CM and Mix-SF10RCA25. As a result, SCC mixes that contain SF (i.e., SF10) are more resistant to sulphate solution (*Figures 16-21*). The RCA's microstructure and compactness are greatly enhanced as a result of the reaction between the connected mortar and CO_2 on the surface of the RCA. Fibers and RCA can be used to increase the microstructure and performance of ITZ in concrete, which improves the mechanical characteristics and durability of the material [14]. At 28 days of curing, Ettringite peaks were found to be higher in FA mixed mixtures. This could be due to FA's increased alumina concentration [36]. Ettringite production often aids in the densification of concrete matrix. At subsequent curing ages, the peaks of ettringite diminished, which could be due to the conversion of the ettringite phase into calcium monosulphate phase [37]. It was also likely that hydration phases of FA could not be easily recognised by XRD at later curing ages; this could be due to their non-crystalline nature, as other investigations have found [38]. Albite phases have been found to be beneficial in the creation of extra C-S-H gels [39].

A complete list of abbreviations is shown in *Appendix I.*



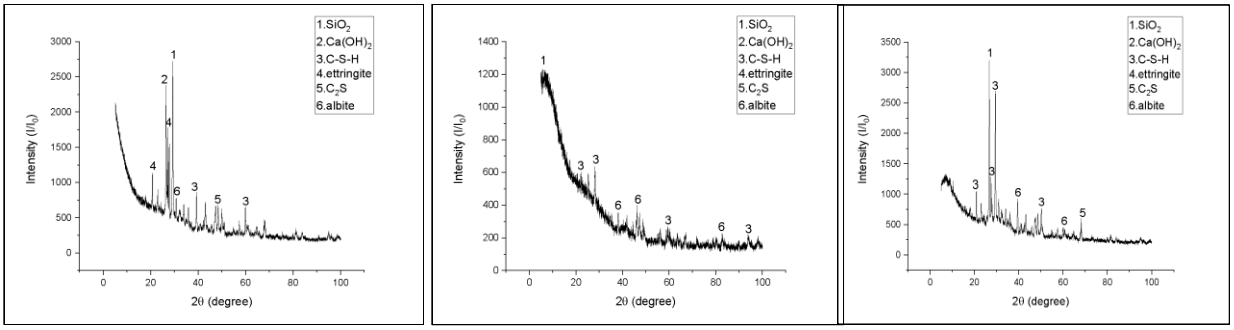
(a) (b) (c)

Figure 16 XRD image of CM under normal tap-water; (a) at 28 days; (b) at 180 days; (c) at 270 days



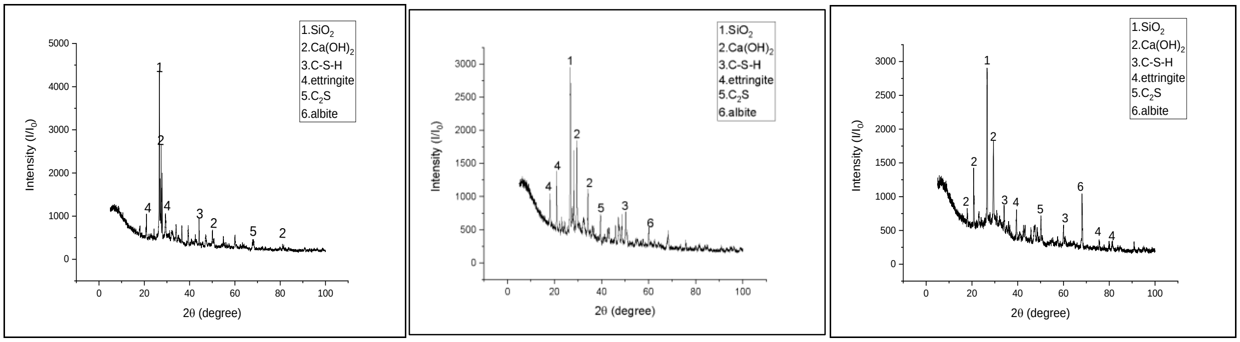
(a) (b) (c)

Figure 17 XRD image of CM under 2.0 g/l sulphate solution; (a) at 28 days; (b) at 180 days; (c) at 270 days



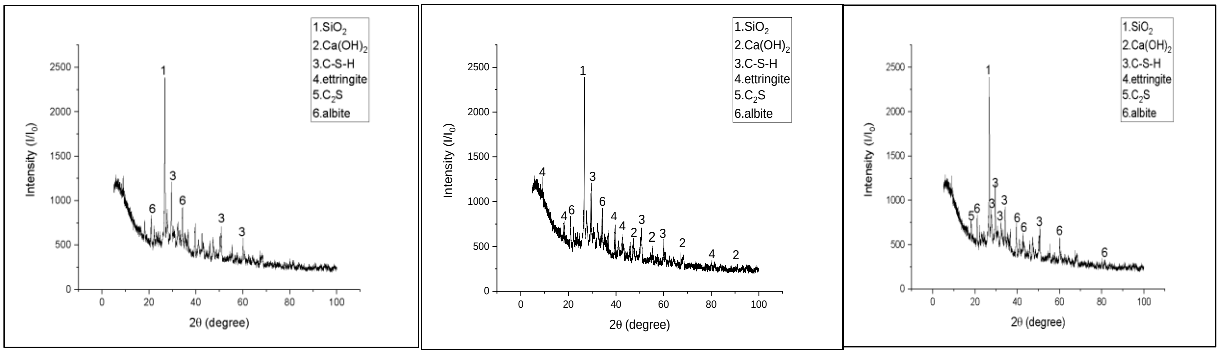
(a) **(b)** **(c)**

Figure 18 XRD image of SF10 under Normal Tap-Water; (a) at 28 days; (b) at 180 days; (c) at 270 days



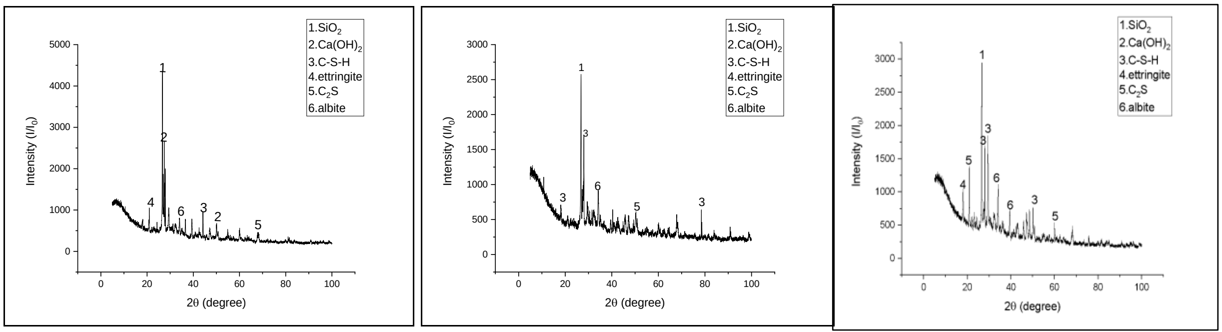
(a) (b) (c)

Figure 19 XRD image of SF10 under 2.0 g/l sulphate solution; (a) at 28 days; (b) at 180 days; (c) at 270 days



(a) (b) (c)

Figure 20 XRD image of SF10RCA25 under Normal Tap-Water; (a) at 28 days; (b) at 180 days; (c) at 270 days



(a) (b) (c)

Figure 21 XRD image of SF10RCA25 under 2.0 g/l sulphate solution; (a) at 28 days; (b) at 180 days; (c) at 270 days

5.Conclusion and future work

This research paper examines the impact of OPC, SF, NCA, and RCA on the CSs of the SCC mixes. Some of the inferences that can be made are as follows:

- Adding SF to the SCC mixes for the partial replacement of the OPC, enhances the mixes' CSs, allowing for usage in structural applications.
- The slump flow (mm) is increased up to the optimum level of SF content (10%), while the T-50 time, U-box V-funnel, J-ring and L-box values decreased; however, the trend reversed when RCA was used to replace NCA at a level of 25%.
- When NCA is partially replaced (25%) by RCA content, the CSs is reduced as compared to Mix-SF10, but it is higher compared to the CM.
- All the SCC mixtures viz., CM, SF10, and SF10RCA25 gain CSs up to 180 days after being exposed to sodium sulphate solution (2.0 g/l), and thereafter, it decreases.

More research may be done to study how the aspect ratio of SF and SF+RCA affect the different characteristics of the SCC. This study was limited to laboratory tests on the material; hence the future works may focus on evaluating the performance of the SCC in a model/prototype. The impact of the SF and RCA inclusion on the fresh characteristics, CO_2 emissions, and cost of the SCC structures can be investigated.

Acknowledgment

None.

Conflicts of interest

The authors have no conflicts of interest to declare.

Author's contribution statement

Anjali Singh: Data collection, conceptualization, writing – original draft, analysis and interpretation of results. **P.K. Mehta and Rakesh Kumar**: Study conception, design, data collection, supervision and investigation on challenges.

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Appendix I

S. No.	Abbreviation	Description
1	CM	Control Mix
2	C-S-H	Calcium-Silicate Hydrate
3	CSs	Compressive Strength
4	FA	Fly Ash
5	FRA	Fine Recycled Aggregates
6	GGBS	Ground Granulated Blast-Furnace Slag
7	HVFA	High Volume FA
8	ITZ	Interfacial Transition Zone
9	$MgSO_4$	Magnesium Sulphate
10	MS	Micro-Silica
11	NCA	Natural Coarse Aggregate
12	NS	Nano-Silica
13	Na_2SO_4	Sodium Sulphate
14	OPC	Ordinary Portland Cement
15	RCA	Recycled Coarse Aggregates
16	RHA	Rice Husk Ash
17	SF	Silica Fume
18	SF10	Self-Compacting Concrete made with 90% OPC and 10%SF
19	SF10RCA25	Self-Compacting Concrete Made with 90% OPC, 10% SF, 75% NCA and 25% RCA.
20	SCC	Self-Compacting Concrete
21	SCMs	Self-Compacting Mortars
22	SBA	Sugarcane Bagasse Ash
23	XRD	X-Ray Diffraction