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Performance Analysis of Self-Compacting Concrete with Use of Artificial Aggregate and Partial Replacement of Cement by Fly Ash

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Abstract: Artificial aggregate (AF), i.e., silico manganese (SiMn) slag aggregate, is a byproduct of ferromanganese and silico manganese alloy production. The utilization of industrial waste and industrial byproducts in construction has increased the aim of conserving natural resources to nurture a pollution-free environment. The current study examines the performance of the use of artificial aggregate (AF) and partial replacement of cement with fly ash (FA). The properties of fresh concrete, as well as the compressive and flexural strength and split tensile strength of concrete were evaluated. Seven mix proportions were prepared for M30-grade concrete. The first was a control mix (with 0% AF and FA), three other mixes contained varying amounts of AF (20%, 40%, and 60%) as a partial replacement of CA with AF. The average compressive strength of the control SCC was found to be 32.87 MPa (megapascals) at the age of 28 days, and after replacing 20% natural aggregate with artificial aggregate, the compressive strength increased by 8.27%, whereas for 40% and 60% replacement, it decreased by 4.46% and 12.55%, respectively. Further investigation was performed on the optimum value obtained by replacing 20% of CA with AF. At this percentage, cement was replaced by FA at (15%, 25%, and 35%) where at 15%, the average compressive strength increased by 7.41%, whereas for 25% and 35% replacement, it decreased by 7.47% and 17.19%, respectively. For SCAF20 and SCF15, all strengths were at maximum due to the increase in its density. The findings show that the development of advanced construction materials is environmentally sustainable.

Keywords: self-compacting concrete; viscosity modifying agent; artificial aggregate; superplasticizer; fly ash

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1. Introduction

In addition to the terms "self-compacting concrete" (SCC) and "high-performance concrete", self-compacting concrete is also known as "self-consolidating concrete", and has emerged as one of the most significant innovations in the construction industry in recent years [1,2]. No vibration or compaction technique is required with this concrete type during the casting phase to effectively fill the spaces between reinforcements and the corners of molds [3–6]. It can be utilized in both precast applications and for on-site concrete placement [7]. Self-consolidating concrete (SCC) is utilized in construction projects to produce long-lasting structures with reduced labor costs and pollution levels associated with consolidation processes [1,7]. The seminal contributions of Okamura [2] and Okamura and Ouchi [1] have played a pivotal role in the advancement of self-consolidating concrete (SCC). Henceforth, this approach shall be referred to as the Japanese method. According to this methodology, it is indicated that the sand content in the mortar is approximately 50% of its compacted density, and a concrete mixture containing gravel corresponds to 50% of its compacted density [7–10].

SCC has several advantages and applications as shown in Figure 1. As its name suggests, SCC is a type of concrete that eliminates the need for compaction that occurs externally or internally, as it naturally levels and compacts under its own weight [8,11]. Concrete technology has been revolutionized by the advent of SCC. The utilization of concrete placement and compaction techniques can result in a significant reduction in noise levels, as there is no requirement for vibrators [12,13]. Additionally, these techniques have the potential to greatly enhance the speed at which concrete is placed. SCC is capable of completely filling the most challenging forms or molds [14,15]. The utilization of SCC at a construction site provides an inherent assurance of consistent placement and the complete consolidation of the concrete [16–20]. The presence of SCC is likely to result in enhanced durability due to the reduced occurrence of air voids and other imperfections [21,22].

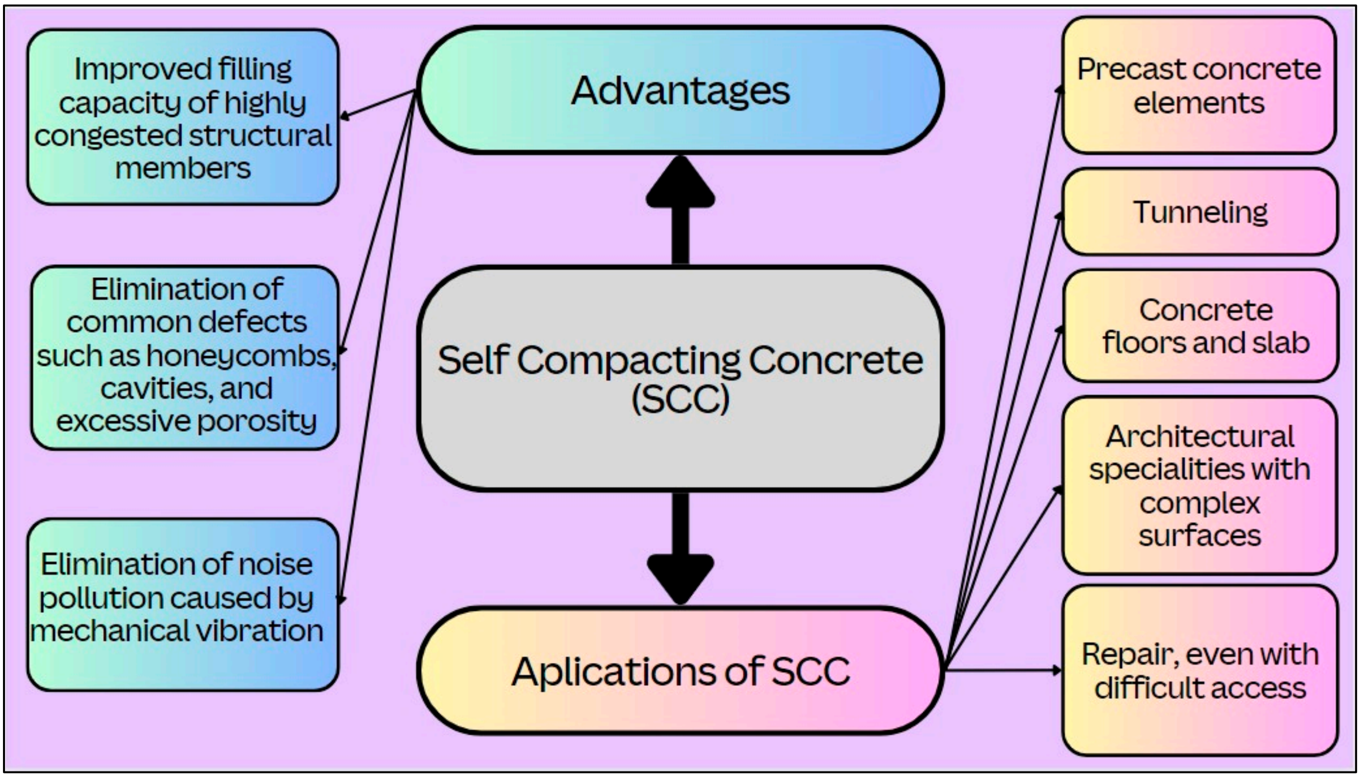


Figure 1. Advantages and Application of SCC.

Self-compacting concrete (SCC) is highly suitable for the efficient placement of concrete through pumping, as it possesses the desired characteristic of matching the rate of pumping with the rate of placing [11,23]. This particular type of concrete is highly suitable for utilization in conjunction with ready-mixed concrete due to its characteristic of minimal waiting time for transit mixers [24]. Consequently, the turn-around times are significantly reduced, leading to enhanced productivity per transit mixer [25,26]. The implementation of this technology is expected to yield several benefits in terms of environmental sustainability, concrete quality, and casting precision [27]. Firstly, the absence of vibration and pollution that is associated with this method will significantly reduce its environmental impact.

Secondly, the elimination of vibration will prevent any potential damage to the air-void structure of the concrete, thereby enhancing its overall quality [28]. Lastly, the use of this technique will also contribute to a reduction in defects that may arise during the casting process, especially in complex details and areas with dense reinforcement [1,29].

SCC's strength and longevity have been so impressive that its Japanese creators dubbed it "high-performance concrete". With the high flowability demanded of SCC, the fine materials content of the concrete can be increased by using more mineral admixtures like fly ash, blast furnace slag, limestone aggregate, and other similar materials [29]. By adding powder materials of varying morphologies and grain size distributions known as mineral admixtures, it is possible to increase particle packing density while decreasing interparticle friction and viscosity. As a result, mineral admixtures enhance the flexibility, the ability to coexist with other materials, and the robustness of self-consolidating concrete (SCC). The utilization of FA in concrete offers notable benefits, including enhanced rheological properties and decreased concrete cracking resulting from the reduced heat of hydration [30,31]. These advantages extend to the application of FA as a filler in SCC. The utilization of fly ash has also been documented in the advancement of cost-effective and environmentally sustainable SCC. Self-compacting concrete blends demonstrate unique properties that are not observed in traditional concrete due to the modification of the aggregate content and the incorporation of chemical and mineral admixtures [32–35]. The utilization of admixtures, specifically high-range water-reducing (HRWR) and viscosity-modifying admixtures, meets the stipulated criteria as per code. The formulation of self-consolidating concrete (SCC) necessitates careful consideration to mitigate issues such as segregation, excessive bleed water, and the sedimentation of the coarse particles [27,36,37]. The resistance of SCC to frost and frost-thawing compounds can be enhanced through the incorporation of air entrainment [38,39].

The comprehensive evaluation of flow velocity losses and blockage phenomena in concrete transportation through confined spaces necessitates the consideration of various construction factors [29]. The matrix precedes the aggregate particles as the fresh concrete flow progresses toward a confined region. Literature research offers a wide range of methods for determining the appropriate proportions of cement in concrete mixtures [6,40–42]. The ACI absolute volume approach is widely employed by the concrete industry as a primary method for mix proportioning [24,27,43]. The conventional approach to concrete proportioning must be adjusted or adapted to accommodate the distinct demands of self-consolidating concrete (SCC) in its plastic state. Self-consolidating concrete (SCC) generally conforms to the same specifications as conventional concrete in its hardened state. However, during the fresh stage, the designer encounters various challenges. There are typically three main approaches to SCC design and manufacture. High-power content (powder type), viscosity-modifying agents (VMA type), and hybrids of the two (combination type) are all viable options for SCC production. A superplasticizer is typically used in SCC unlike in regular concrete. Based on the available research background, it is apparent that numerous studies have been conducted on the partial replacement of cement with silico manganese (SiMn) Slag [4,5,44,45]. Silico manganese slag is a result of the carbothermic reduction of high-MnO ferroalloys in submerged arc furnaces. Despite having a higher SiO_2 content and a lower CaO content, a problem that can be addressed by blending it with fly ash [46–48], it has considerable potential as a supplementary cementitious material (SCM) due to its comparable reactivity [46] and quick cooling which promotes an amorphous form [47]. These studies have identified the coexistence of FA-derived slag-activated gel (C–S–H/C–A–S–H) and geopolymer gel (N–A–S–H) within the blended matrix [29]. Here, N represents Na_2O, A represents Al_2O_3, C represents CaO, S represents SiO_2, and H represents H_2O [29]. Additionally, the EDS analysis conducted by the researchers confirmed the observed changes in the Si/Al, Ca/Si, and Na/Al ratios of the binder as a result of the alteration of the reaction products. The enhanced compressive strength observed in binders with high slag content can be the result of gel formation phases rich in calcium [29,32,34,49].

Figure 2 represents the cluster of network visualization using the keywords of the research papers reviewed for this experiment [29–52].

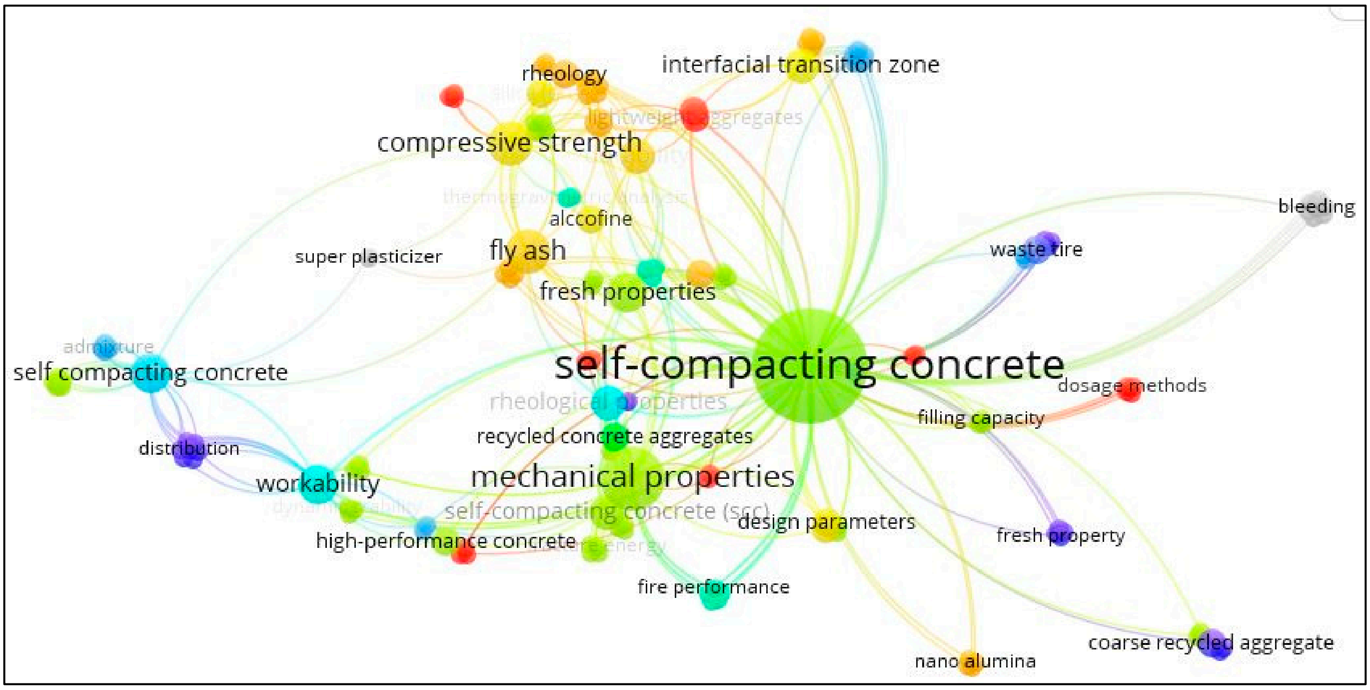


Figure 2. Network visualization of a cluster created by using the keywords of research papers from the year 2016 to 2023.

This study's primary goal includes the formulation of self-compacting concrete (SCC) with varying sand-to-aggregate (S/A) ratios, superplasticizer (SP) dosages, viscosity modifying agents (VMA), and fly ash (FA) contents. These objectives attempt to exhaustively investigate the fresh-state properties of SCC, which include passing ability, filling capacity, and segregation resistance. In addition, the study seeks to evaluate the effect of replacing cement with fly ash (FA) on the fresh properties of SCC, such as filling capacity, segregation resistance, and transit ability. This study also aims to determine how artificial aggregate (AF) replacement influences the strength of SCC at three distinct periods, namely 7, 14, and 28 days. By exploring the influence of fly ash (FA) on SCC properties, this research contributes to the development of more sustainable and high-performance construction materials, ultimately benefiting society through improved construction practices and reduced environmental impact.

2. Materials and Methods

The current study examines the performance using AF and partially replacing cement with FA. The fresh concrete properties, strength in compression, flexural strength, split tensile strength, and concrete density are evaluated.

2.1. Cement

One batch of 53-grade OPC was used to prepare concrete mixes during the research as shown in Figure 3a. Despite its freshness, it did not contain any lumps. In accordance with IS:269-2015 [53], the cement was tested, and various tests were conducted. The results have been reported as shown in Table 1, and its SEM and EDS test results are shown in Figure 6a.

Figure 3. Materials used (**a**) OPC of grade 53; (**b**) artificial aggregate; (**c**) fly ash; (**d**) fine aggregate.

Table 1. Results of the cement test.

Characteristics	Experimental Observations	Standards Value as per IS: 269-2015
Normal consistency	29%	-
IST (minutes)	85 min	≥30 min
FST (minutes)	428 min	≤600 min
Specific gravity	3.12	-

2.2. Fine Aggregate

In accordance with grading zone II, local sand of the Kanahan River obtained from Nagpur was used in the size depicted in Figure 3b. In order to remove particles larger than 4.75 mm, the sand was first sieved through a sieve with a size of 4.75 mm. As per IS: 383-2016 [54], fine aggregate is analyzed by sieve and assessed for physical properties and the result is shown in Figure 4.

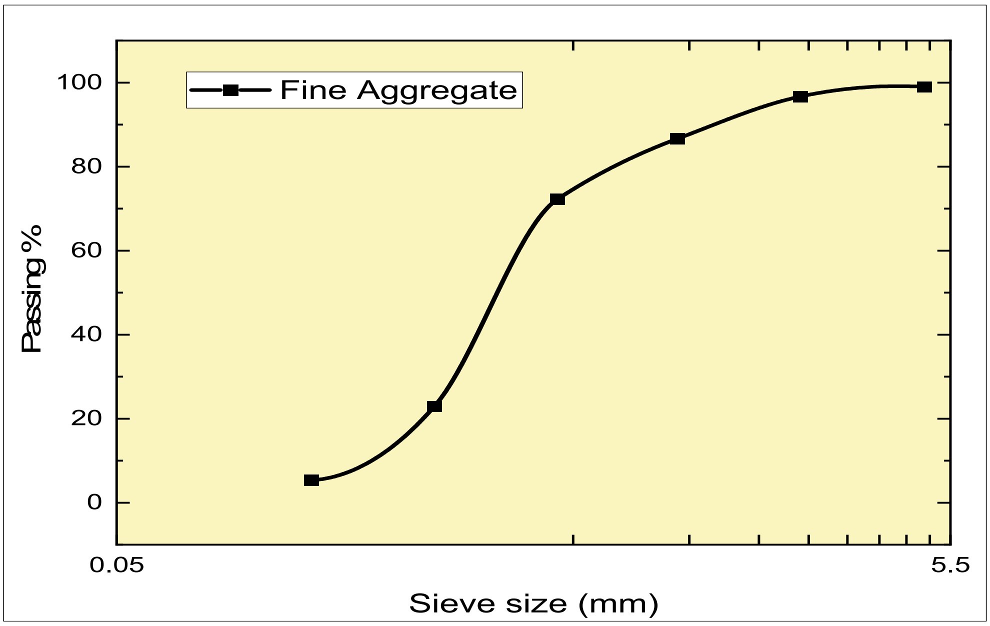


Figure 4. Fine aggregate sieving analysis, total weight of sand = 1000 gm.

2.3. Coarse Aggregate

Crushed stone, in two sizes, 10 mm and 20 mm, was mixed together to make the coarse aggregate. We decided to maintain a 75:25 proportion in order to minimize the large size of the coarse aggregate. The coarse aggregate complied with IS: 383-2016 [54] requirements for sieve analysis and physical properties and the result is presented below in Figure 5.

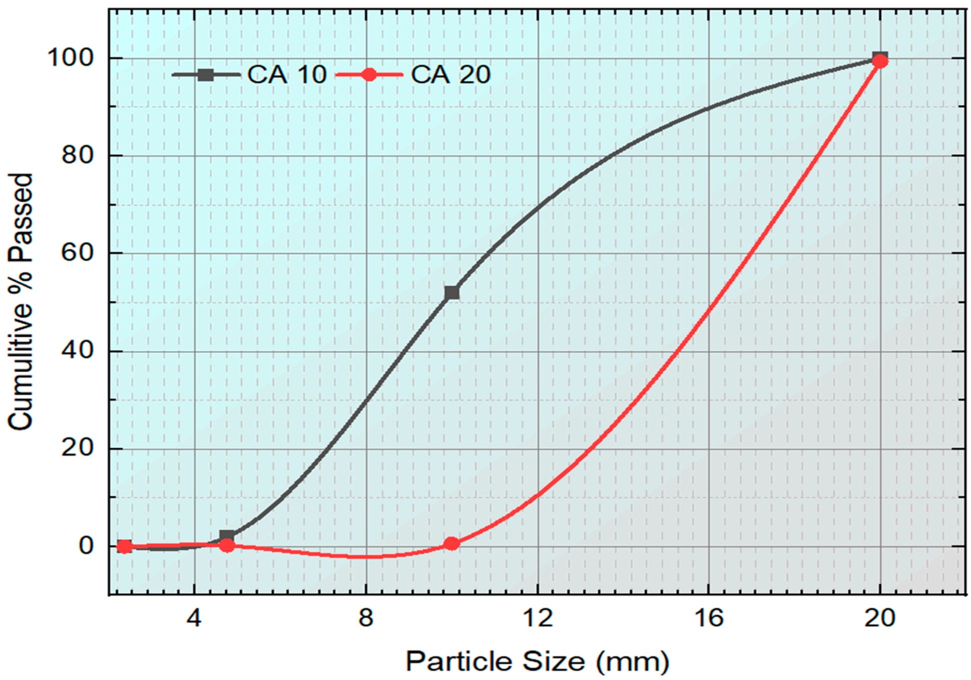
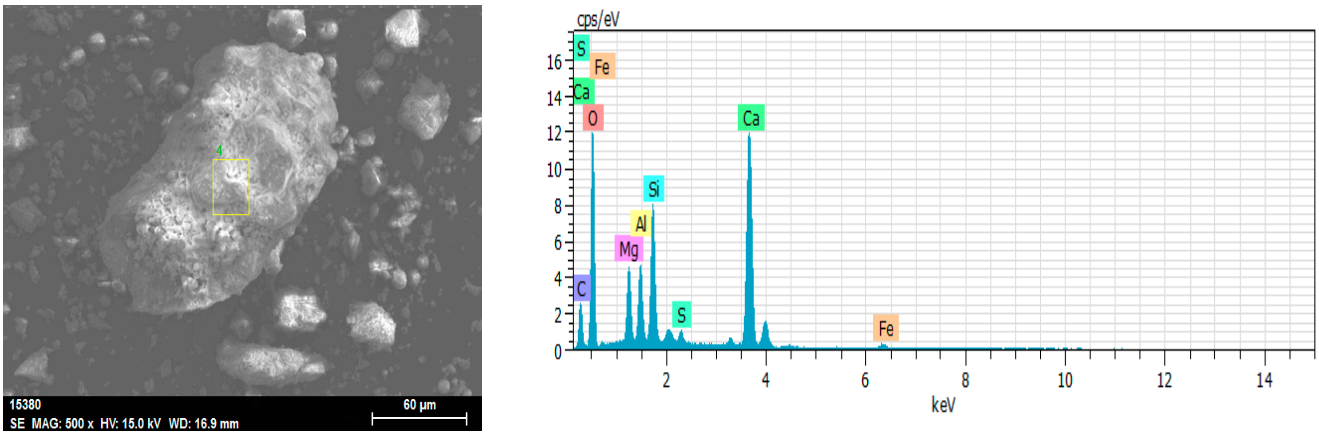


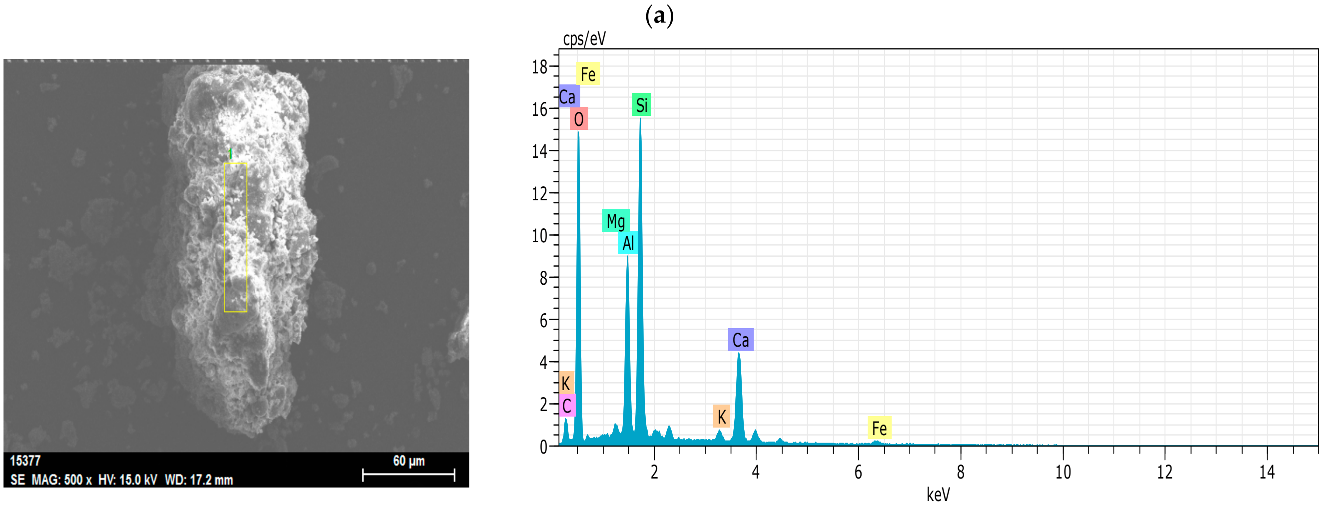
Figure 5. Sieve analysis for coarse aggregate with the total weight of the 10 mm and 20 mm aggregate = 5000 gm.

2.4. Fly Ash

The Khaperkheda Power Plant near Nagpur, India was the source of FA for this study as shown in Figure 3c. In this process, FA passing through 45 microns is used. The index properties of the FA were colour: dark grey, class: F, bulk density in kg/m^3 = 1000, surface area in cm^2/gm = 4680, specific gravity = 2.05, and lime reactivity in kg/cm^2 = 59.80, and its SEM and EDS test results are shown in Figure 6b.



(**a**)



(**b**)

Figure 6. Scanning electron microscope and energy dispersive spectroscopy (EDS) pattern of (**a**) OPC 53 cement (**b**) fly ash.

2.5. Artificial Aggregate

The artificial aggregate (silico manganese slag aggregate) is locally available as a waste product of the ferroalloys industry as shown in Figure 3b. The AF was procured from Bhartiya Commercials Private Limited, Ganeshpeth, Nagpur, Maharashtra. The basic properties of the aggregates depend on their cooling process. The aggregates are used in 20 mm and 10 mm sizes. The physical properties are shown in Table 2. The chemical composition of silico manganese slag is shown in Figure 7.

Table 2. Physical properties of of CA, fine aggregate, AF, and FA.

Characteristic	CA	Fine Aggregate	AF	FA
Size	20 mm max	4.75 mm max	20 mm max	<45 µm
Specific Gravity	2.67	2.61	3.5	2.05
Amount of total water absorbed (%)	0.57	1.91	0.44	-
Index of fineness	6.0	2.39	-	-
Color	Grey	-	Grey	Grey
Crushing Value	28%	-	35.5%	-
Impact value	8.66%	-	6.10%	-

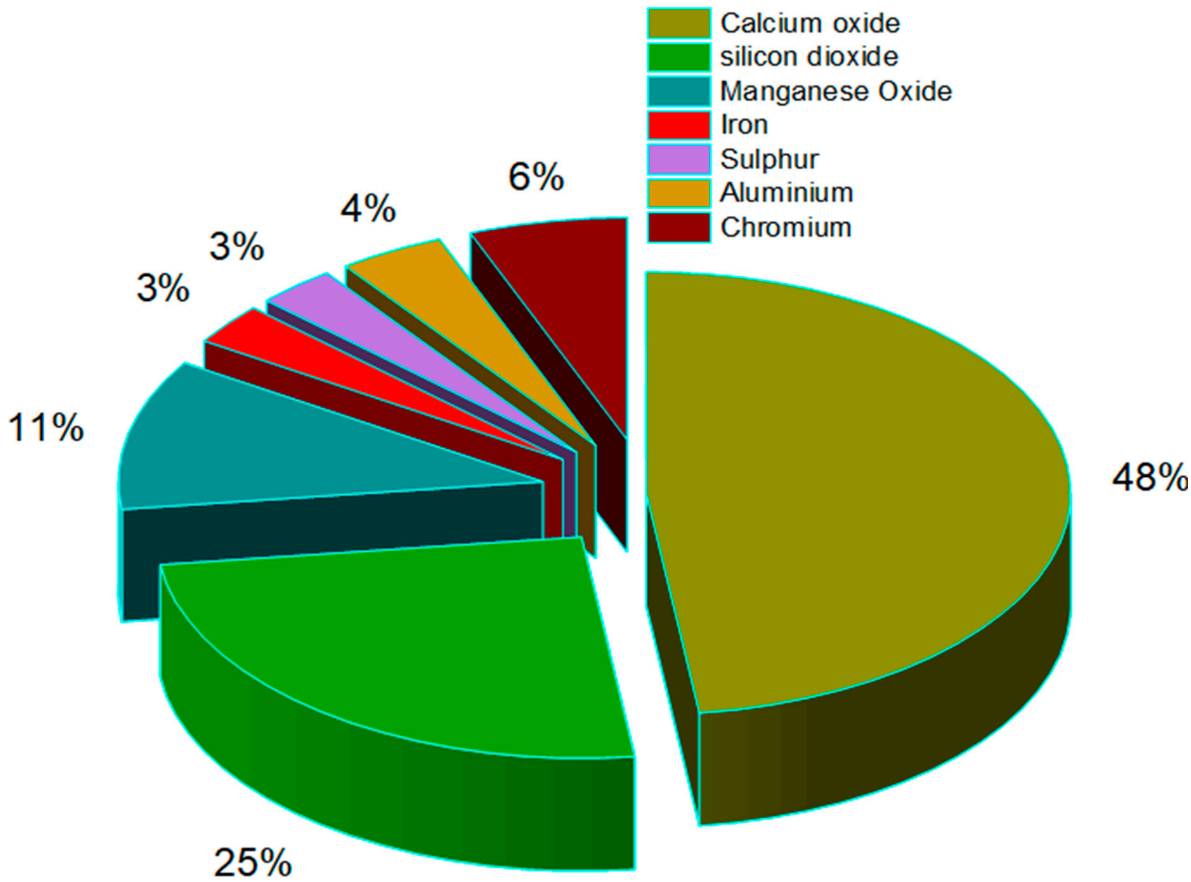


Figure 7. Chemical composition of artificial aggregate.

2.6. Super Plasticizer and Viscosity Modifying Agent

The superplasticizer "CAC Super 35 U (N4)" and the viscosity modifying admixture "VICO 10R" were used and procured from Concrete Additives and Chemicals Pvt. Ltd., W-11, TTC Industrial area, MIDC Pawane Navi Mumbai, India.

2.7. Specimen Preparation

To prepare specimen molds for casting, they were cleaned, oiled, and tightened properly. IS 516: 2021 [55,56] was followed when casting the specimen. It was recommended that the specimens remain in the molds for 24 h at room temperature after casting. In the water tank, these were placed at ambient temperature after demolding. Seven, fourteen, and twenty-eight days after curing, the specimens were tested [29].

2.8. Mixture Proportioning

Seven mix proportions were made for M30-grade concrete. The first was a control mix (with 0% AF and FA), three other mixes contained AF with varying percentages (20, 40, and 60) partially replacing CA. As for the parameters that were constant, they were the amount of fine aggregate (1233.153 kg/m^3), water (191 Lt/m^3), cement (383.2 kg/m^3), SP content (1.4%), VMA (0.3%), and S/A ratio (0.44). Moreover, three mixes contained fly ash with varying percentages (15, 25, and 35) as it can be used as a partial substitute for cement. The constant parameters included the amount of fine aggregate (1233.153 kg/m^3), water (191 Lt/m^3), CA (986.523 kg/m^3), AF (246.63 kg/m^3), SP content (1.4%), VMA (0.3%), and S/A ratio (0.44). 27 samples were prepared for each mix, which included 9 cubes (150 mm $\times$ 150 mm $\times$ 150 mm) for compressive strength, 9 cylinders (150 mm $\times$ 300 mm) for splitting tensile strength, and 9 beams (100 mmx100 mmx500 mm) for flexural strength testing. Table 3 shows the mix proportions [27].

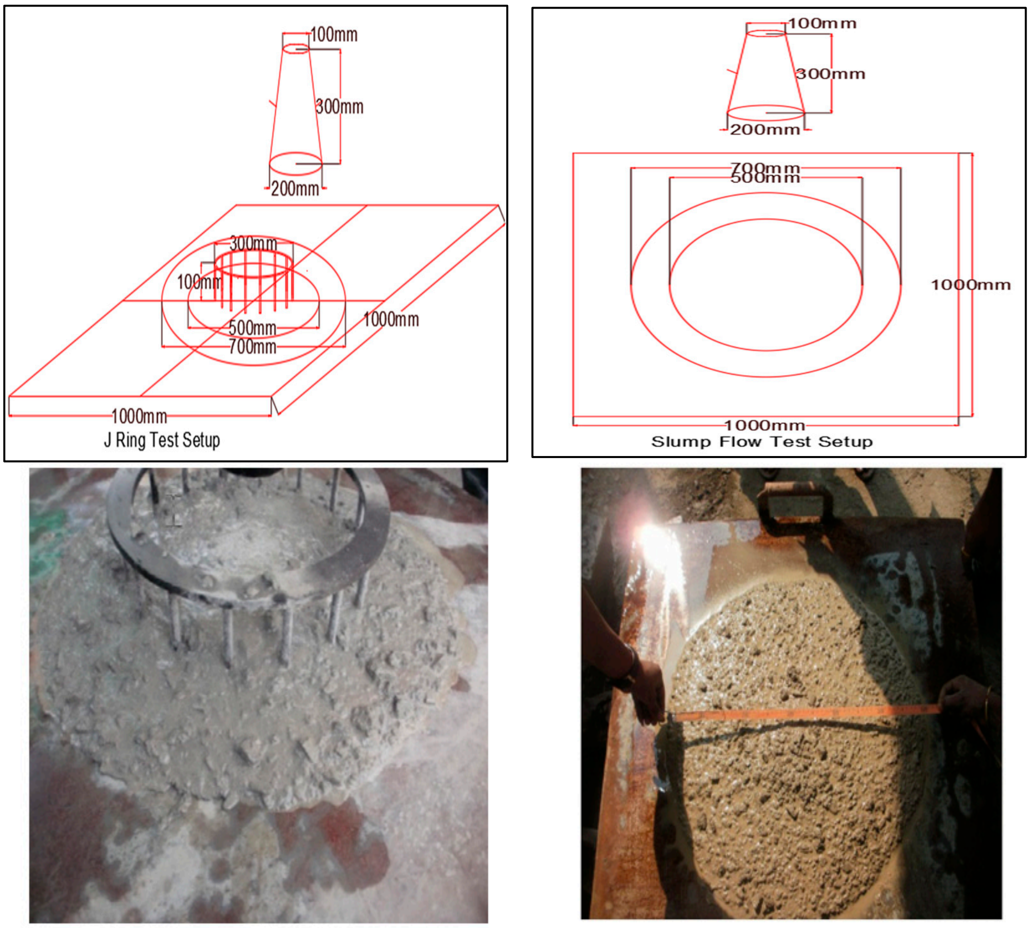
Table 3. SCC mix proportions for various mixes.

S.No	Mixture ID	Cement kg/m^3	Fine Aggregate kg/m^3	CA kg/m^3	AF %	AF kg/m^3	FA %	FA kg/m^3	Water lit/m^3	S.P %	VMA %	S/A Ratio
1	SCC	383.2	546.086	1233.153	0	0	0	0	191	1.4	0.3	0.44
2	SCAF20	383.2	546.086	986.523	20	246.63	0	0	191	1.4	0.3	0.44
3	SCAF40	383.2	546.086	739.893	40	493.26	0	0	191	1.4	0.3	0.44
4	SCAF60	383.2	546.086	493.26	60	739.89	0	0	191	1.4	0.3	0.44
5	SCF15	325.72	546.086	986.523	20	246.63	15	57.48	191	1.4	0.3	0.44
6	SCF25	287.4	546.086	986.523	20	246.63	25	95.8	191	1.4	0.3	0.44
7	SCF35	249.08	546.086	986.523	20	246.63	45	134.12	191	1.4	0.3	0.44

2.9. Test Methods

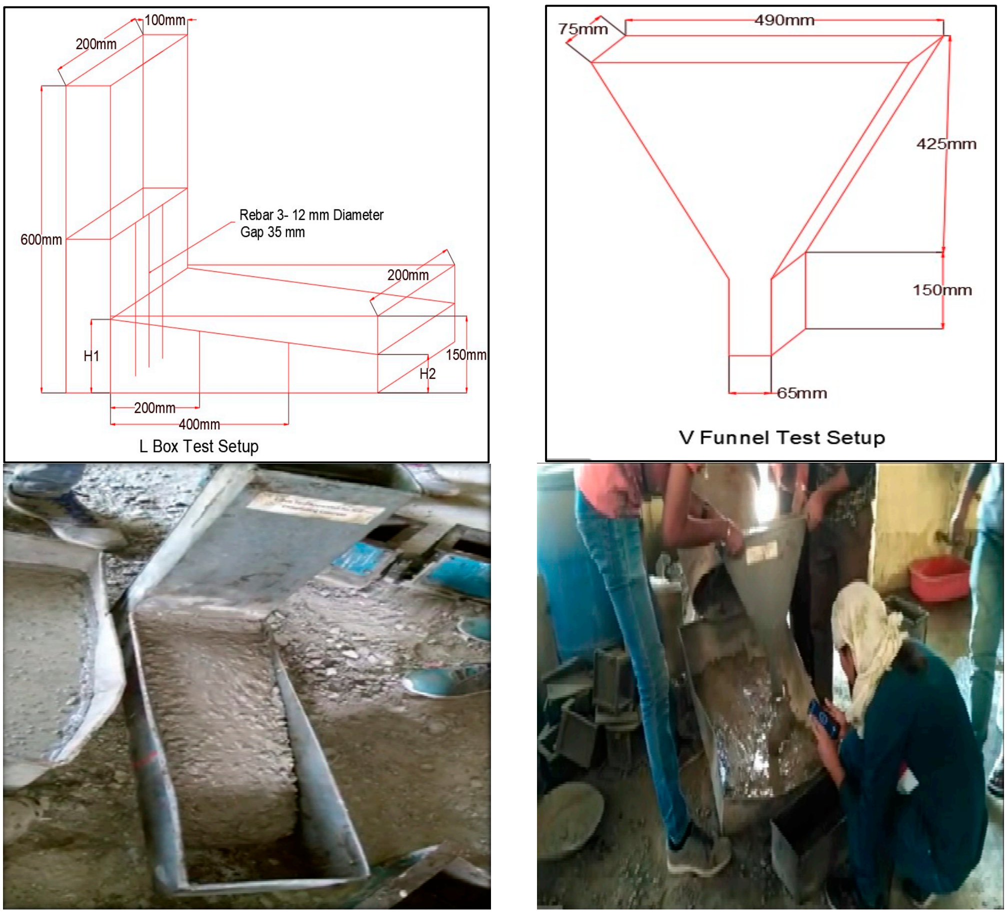
2.9.1. Properties of Fresh Concrete

SCC mixes must meet all three of the following requirements: filling, passing, and segregation resistance [57,58]. Several basic tests were conducted to ensure that these requirements are met as shown in Figure 8a–d. Testing included slump flow, V-funnels for filling, and L-boxes and J-rings for passing. EFNARC (2002) [57–62] methods were followed for all these tests. According to EFNARC (2002), SCC must meet the following criteria shown in Table 4 [29].



(a) (b)

Figure 8. *Cont.*



(**c**) (**d**)

Figure 8. Testing for (**a**) J-ring test; (**b**) slump flow test; (**c**) L-box test; (**d**) V-funnel test.

Table 4. A comparison of the properties of fresh concrete mixes with and without FA compared to the EFNARC (2002) results.

Test Type	In the Range EFNARC, 2002	SCC	SCAF20	SCAF40	SCAF60	SCF15	SCF25	SCF35
Slump Flow in (mm)	650–800	725	715	700	670	720	690	620
V-Funnel (s)	6–12	6	8	9	11	9	12	13
L-Box (H2/H1)	0.8–1	1	1	0.9	0.8	0.9	0.9	Blocking
J Ring Test in (mm)	0–10	4	4	5	7	5	8	9

2.9.2. The Mechanical Properties of the Materials

During the first 7 days, 14 days, and 28 days of age, 150 mm × 150 mm × 150 mm cubes were tested for split tensile strength and compressive strength. They were tested according to IS: 516 (2021) [29,30,35,58,63].

2.9.3. Microstructure Analysis

Using a scanning electron microscope (SEM), the microstructure of the concrete specimens was analyzed to determine the optimum result obtained by mixed proportion. On crushed sample surfaces, observations of hydrate mixes showed their original microstructures [49]. X-ray diffraction (XRD) was performed with 2 Theta on crushed and pulverized samples that have already been cast and cured for 28 days [29].

3. Result and Discussion

3.1. Fresh Properties

The slump flow measurement is a tool for assessing SCC's horizontal flow without obstructions. To determine the concrete's flowability, its diameter was measured. The influence of variations in the S/A ratio, superplasticizer, VMA, AF, and FA on the slump flow test values (filling ability) was investigated by varying (increasing) the sand aggregate (S/A) ratio, varying the dosage of the superplasticizer, varying the dosage of the VMA and the AF, and replacing cement with FA. The slump flow variation for various trial mixes has been shown in Figure 9. A slump flow value of 342 mm is evident for trial mix TR1, which had a sand-to-aggregate ratio of 0.3 [27]. It increased to 453 mm for trial mix TR2 due to a change in the S/A ratio, i.e., 0.35. Then, slump value increased in a nearly uniform fashion from 453 mm to 504 mm, 578 mm, and 651 mm for trial mixes TR3, TR4, and TR5 for ratios of (S/A) 0.4, 0.42, and 0.44, respectively. For TR6, TR7, TR8, TR9, and TR10 in which superplasticizer dosages were increased by 1%, 1.1%, 1.2%, 1.3%, and 1.4%, respectively, the slump value increased to 674 mm, 680 mm, 692 mm, 701 mm, and 705 mm, respectively [29,34,61]. For trial mixes TR11, TR12, and SCC a slump flow of 763 mm, and 706 mm was obtained.

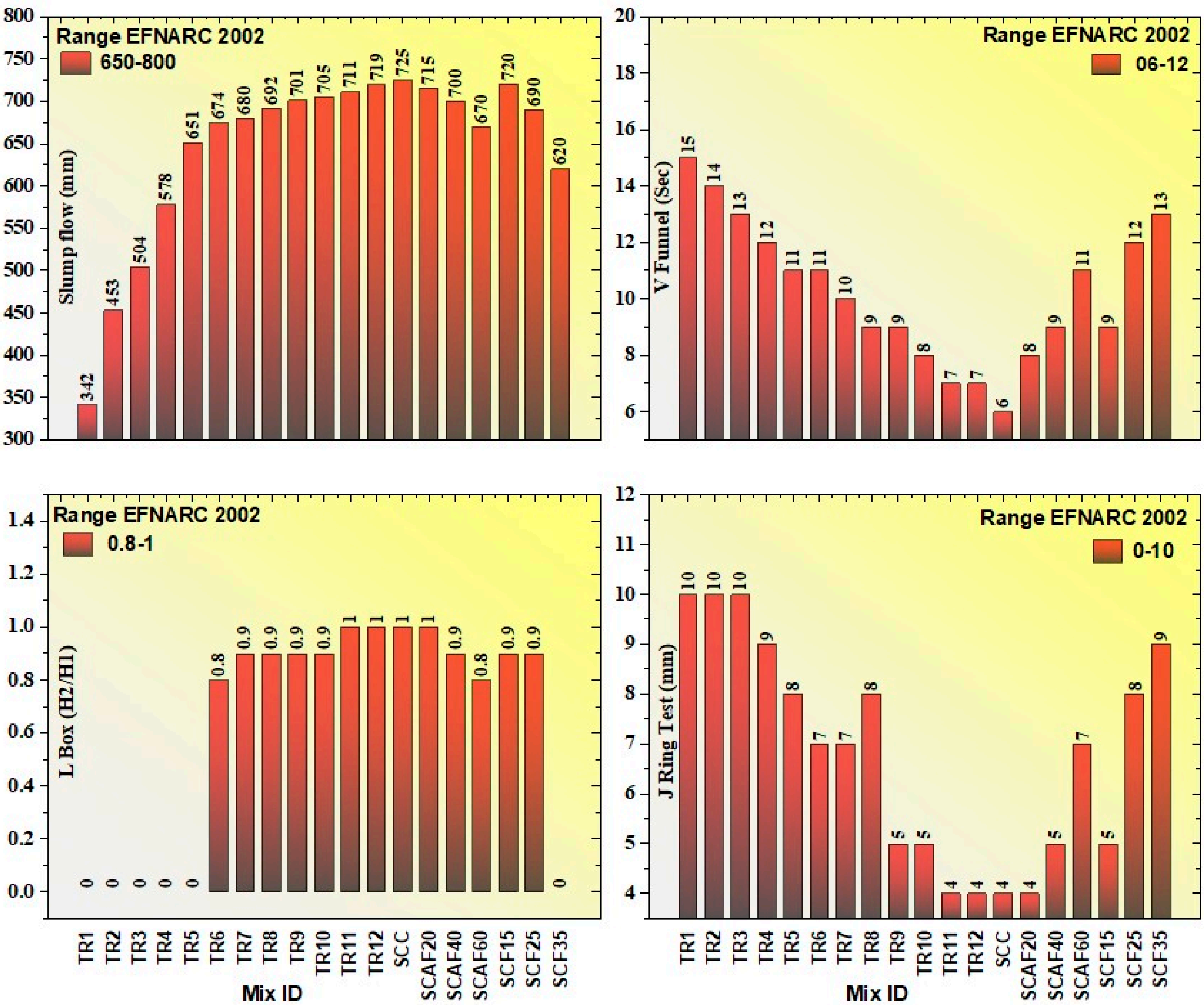


Figure 9. Test results of slump flow; V-funnel; L-box; and J ring tests.

In these mixes, the dosages of VMA were increased from 0.1% to 0.3%. The slump flow values obtained for mixes SCAF20, SCAF40, SCAF60, SCF15, SCF25, and SCF35 were

715 mm, 700 mm, 670 mm, 720 mm, 690 mm, and 620 mm, respectively. The slump flow and V-funnel tests indicate the filling ability of SCC, whereas the L-Box and J-ring tests indicate the passing ability of SCC in a clear and concise manner, all results are shown in Figure 9.

Fresh concrete properties have been tested with various mixes. There was a variation in the SP content of 1 to 1.4% and a variation in the S/A ratio of 0.3 to 0.45. Mixing with 1.4% SP and a 0.44 S/A ratio yielded the best results [29]. In Table 4, we present the results of all self-compacting concrete mixes based on their fresh properties. The slump flow, V-funnel, L-box, and J-ring properties are all listed in Table 4 [29]. The slump flow of all SCCs ranged from 650–800 mm, indicating good deformability when considering slump flow [29]. The values provided by European guidelines matched well with all of the values for fresh concrete properties. Mixtures containing 35% FA had the lowest workability. As FA and AF content increased, workability decreased. It was found that similar results were obtained by [29]. According to EFNARC (2002), the fresh properties met EFNARC standards [59].

3.2. Compressive Strength

Tests were conducted according to IS code 516-2021 [29]. At 7, 14, and 28 days after moist curing, the specimens were removed from the curing tank containing tap water and the test was performed immediately after being removed from the water, as shown in Figure 10a,b. This allowed for the surface water to drip down. A test machine capable of compression of up to 200 tons was used to test the specimens (CTM). An alignment was carefully performed between the machine axis and the axis of the cube specimen. In order to determine the specimen's compressive strength, a gradual load was applied at a constant rate of 14 N/mm^2/minute without causing any shock until failure occurred. 150 mm × 150 mm × 150 mm size cubes for all mix combinations were tested, and, the average compressive strength of the control SCC was found to be 32.87 MPa (megapascals) at the age of 28 days, after replacing 20% of natural aggregate with artificial aggregate, the compressive strength is increased by 8.27% whereas, for 40% and 60% replacement, it decreased by 4.46% and 12.55%, respectively. Further investigation was performed on the optimum value obtained by replacing 20% of CA with AF. At this percentage cement was replaced by FA at (15%, 25%, and 35%) where at 15%, the average compressive strength increased by 7.41%, whereas for 25% and 35% replacement, it decreased by 7.47% and 17.19%, respectively as shown in Figures 10c and 10d, respectively. FA's pozzolanic activity and micro-filling ability play a major role in the improvement of compressive strength in the present study [29]. As a result of the reaction between FA and calcium hydroxide, additional C-S-H is produced. By filling capillary pores, additional C-S-H reduces the concrete's porosity, resulting in a better microstructure and higher compressive strength in bulk pastes and transition zones [21]. Compressive strength decreased with 35% FA replacement with cement. It is likely that too much silica was present in the hydrated blended cement matrix in this case, and not enough C-H was produced to react with it. As a result, some silica was left with no chemical reaction [29]. This is shown in the SEM test results.

3.3. Flexural Strength

To evaluate the flexural strength of the self-compacting concrete (SCC) mixes, 100 mm × 100 mm × 500 mm beams were tested, as depicted in Figure 11a,b. The control SCC, without any replacements, exhibited an average flexural strength of 4.28 MPa [64]. After replacing 20% of coarse aggregate (CA) with artificial aggregate (AF), the flexural strength showed a significant improvement of 4.72%. This suggests that the incorporation of AF positively influenced the flexural performance of SCC. However, when CA was replaced by AF at higher percentages (40% and 60%), there was a slight decrease in flexural strength, amounting to 0.62% and 3.19%, respectively. This indicates that higher levels of AF replacement may have a limited effect on enhancing the flexural strength of the concrete. As AF has a smoother surface compared to coarse aggregate, higher levels of AF replacement may reduce flexural strength [50,51].

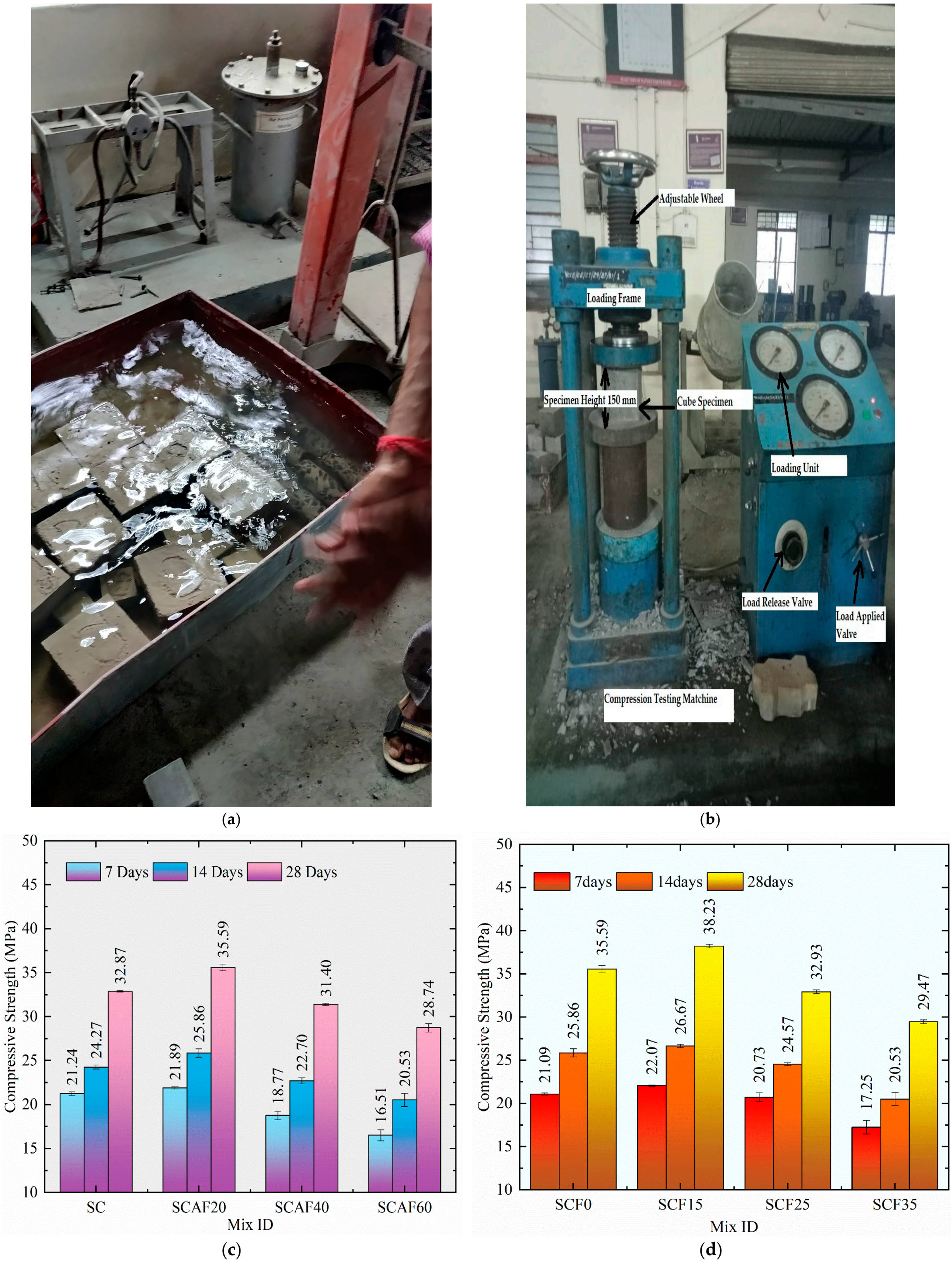


Figure 10. (**a**) Specimen curing. (**b**) Specimen compression test. (**c**) Compressive strength for the partial replacement of CA by AF. (**d**) Compressive strength for the partial replacement of Cement by FA.

Further investigation focused on the optimal value obtained by replacing 20% of CA with AF. At this percentage, the cement was partially replaced by fly ash (FA) at varying levels (15%, 25%, and 35%). The results showed that when replacing 15% of cement with FA, the average flexural strength increased by 1.55%. However, when the cement replacement reached 25% and 35%, the flexural strength experienced a decrease of 3.78% and 8.24%, respectively. This indicates that an excessive amount of FA replacement might have a negative impact on the flexural strength of SCC. Figure 11c,d present a graphical representation of the flexural strength results for the different mix combinations. The findings suggest that an optimized combination of 20% AF replacement for CA and 15% FA replacement for cement (SCF15) resulted in the highest flexural strength. It is important to carefully balance the percentages of AF and FA replacements to achieve the best flexural performance in SCC.

3.4. Split Tensile Strength

The split tensile strength of the self-compacting concrete (SCC) was evaluated using cylinders with dimensions of 150 mm in diameter × 300 mm in height, as shown in Figure 12a,b. The control SCC, without any replacements, exhibited an average split tensile strength of 4.50 MPa [15,35]. Upon replacing 20% of the coarse aggregate (CA) with artificial aggregate (AF), the split tensile strength demonstrated a notable increase of 7.33%. This indicates that the incorporation of AF positively impacted the tensile performance of SCC. However, as the percentage of AF replacement was increased to 40% and 60%, the split tensile strength showed a slight decrease of 0.51% and 4.15%, respectively. This suggests that higher levels of AF replacement might lead to a reduction in the tensile strength of the concrete. Further investigation focused on the optimum value obtained by replacing 20% of CA with AF. At this percentage, the cement is partly replaced by fly ash (FA) at different levels (15%, 25%, and 35%). The results indicated that when replacing 15% of cement with FA, the average splitting tensile strength increased by 3.31%. However, when the cement replacement reached 25% and 35%, the splitting tensile strength experienced a decrease of 7.66% and 11.59%, respectively. This suggests that excessive FA replacement may have an adverse effect on the splitting tensile strength of SCC. Figure 12c,d present a graphical representation of the splitting tensile strength results for the various mix combinations. The findings suggest that an optimized combination of 20% AF replacement for CA and 15% FA replacement for cement (SCF15) resulted in the highest splitting tensile strength. These findings contribute to enhancing the understanding of the influence of AF and FA replacements on the tensile properties of SCC, facilitating the development of more durable and high-performance concrete mixes in construction applications.

3.5. X-ray Diffraction (XRD) and Scanning Electron Microscope (SEM)

X-ray diffraction analysis was conducted on the cured self-compacting concrete (SCC) samples after 28 days of curing to gain insights into the crystalline composition of the material [36,37]. The XRD analysis aimed to identify the mineral phases present in the SCC specimens containing artificial aggregate (AF) and fly ash (FA) as partial replacements for CA and cement, respectively. The typical XRD details, presented in Figure 13a,b, revealed the prominent crystal phases found in the SCC samples [29]. These phases included portlandite (C-H), quartz (Q), and ettringite (e). Each of these phases plays a significant role in determining the concrete's mechanical properties and overall performance. The XRD results indicated that both the SCAF20 and SCF15 mixes exhibited higher peak intensities of quartz (Q) and major peaks of C-H. This suggests that these mixes had a higher crystalline silica structure content compared to other mixes.

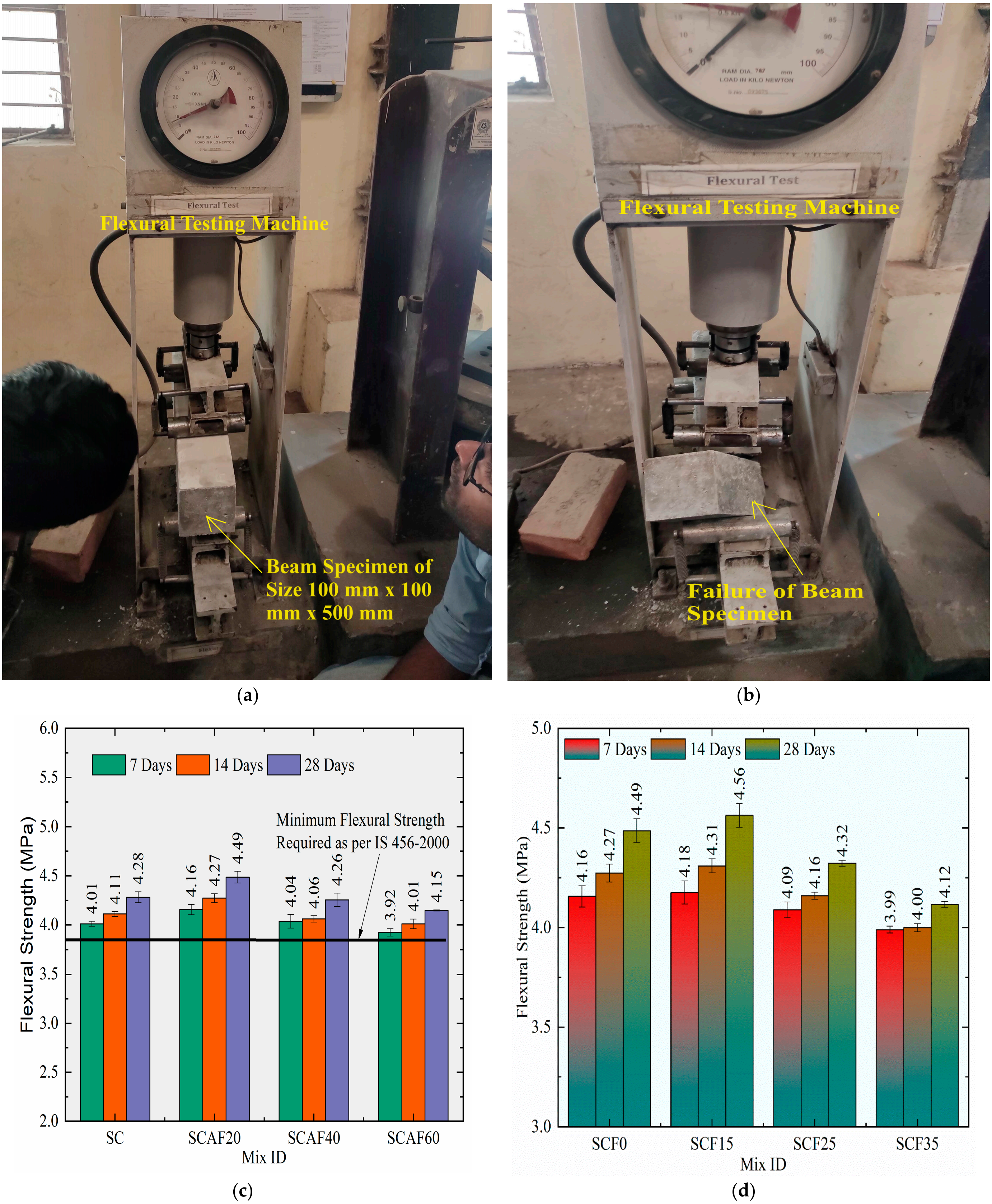


Figure 11. Flexural strength (**a**) test setup. (**b**) Failure of beam specimen. (**c**) Flexural strength for partial replacement of CA by AF. (**d**) Flexural strength for partial replacement of cement by FA.

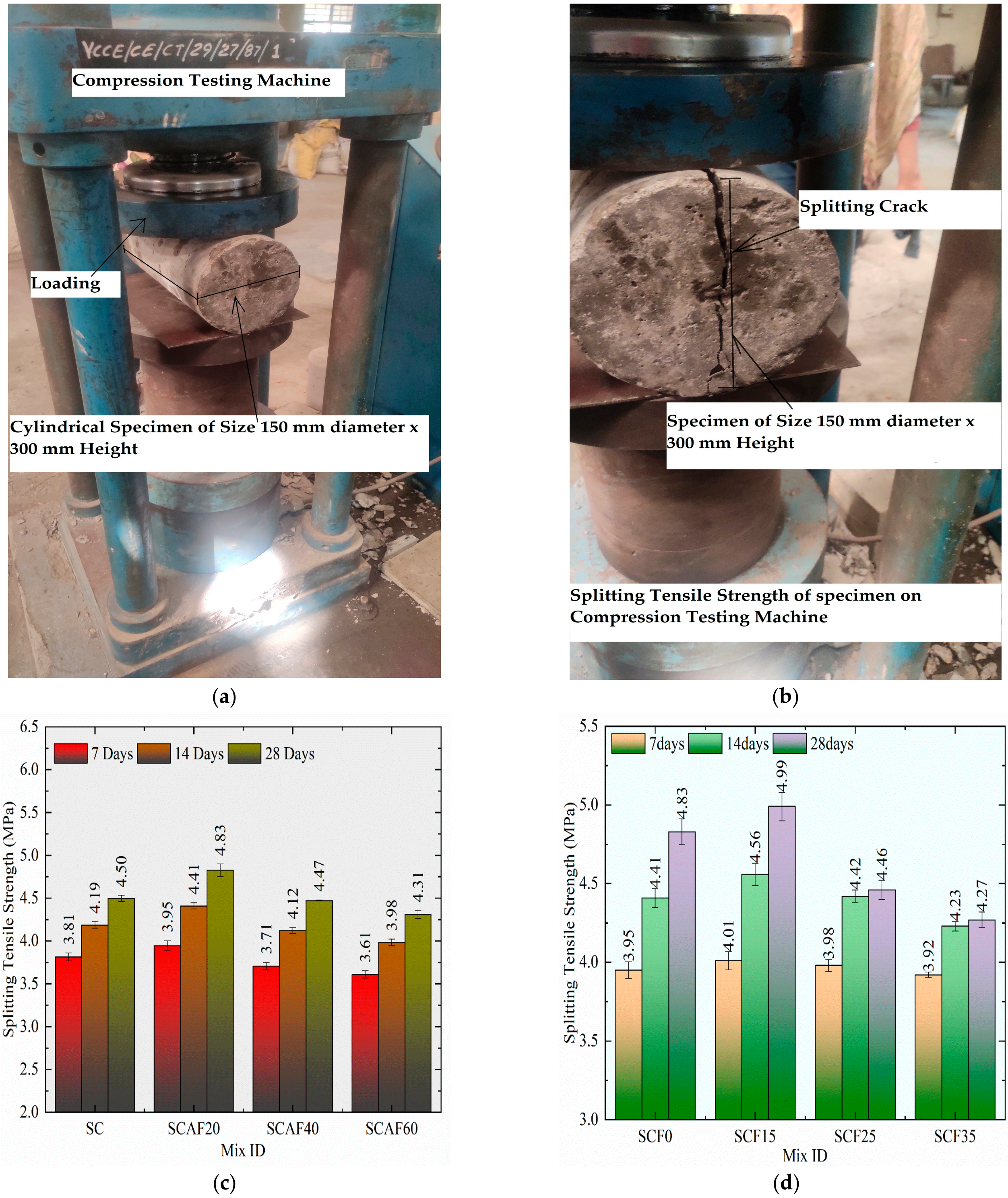
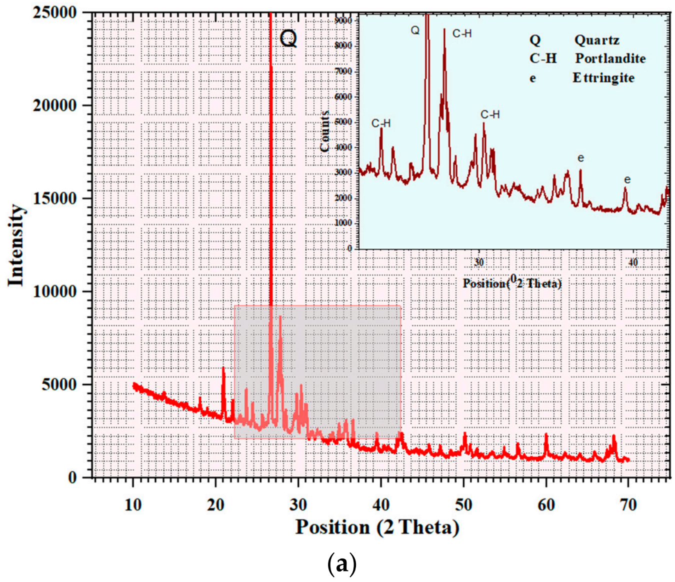


Figure 12. Splitting tensile strength (**a**) test setup. (**b**) Failure of specimen. (**c**) Splitting tensile strength for partial replacement of CA by AF. (**d**) Splitting tensile strength for partial replacement of cement by FA.



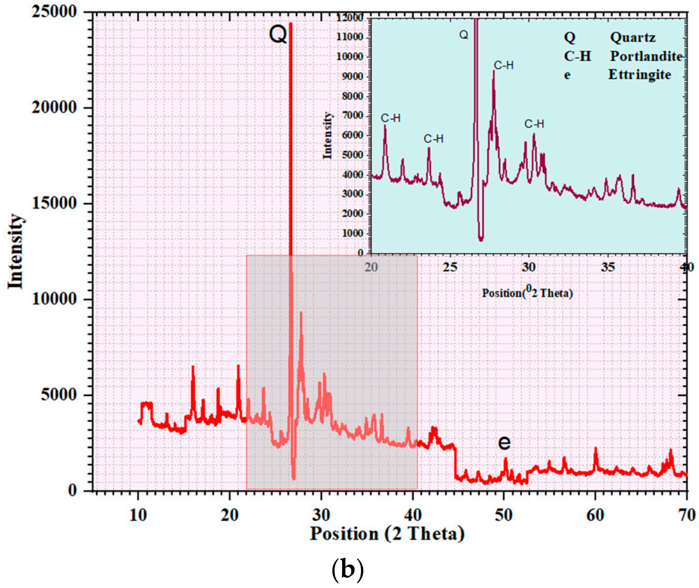
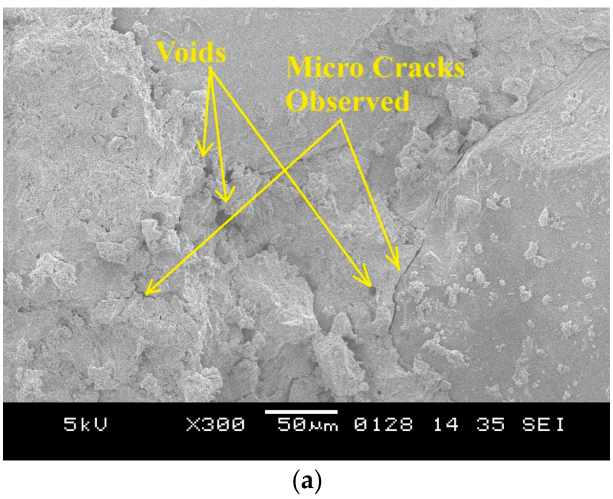


Figure 13. XRD traces after 28 days of curing: (**a**) SCAF20 and (**b**) SCF15.

SEM tests were performed on crushed samples of the optimum resulting mix proportions. Observations of the hydrate mixes showed their original microstructure. More formation of C-S-H gel, "calcium silicate hydrate gel," which is a crucial component in the formation of cementitious materials like concrete, was observed. C-S-H gel is a key product of the chemical reactions that occur when water is mixed with the cement particles in concrete. The quality and quantity of C-S-H gel in concrete play a significant role in its long-term durability. The proper curing and hydration of the concrete are crucial to ensure the formation of a dense and strong C-S-H gel network, which likely explains the observed enhancement in the strength of the SCC in these particular mixes. Notably, SCF15 demonstrated an even denser C-S-H gel structure compared to SCAF20, indicating that the combination of 20% AF replacement for CA and 15% FA replacement for cement led to an optimized microstructure, resulting in the higher strength characteristics of the SCC as shown in Figure 14a,b.



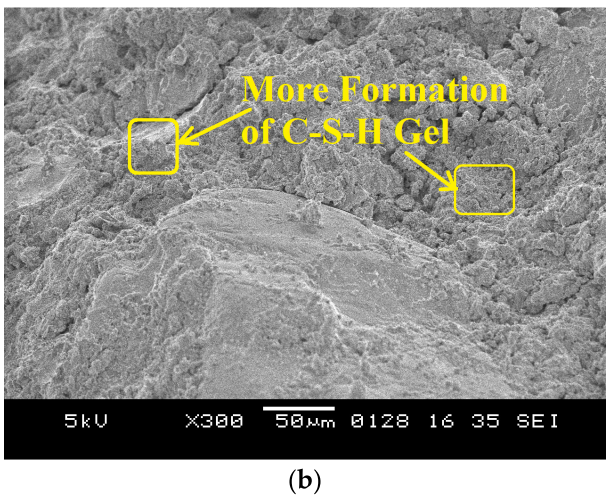


Figure 14. SEM test on the optimum resulting mix proportions: (**a**) SFAF20 and (**b**) SCF15.

4. Conclusions

In summary, this study investigated the application of self-compacting concrete (SCC) incorporating artificial aggregate as a partial replacement for coarse aggregate and fly ash as a partial substitute for cement. The study encompassed the assessment of several characteristics of self-compacting concrete (SCC), encompassing its properties in the fresh state, as well as its compressive strength, flexural strength, and split tensile strength. The results of the study indicate that the substitution of 20% of coarse aggregate (CA) with artificial aggregate (AF) in self-compacting concrete (SCC) led to the most favorable outcomes during the curing process at various time intervals (7, 14, and 28 days). Subsequent increases in the AF content resulted in a decrease in the overall strength characteristics, suggesting that a replacement proportion of 20% was the most optimal. In a similar vein, the utilization of fly ash (FA) as a partial substitute for cement, at a maximum proportion of 15% exhibited a favorable impact on all aspects of self-compacting concrete (SCC). In addition to this limit, a reduction in workability was seen in the fresh concrete mixtures, with SCF35 exhibiting the least workability among the combinations. Moreover, a significant improvement in tensile strength, flexural strength, and splitting strength was achieved when 20% of CA was replaced by AF and 15% of cement was replaced by FA. This combination resulted in the formation of a denser material, which positively influenced the strength properties of the concrete. With evidence from SEM and XRD analyses, it was also verified that replacing 15% of the cement with FA resulted in the highest compressive strength.

Furthermore, microstructural analysis of SCC mixes provides a better understanding of the interactions between AF, FA, and cement, which influence the concrete's mechanical properties. Additionally, conducting durability tests and investigating the long-term behavior of these SCC mixes would provide valuable insights for practical applications in real-world construction projects. Overall, this research lays a solid foundation for further advancements in the field of sustainable and high-performance concrete technology.

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Nomenclature Abbreviations

SCC	Self-compacting concrete
FA	Fly ash
AF	Artificial aggregate
CA	Coarse aggregate
SP	Super plasticizer
VMA	Viscosity modifying agent
OPC	Ordinary portland cement

S/A	Sand to aggregate ratio
SC	Self-compacting control mix
TR	Trail mix
IST	Initial setting time
FST	Final setting time
SCAF20	SCC with 20% replacement of CA by AF
SCAF40	SCC with 40% replacement of CA by AF
SCAF60	SCC with 60% replacement of CA by AF
SCF0	SCC with 20% replacement of CA by AF, 0% replacement of cement by FA
SCF15	SCC 20% replacement of CA by AF, 15% replacement of cement by FA
SCF25	SCC with 20% replacement of CA by AF, 15% replacement of cement by FA
SCF35	SCC with 20% replacement CA by AF, 35% replacement of cement by FA

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