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Assessment of Strength and Durability Properties of Self-Compacting Concrete Comprising Alccofine

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Abstract: Self-Compacting Concrete (SCC), a high-performance concrete with exceptional fluidity and cohesiveness, has gained popularity recently. The consolidation qualities and durability demands of this material require the application of Supplemental Cementitious Materials (SCMs). Alccofine is a type of additive material that has the potential to increase SCC characteristics while lowering the environmental effect of Portland cement manufacturing. In light of these facts, this study focused on the fresh, strength, and durability properties of SCC by partially replacing cement with varying percentages of alccofine such as 0%, 10%, 20%, 30%, 40%, 50%, and 60%. The fresh properties are examined using slump flow, T_{50}, V-funnel, and L-box as per ISO 1920-13. The mechanical and durability properties were investigated, such as compressive strength test, modulus of rupture, Young's modulus of concrete and water absorption, sorptivity, sulphate resistance, and acid resistance, and were compared with conventional SCC. Results indicated that the replacement of 30% alccofine exhibited superior performance in both the strength and durability properties compared to other mixes.

Keywords: self-compacting concrete; alccofine; fresh properties; mechanical properties; durability properties

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1. Introduction

Self-Compacting Concrete (SCC) is a modern technique invented to replace conventional vibrated concrete (CVC). The external vibration is required in CVC and special attention at congested reinforcements. It leads to elapsed duration and an improper surface finish. Concrete placement in various places necessitates extensive investigations into the origin and impact of concrete degradation. Carbonation, sulphate, acid, and chloride attack cause serious durability problems in environments such as the marine environment, underground, etc. These drawbacks can be eradicated with SCC usage with several advantages, such as the quick placing of concrete, homogeneity, elimination of vibrating equipment, less noise, reduction in air voids, decreased duration, increased productivity, and improvement of strength and durability. The critical factors of SCC include the amount of powder content, the particle size of ingredients, and chemical admixture. A higher amount of cement in SCC would increase the production costs. Many researchers have suggested alternate supplementary cementitious materials (SCMs) or mineral admixtures to achieve better economic value, considering fast-growing industries. The modification of traditional concrete became popular with the consumption of industrial derivatives or mineral admixtures [1]. The use of mineral admixture would minimize the amount of chemical admixture, thus reducing the cost of construction [2].

Additionally, its use could improve workability, resistance to sulphate attack, and productivity [3]. Apart from these economic benefits, incorporating mineral admixtures could reduce the heat of hydration [4]. Hajime Okamura has suggested using SCC as a solution for achieving durable concrete that can be compacted into all corners of shuttering merely through its self-weight and without any vibrating compaction [5]. SCC was more durable than CVC in high permeability voids, water absorption, and segregation resistance [6]. The ready-mixed concrete plants have started to use SCC because of its good consolidation, uniformity, and reliability [7]. ISO 1920-13 has given the directives to achieve these properties in SCC [8].

According to some studies [2,3,9], the combination of mineral admixtures (ternary and quaternary blends) in SCC has reduced the early age compressive strength compared to the conventional mix. At all ages of concrete, lowered compressive strength was experienced with the incorporation of slag up to 15% [10]. To overcome this, incorporating materials with high pozzolanic activity into SCC might perform better in improving the compressive strength [11]. Alccofine 1203 has superior pozzolanic activity and is a mainly processed product based on the slag of high glass content with high reactivity achieved through controlled granulation. Alccofine gives better workability with decreased water requirements of up to 70% replacement in CVC due to its ultrafine-sized particles [12]. Alccofine has higher compressive strength and improves concrete durability when combined with other binary or ternary SCMs [12–14].

Domone [15] studied approximately seventy case studies of essential SCC usage from 1993 to 2003 and found that 41% of the instances used binary or ternary OPC blends, while 70% used an aggregate between 16 and 20 mm in size. This study uses well-graded aggregates (20 to 4.75 mm). This well-graded aggregate group is selected as the optimum range of aggregate based on the comparative compressive strength and fresh property analysis among five different aggregate groups, such as C1-10 to 4.75 mm, C2-12.5 to 10 mm, C3-16 to 12.5 mm, C4-20 to 16 mm, and C5-20 to 4.75 mm [16]. A mixed type of aggregate in SCC could considerably reduce the voids and improve the packing density. Due to fewer voids, the required volume of paste content can be minimized, reducing the shrinkage, temperature rise, permeability, and increasing the hardened properties. Previously, the water–binder (W/B) ratio was set at 0.4, and the superplasticizer (polycarboxylic ether) dosage was set at 1% of the total cementitious materials of SCC [16–18].

Based on the literature review, only a few research studies on the durability of alccofine in SCC have been conducted. There has been no research on the chemical resistance of SCC as a binary combination of cement and alccofine, particularly in terms of durability. Furthermore, no effective alccofine utilization has been carried out until now. In light of this, the current study focused on the durability characteristics of SCC when alccofine was utilized effectively. SCC is made in one of three ways: by adding mineral admixtures to increase powder content, by adding chemical admixtures such as Superplasticizer and Viscosity Modifying Agents (VMA), or by mixing the two [19]. Likewise, SCC was produced in this work with a mineral admixture of alccofine (0 to 60% replacement) and a chemical admixture of polycarboxylic ether. The scope of this experimental work is to discover the rheological characteristics such as slump flow, T_{50}, V-funnel, and L-box, mechanical properties such as compressive strength, the modulus of rupture, and Young's modulus of concrete, and the durability characteristics such as density, absorption, and the voids in the hardened concrete, sorptivity, sulphate resistance, and acid resistance of SCC.

2. Experimental Investigation

2.1. Materials

In this experimental study, OPC 53 grade (Ultra Tech brand) is used, conforming to IS 12269-2013 [20]. Alccofine 1203 is utilized as a mineral admixture, procured from Counto Micro Fine Products Pvt. Ltd., Satari, Goa, India, and the chemical properties of cement and alccofine obtained from the supplier are given in Table 1. The Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscopy (EDS) outputs of OPC 53 grade and Alccofine particles are shown in Figure 1, which were acquired from the Centralised Instrumentation and Service Laboratory (CISL) at Annamalai University. It is clear that cement particles are irregular in shape, and alccofine is irregular in shape with sharp edges. Locally available natural river sand is chosen as fine aggregate, passing through a 4.75 mm sieve. It conforms to zone III with a specific gravity of 2.68 and a fineness modulus of 2.88. A crushed angular coarse aggregate with a specific gravity of 2.7 and a size passing through 20 mm and held on a 4.75 mm mesh is adopted, with both aggregates complying to IS 383-2016 [21]. Potable tap water with a pH range of 6 to 7 is utilized. As a chemical admixture, BASF-Master Glenium Sky 8233, a polycarboxylic, ether-based superplasticizer, is utilized in accordance with IS 9103-1999 [22].

Table 1. Chemical properties of OPC and Alccofine 1203.

Component	Chemical Composition (%)	
	Cement	**Alccofine 1203**
CaO	66.67	32.20
SiO_2	18.91	35.30
Fe_2O_3	4.94	1.20
Al_2O_3	4.51	21.40
SO_3	2.5	0.13
MgO	0.87	6.20
K_2O	0.43	-
Na_2O	0.12	-

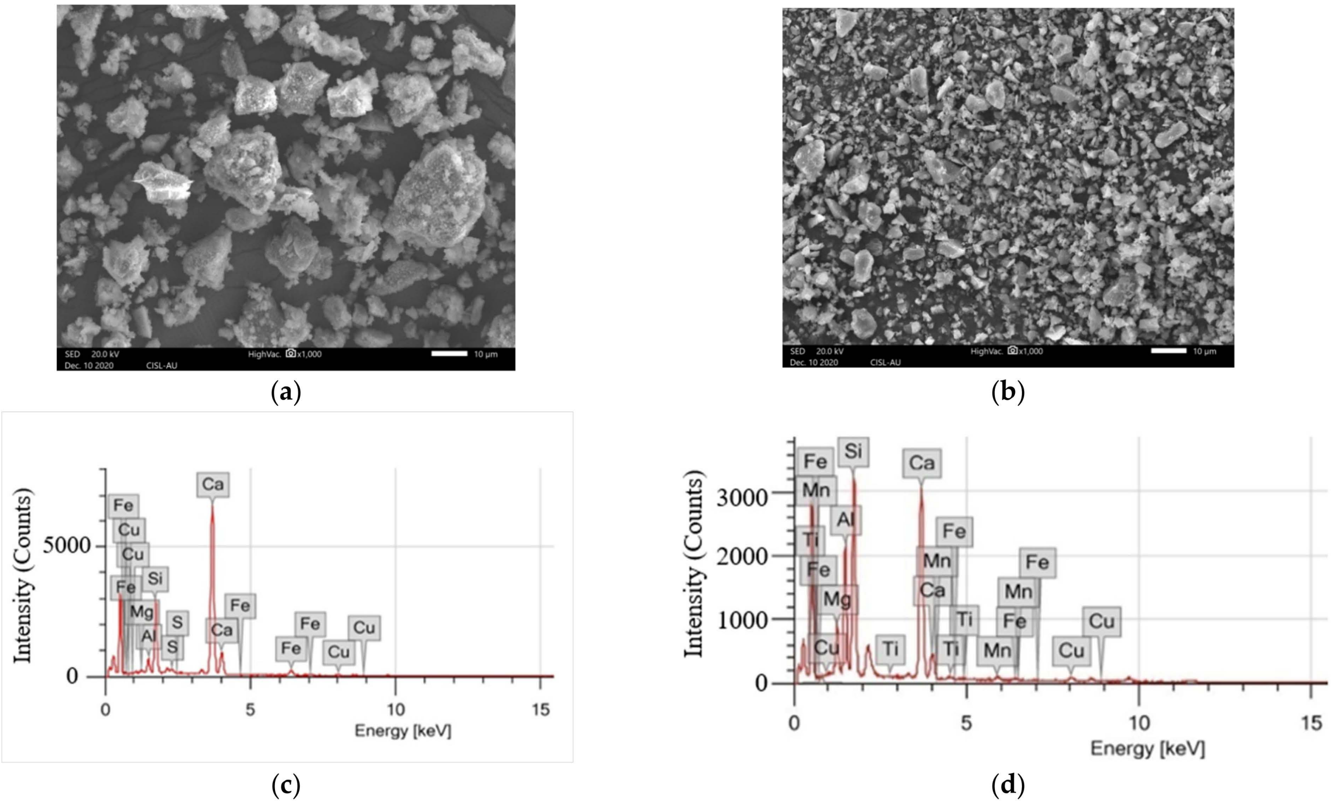


Figure 1. SEM (**a**,**b**) and EDS (**c**,**d**) outputs of OPC and Alccofine 1203.

2.2. Mix Proportions

A reasonable mix design procedure is required for self-compacting concrete. Researchers have previously presented a simple mix proportioning method in which the filler ingredients are kept constant while the water powder ratio and superplasticizer doses are kept variable [5]. In this study, seven sequences of mix proportions, of which one was conventional and the other six mixtures with alccofine, were prepared in different combinations. These mix proportions are specified in Table 2. The mixes are called C5-A10, C5-A20, C5-A30, C5-A40, C5-A50, and C5-A60. The aggregate size range of 20 to 4.75 mm is denoted by C5, and the proportion of alccofine replacement is denoted by A10 to A60, which is a continuation of the previous study [16].Cement is replaced by alccofine with varying proportions (10%, 20%, 30%, 40%, 50%, and 60%), with a total powder content of 465 kg/m^3; other ingredients are kept constant. The W/B ratio of 0.4 and the SP dosage of 1% are used for all the mixes.

Table 2. Mix proportions of SCC mixes(kg/m^3).

Description	Mix ID						
	C5-A0	**C5-A10**	**C5-A20**	**C5-A30**	**C5-A40**	**C5-A50**	**C5-A60**
Cement	465	418.5	372	325.5	279	232.5	186
Alccofine	0	46.5	93	139.5	186	232.5	279
Fine aggregate	915	915	915	915	915	915	915
Coarse aggregate	836	836	836	836	836	836	836
Water	186	186	186	186	186	186	186
Superplasticizer	4.65	4.65	4.65	4.65	4.65	4.65	4.65

2.3. Testing of Fresh and Mechanical Properties of SCC

To satisfy the workability of SCC as per ISO 1920-13 [8], fresh property assessments (slump flow, T_{50}, V-funnel, and L-box) are performed. Figure 2 shows the testing of fresh state SCC in the laboratory. To carry out necessary mechanical properties such as compressive strength, modulus of rupture, and E-for concrete, it is essential to arrive at the quantity of material as per IS 516-2018 [23]. For each mix, three samples are cast. From the date of casting, 28 days of compressive strength, modules of rupture, and E-for concrete are calculated. The test set-up and failure modes of the mechanical properties' determination are shown in Figure 3.

(a) (b) (c)

Figure 2. Testing fresh state of SCC in laboratory (**a**) slump flow, (**b**) V-funnel, and (**c**) L-box.

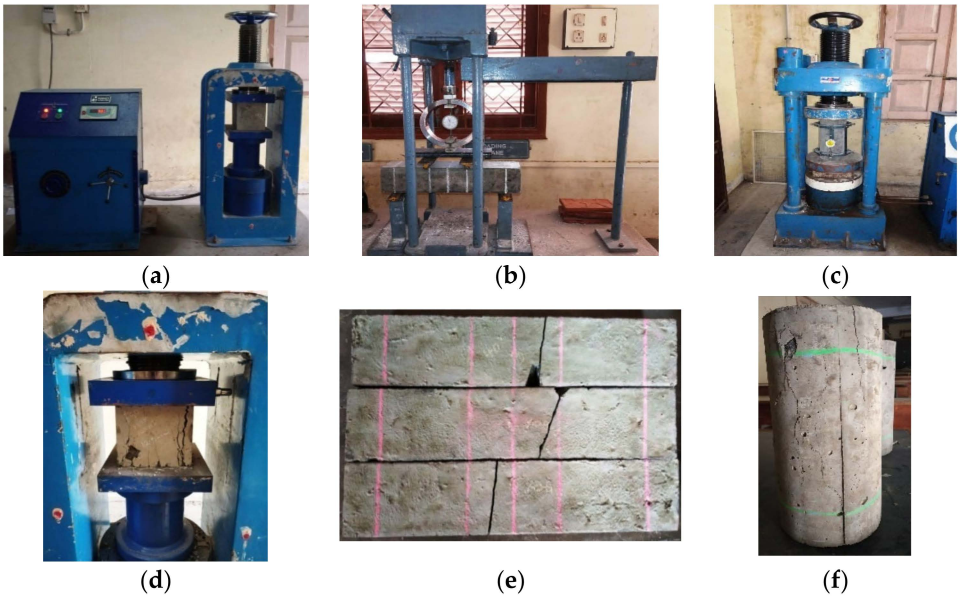


Figure 3. Testing of specimens in laboratory (**a**–**c**). Test setup of compression, flexure, and E-for concrete and (**d**–**f**) failure pattern of cube, prism, and cylinder.

2.4. Testing of Durability Properties of SCC

2.4.1. Determination of Density, Absorption, and Voids in Hardened Concrete

This test was performed in accordance with ASTM C 642-97 [24]. After 28 days of curing, the samples are taken out and undergo an oven process (Figure 4a) for 24 h at 100–110 °C to determine the dry mass. Then, the samples are immersed in water for no less than 48 h (Figure 4b). They are then taken out, and the surface of the specimens is dried with a cotton cloth to determine surface dry mass. Following that, specimens are placed in the water and heated for 5 h (Figure 4c), allowing them to cool for 14 h at 20–25 °C and are then surface dried to find the mass. Finally, the samples are kept in an apparent basket suspended by wire (Figure 4d) to find the apparent mass underwater. Based on the observation, the calculations were carried out.

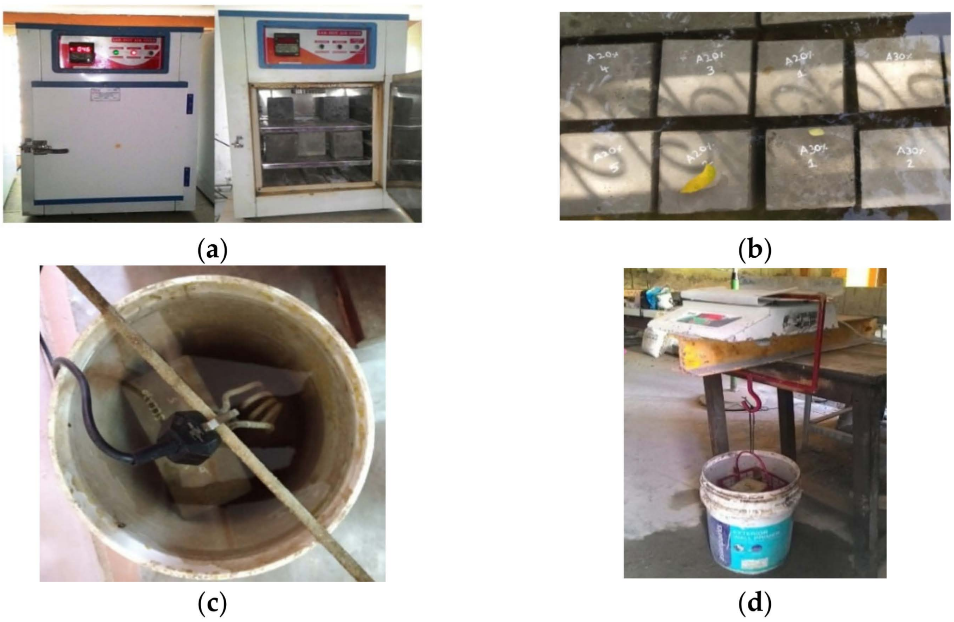
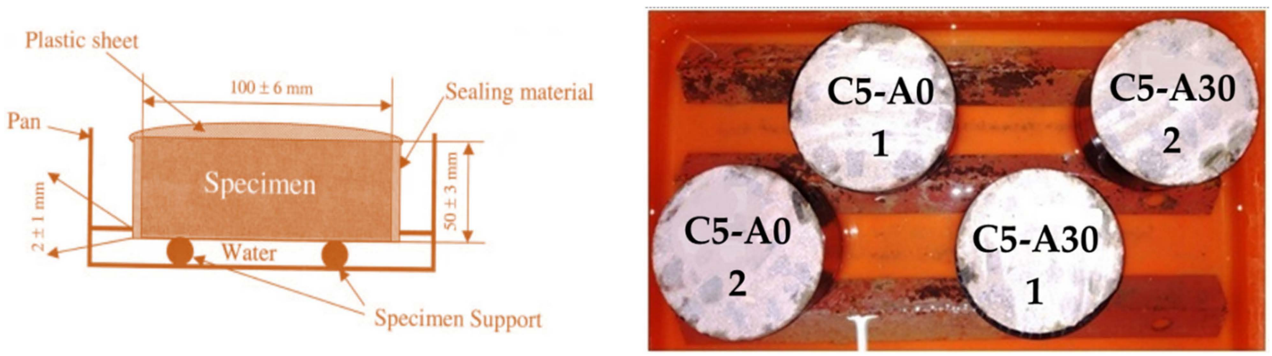


Figure 4. (**a**) Samples in oven drying; (**b**) samples immersed in water; (**c**) samples in boiling water; (**d**) Sample in apparent basket.

2.4.2. Determination of Sorptivity

The purpose of this experiment was to measure the rate of water absorption (sorptivity) of a specimen when just one surface of the specimen was exposed to water, as specified by ASTM C 1585-13 [25]. The specimens are collected and dried for three days at 50 ± 2 °C for 3 days. Then, they are stored in a sealable container for 15 days at 23 ± 2 °C. After that, the samples are weighed, and the side surface is sealed with vinyl electrician's tape to determine the initial mass. The sealed samples are placed in the pan and the water is poured to a level of 1 to 3 mm above the supports. The schematic procedure and samples placed in the pan are shown in Figure 5a,b. The sample mass is recorded for 6 h using the square root of time intervals of 10 s. Using the expression $I = S\sqrt{t}$, the sorptivity coefficient (S) was determined. Where I-is the total amount of water absorbed per unit area of the inflow surface, and t-is the amount of time that has passed (s).

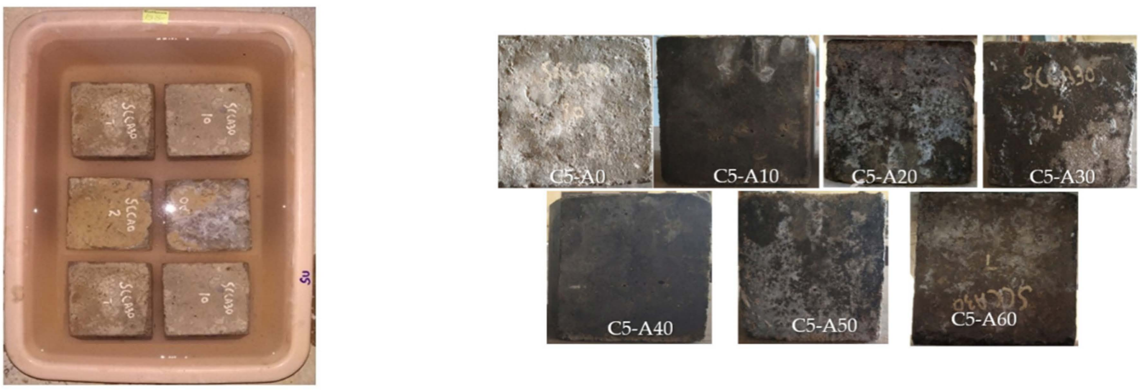


(**a**) (**b**)

Figure 5. (**a**) Schematic procedure of sorptivity and (**b**) samples placed in the sorptivity pan.

2.4.3. Sulphate Resistance

This test is carried out as specified by ASTM C1012-04 [26] to determine the sulphate attack on concrete cube specimens when fully immersed in the sulphate solution. After 28 days of curing, the cubes were weighed to determine their original weight. Then, the specimens are immersed in a magnesium sulphate ($MgSO_4$) dissolved water solution for 28 and 56 days at 23 ± 2 °C (Figure 6a). Then, the specimens are taken out of the solution, surface dried (Figure 6b), and weighed to record the final weight. Following the aforementioned procedure, a white-coloured deposit was detected on the concrete's surface. Finally, the cube specimens are subjected to a compression test, and the results are compared with normal water-cured concrete.

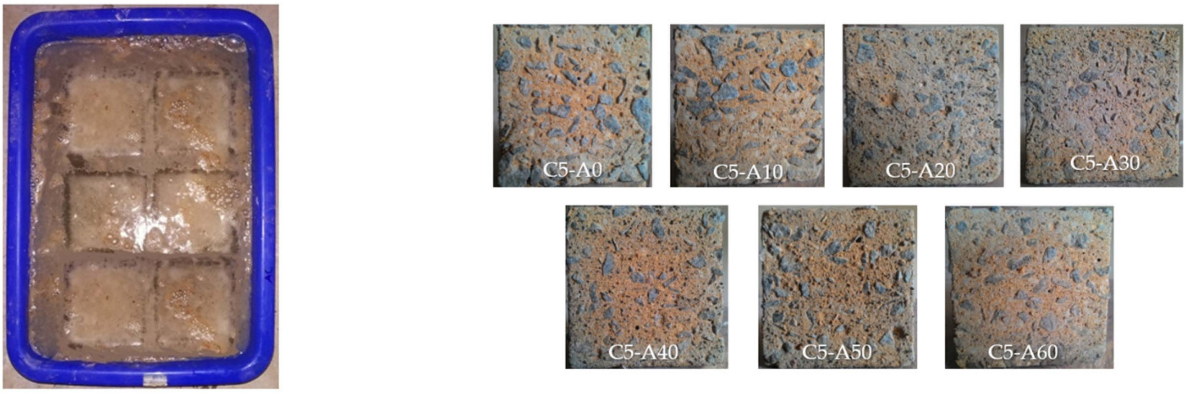


(**a**) (**b**)

Figure 6. (**a**) Specimens immersed in $MgSO_4$ solution and (**b**) specimens after immersion in $MgSO_4$ solution.

2.4.4. Acid Resistance

This test is performed in accordance with ASTM C 1898-20 [27] to assess acid attack on hardened concrete in an acid solution. The specimens were taken out of curing after 28 days, left to dry for 24 h, and weighed. Is the result was considered to be the initial weight. To perform this test, 5% hydrochloric acid (HCl) was taken and diluted to a pH value of about 2. In that, cubes were immersed for a period of 28 and 56 days (Figure 7a). The solution was verified once a week to maintain its concentration. After 28 and 56 days, the cubes were taken out (Figure 7b). The cubes were cleaned to remove unstable particles leached by acid and were weighed (final weight) and tested in a compression testing machine. Using the initial weight, final weight, and compressive strength, the loss in percentage of weight and strength are obtained.



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

Figure 7. (**a**) Specimens immersed in HCl solution and (**b**) specimens after immersion in HCl solution.

3. Results and Discussion

3.1. Properties of Fresh Concrete

Three major tests are executed to acquire the workability of SCC, such as flowability, filling ability, and passing ability. The consequences of all SCC mixtures are shown in Table 3. Initially, flowability is tested and measured. The slump flow results are in the range of 525 to 690 mm, with an estimated T_{50} of 4 to 8 s. All the mixes except C5-A60 satisfy the ISO 1920-13 guidelines. However, slump values of 500 to 700 mm were recommended for SCC [28]. The diagrammatic representations of the slump flow and T_{50} for all mixes are shown in Figure 8. There is a variation in slump flow observed concerning the different percentages of alccofine. The C5-A20 and C5-A30 showed a higher value, and C5-A0 and the C5-A60 showed comparatively lower values. It is recorded that there is a gradual increase in the flow value between the ranges of 0% and 30%; further, increased replacement resulted in decreased slump flow. Better flowability of up to 30% replacement of alccofine was due to high lubrication behaviour between the finer particles. The reduction in slump value was due to an increase in the percentage of alccofine, since the excess finer particles demand more water content and result in sultry concrete. Due to water demand, effective hydration would not take place, and homogeneity would be reduced.

Table 3. Fresh properties of SCC mix.

Description	Mix ID						
	C5-A0	**C5-A10**	**C5-A20**	**C5-A30**	**C5-A40**	**C5-A50**	**C5-A60**
Slump (mm)	562	650	687	690	645	580	525
T_{50} cm (s)	6	5	4	4	5	6	8
V-Funnel (s)	6	4	3	3	7	17	23
L-Box (h2/h1)	0.81	0.86	0.95	0.95	0.84	0.76	0.62

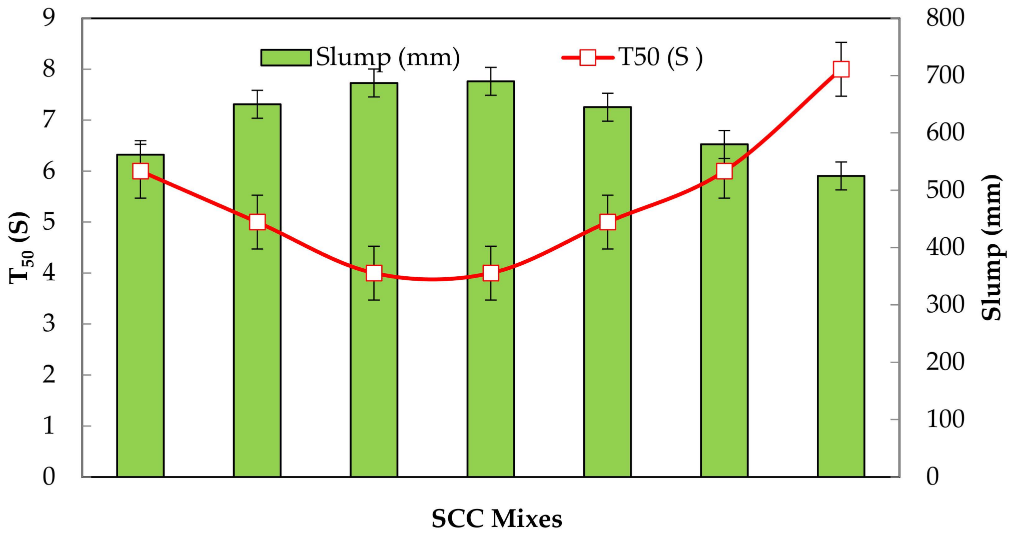


Figure 8. Slump flow and T_{50} time of SCC mixtures.

A V-funnel is performed to calculate the elapsed time between releasing the end shutter and draining the funnel. The suggested value by ISO 1920-13 for V-funnel is ≤8 and 9–25 s. From the test results, all the mixes met the requirements, and C5-A0 to C5-A30 had a VF time of less than 6 s. Khayat KH suggested a VF time of no more than 6 s for concrete to meet the requirements of SCC [29]. In particular, SCC with a VF timing of above 15 s would be more cohesive and difficult to handle. Moreover, a higher amount of slag content could result in more viscous concrete, thus increasing the V-funnel time. The graphical representation of the V-funnel timing and L-box ratio is illustrated in Figure 9.

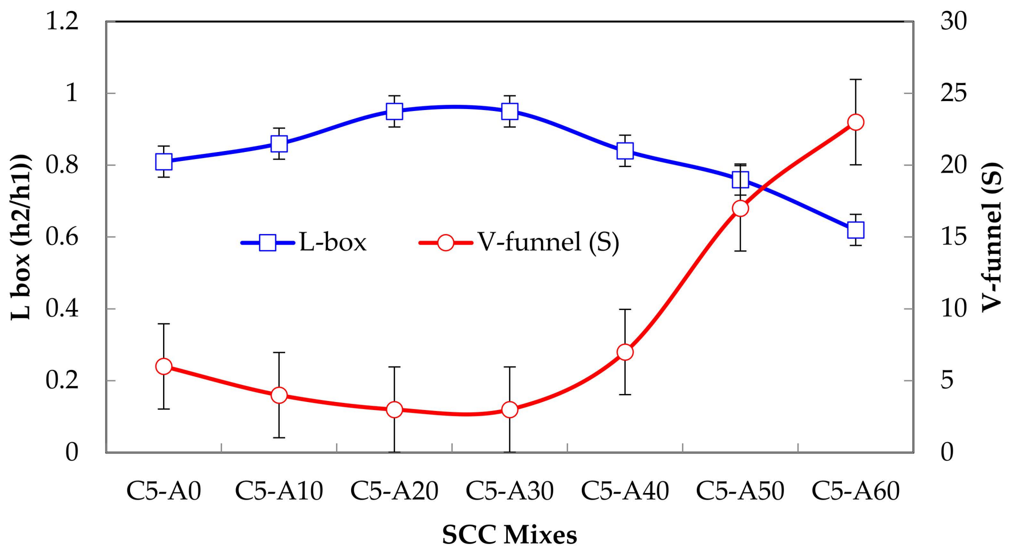


Figure 9. V-funnel time and L-box ratio of SCC mixtures.

In the L-box test, the ratio of height at the two extreme ends is calculated (h1 and h2), which denotes the passing ability of the SCC. Generally, the size of the coarse aggregate is dominant in the L-box test. Because the maximum size of coarse aggregates can affect passing ability, well-graded aggregates ranging from 20 to 4.75 mm are used. In the present case, it was observed that the passing ability ratio for all the mixes was found to be in the range of 0.61 to 0.95. ISO 1920-13 recommends an acceptable blocking ratio of ≥0.8. However, a ratio greater than 0.6 can be accepted for the better filling ability of SCC [30]. During this test, no blocking was observed, since the gap between the L-box reinforcement was 41 mm. However, the flow restriction is found due to the higher amount of alccofine replacement (C5-A50 and C5-A60).

3.2. Properties of Hardened Concrete

Table 4 shows the mechanical characteristics of conventional and alccofine-based mixes. In total, 21 cubes with dimensions of 150 × 150 × 150 mm, 21 cylinders with dimensions of 150 × 300 mm, and prisms with dimensions of 100 × 100 × 500 mm are tested. Three specimens are examined for every mix to determine the mean value. The test results of the mechanical properties showed varying strengths at different amounts of alccofine substitution. The attained compressive strength of 28 days varies from 30.69 N/mm^2 to 48.13 N/mm^2. The mix C5-A30 has an optimal compressive strength of 48.13 N/mm^2, which is 56% greater than conventional SCC. The compressive strength values of all the blends are shown in Figure 10. When comparing alccofine-based SCC to conventional SCC, it can be seen that alccofine-based SCC has a higher strength. Alccofine was used as an SCM in normal concrete and SCC with a variety of admixtures in various studies, and the results were optimal, with 10–15% replacement [31–33]. However, in this study, the best results were obtained when alccofine was replaced by 30%. This is due to the binary blend and moderate cement usage (465 kg/m^3). One cause of the increase in compressive strength was the existence of more calcium, silica, and alumina in alccofine. Because of the development of supplementary C-S-H gel, it was obvious that the alccofine-added concrete microstructure is denser. Alccofine's fineness would minimize air content by filling pores, resulting in a higher unit weight of fresh concrete. Concrete with a higher unit weight has better strength, which may be attained by adequate constituent material packing. Furthermore, the increase in strength with the substitution of alccofine was recognized to be due to superior packing density and the acceleration of cement hydration.

Table 4. Mechanical properties of SCC mixes.

Description	Mix ID						
	C5-A0	**C5-A10**	**C5-A20**	**C5-A30**	**C5-A40**	**C5-A50**	**C5-A60**
Compressive Strength N/mm^2	30.69	34.09	45.77	48.13	43.84	37.21	34.68
Flexural Strength N/mm^2	3.49	3.67	4.26	4.46	4.17	3.84	3.71
E-for Concrete $\times 10^3$ N/mm^2	26.77	28.21	32.82	33.79	32.1	29.53	28.54

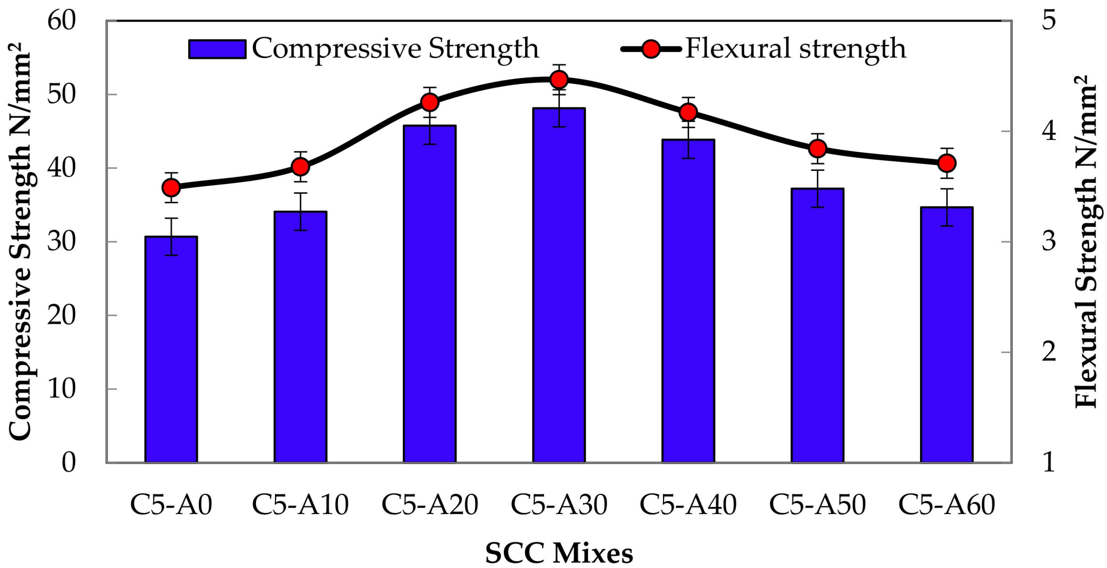


Figure 10. Compressive and flexural strength of SCC mixtures.

The flexural strength values at 28 days vary from 3.49 to 4.46 N/mm^2 and are diagrammatically represented in Figure 10. The pozzolanic reaction is responsible for the increased flexural strength with the replacement of alccofine. This reaction enhances the bond between the binder material and the aggregate, resulting in increased strength in the Interfacial Transition Zone (ITZ). Following the failure of these specimens, a single fracture appeared along with the depth of the specimen during the loading period.The fracture began at the interface zone due to the tensile strain generated by the compressive force and subsequently propagated into the concrete composites. Cracks begin in the interfacial area at low stress and propagate to the concrete matrix at increasing stress during flexural loading, contributing to the specimen's collapse at ultimate load [34].

Young's modulus of concrete is an integrated mechanical parameter that demonstrates the concrete material's ability to deform elastically [33]. The results of Young's modulus of concrete ranged between 26.77 $\times$ 10^3 N/mm^2 and 33.33 $\times$ 10^3 N/mm^2. The optimum result obtained for C5-A30 is 33.33 $\times$ 10^3 N/mm^2, which is 21.83% higher than the conventional SCC mix C5-A0. The mixes C5-A0 to C5-A30 had a gradual increase, but the remaining mixes produced values less than conventional SCC. Generally, Young's modulus values are influenced by the type and volume of coarse aggregate and paste content. SCC produces a larger amount of paste and is distinguished by greater deformability, thereby lowering the concrete's stiffness and reducing aggregate content volume. However, in this study, the type and volume of aggregates were kept constant; however, in the paste content, the replacement of cement with alccofine was made, which enhanced the ITZ and thus influenced the elasticity of concrete. The Initial Tangent Modulus is used to calculate the Young's modulus of concrete for all the mixes as a slope from the origin to the ultimate strength of concrete in stress–strain curves, which are shown in Figure 11.

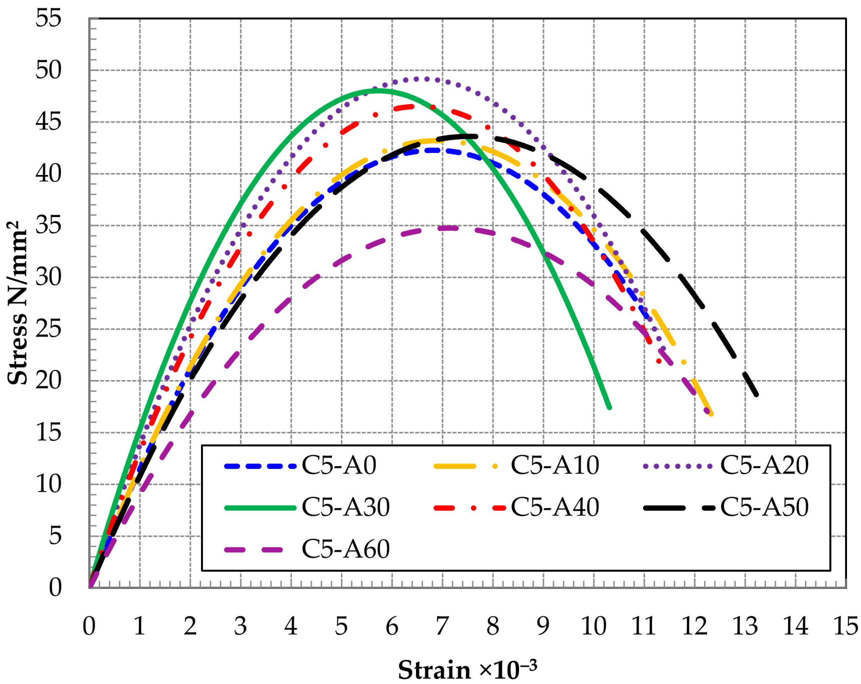


Figure 11. Stress–strain curves of SCC mixes with varying % of alccofine.

3.3. Comparison of Utilization Percentage of Alccofine with Existing Research

The present work is compared with some previous studies based on the incorporation percentage of alccofine that are listed in Table 5. From the gathered data, it is revealed that the utilization percentage of alccofine is in the range of 2.5 to 60%, where only limited amounts of research have been carried out for SCC. The optimum results are achieved in the range of 8 to 30%. The relationship between compressive strength and varying percentages of alccofine is shown in Figure 12. In this research, around 50% of the research is subjected to binary blends with an optimum alccofine replacement of 30%, and the remaining 50% are ternary blends with an optimum alccofine replacement of 15%. This binary and ternary combination with the different percentage of alccofine is shown in Figure 13. Another major influencing factor for attaining the optimum percentage of alccofine is the W/B ratio and total powder content. Figure 14 shows the interpretation between the optimum percentage of alccofine with total powder content and the W/B ratio. From the graph, it is evident that the optimum results are attained with a powder content of 350 to 550 kg/m^3 and a water binder ratio of 0.3 to 0.5 in most of the research. The W/B ratio and the total powder content of the current study are indicated as a dotted line in the graph which lies between the aforementioned values. From the comparative study, it was observed that moderate powder content of 450 to 500 kg/m^3 and a W/B ratio of 0.4 could consume a higher percentage of alccofine.

Table 5. Data analysis of utilization percentage of alccofine from earlier studies.

Reference	Total Powder Content (kg/m^3)	W/B Ratio	Combination		Slump Flow	Compressive Strength (N/mm^2)		Utilization Range of Alccofine %	Optimum Alccofine %
			Binary	Ternary		7 Days	28 Days		
[35]	483	0.45	C + AF	-	580 to 720	24.6 to 31.7	28.55 to 35.25	10	10
[32]	500	0.36	-	C + AF+ FA	-	20 to 24	32 to 34	5–15	10
[36]	550	0.41	-	C + AF+ FA	540 to 690	20 to 30	31 to 41	2.5–10	10
[1]	540	0.34	C + AF	-	700 to 720	46.22 to 48.89	57.33 to 62.67	5–15	10
[37]	650	0.4	C + AF	-	665 to 692	34.66 to 36.44	57.77 to 60.44	5–15	10
[38]	-	-	-	C + AF + GGBS	670 to 720	25.2 to 29.6	38.2 to 42.9	5–20	10
[18]	465	0.4	C + AF	-	521 to 712	16.3 to 37.14	26.34 to 58.11	10–60	30
[16]	465	0.4	C + AF	-	525 to 690	25.86 to 32.11	34.09 to 48.13	10–60	30
[13]	600	0.3	-	C + AF+ FA	-	44.06	54.89	4–14	8
[39]	-	-	C + AF	-	700–710	17.66 to 28.66	27 to 34	5–15	10
[40,41]	360	0.4		C + AF+ FA	630–680	26.5 to 36.8	41.9 to 46.4	5–15	10
[42]	560	0.34	-	C + AF + GGBS	-	28.19 to 30.69	41.85 to 46.79	2.5–10	7.5
[43,44]	496	0.34	C + AF	-	657–670	-	-	10–40	30
[45]	600	0.3	-	C + AF+ FA	720–760	-	71.3 to 80.2	3–15	12
[46]	-	0.4	-	C + AF+ FA	550–612	-	20.05 to 30.88	10–25	15
[47]	525	0.4	C + AF	-	640–670	15.49 to 20.79	43.21 to 51.16	10–50	20

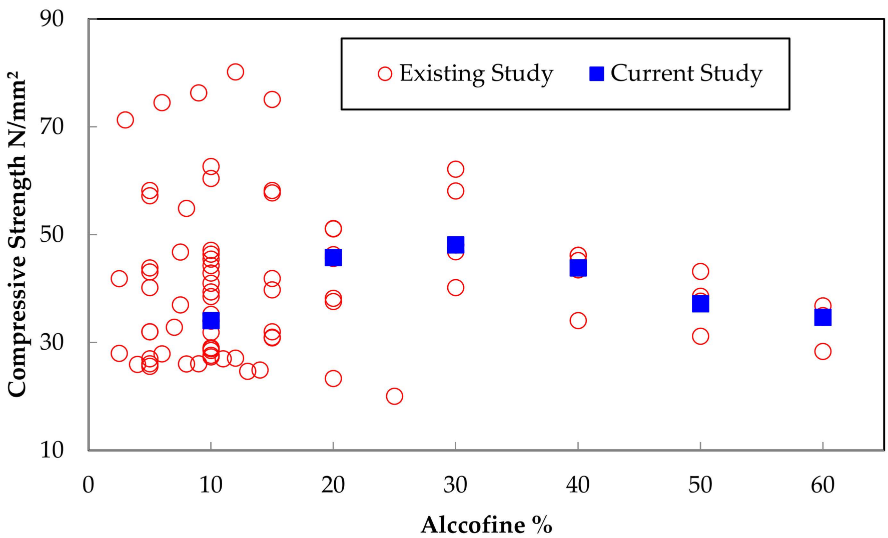


Figure 12. Comparison of compressive strength with existing findings.

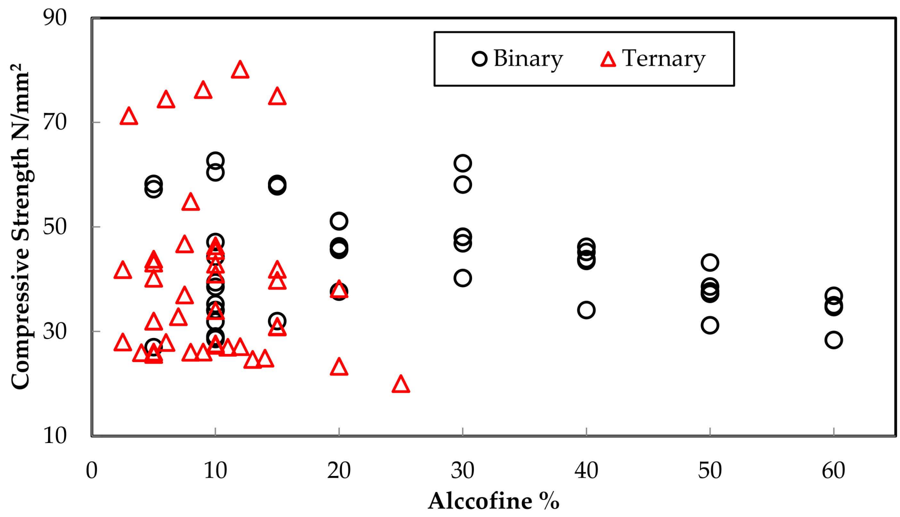


Figure 13. Comparison of compressive strength as binary and ternary combination with existing findings.

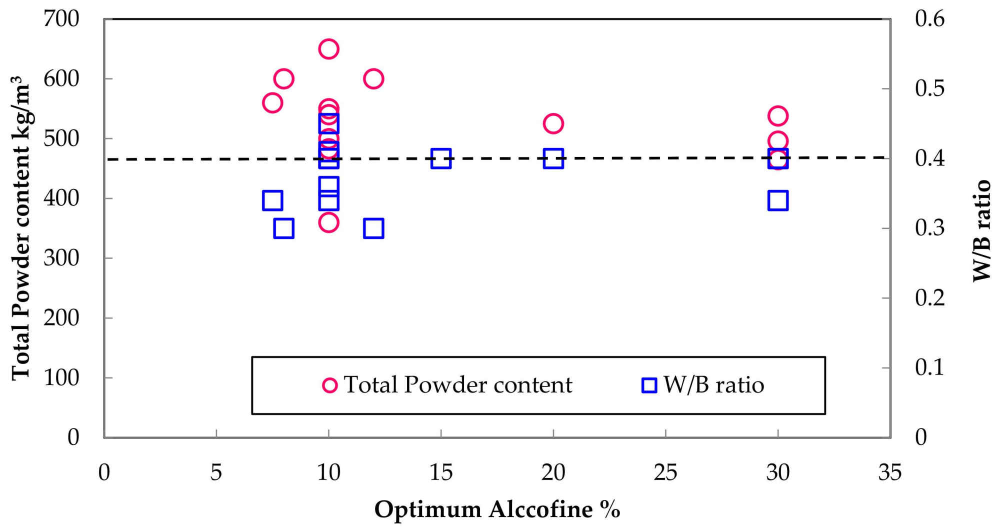


Figure 14. Interpretation between the optimum percentage of alccofine with total powder content and the W/B ratio.

3.4. Density, Absorption, and Voids in Hardened Concrete

Table 6 shows the effect of alccofine replacement on water absorption; pore space and density of SCC mixes are shown in Figures 15 and 16. From Figure 15, it was observed that the water absorption percentage after water immersion varied between 0.16 and 0.29%; after water immersion and boiling, it varied between 0.27 and 0.40%, and the volume of pore space varied between 0.54 and 0.73%. From Figure 16, it was found that the density of concrete had a variation of 1.81 to 2.0 mg/m^3. The findings showed that an increase in the substitute percentage of alccofine in the SCC mix considerably reduced water absorption due to the presence of rich fineness, which leads to fewer pores and higher density in the concrete. Permeability is important for durability because it affects the degree to which moisture enters the concrete. The amount of water infiltration has a significant influence on the degradation of concrete structures because chlorides and sulphates, when combined with water, attack the concrete, causing it to deteriorate. Generally, the microstructural texture, pore size distribution, connectivity, porosity, ITZ characteristics, and micro-cracking are mainly essential to the resistance of fluid permeation in concrete [48]. Permeation characteristics are also affected by the degree of hydration and mineral additives; the two hydration products and small mineral particles can clog the linked pores in the paste and the ITZ, making the capillary system narrower and more complicated for the transfer of fluid [48]. In previous research, significant decreases in permeability characteristics are extensively documented and well recognized for both SCC and CVC when fly ash, slag, or silica fume are used as mineral accompaniments or in multiple cement mixes [49,50]. Although water absorption cannot be used as an indicator of good concrete quality, the measured values are within acceptable limits [51].

Table 6. Density, absorption, and voids of SCC mix.

Description	Mix ID						
	C5-A0	**C5-A10**	**C5-A20**	**C5-A30**	**C5-A40**	**C5-A50**	**C5-A60**
After 48 h immersion	0.290	0.242	0.215	0.202	0.204	0.198	0.170
After boiling	0.405	0.360	0.331	0.315	0.315	0.305	0.273
Bulk density dry, Mg/m^3	1.815	1.873	1.910	1.935	1.958	1.972	2.002
Apparent density Mg/m^3	1.828	1.885	1.922	1.947	1.970	1.984	2.013
Volume of permeable pore space %	0.735	0.674	0.633	0.610	0.618	0.601	0.546

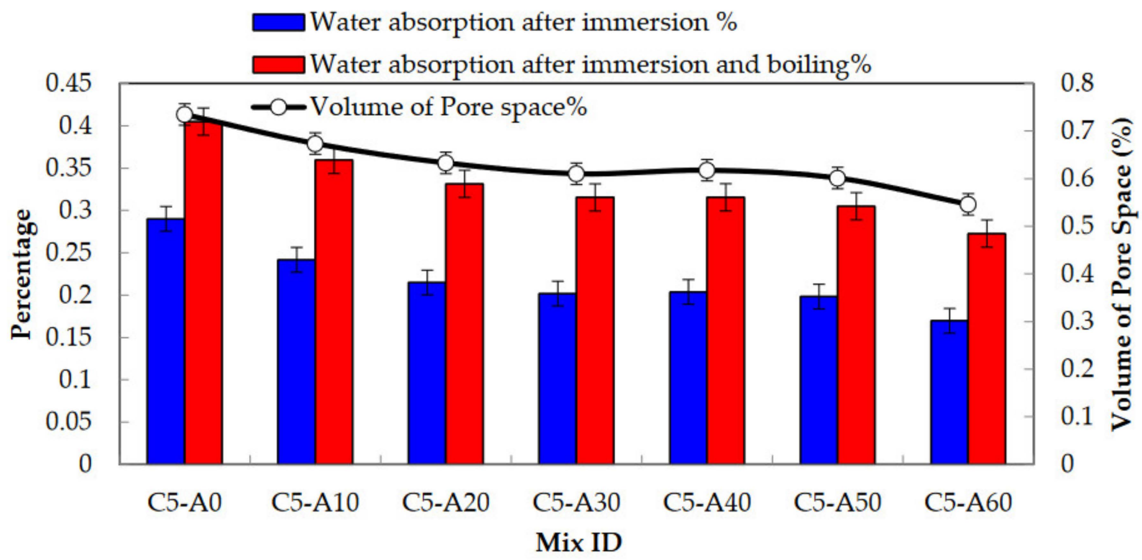


Figure 15. Water absorption and pore space percentage of SCC mixes.

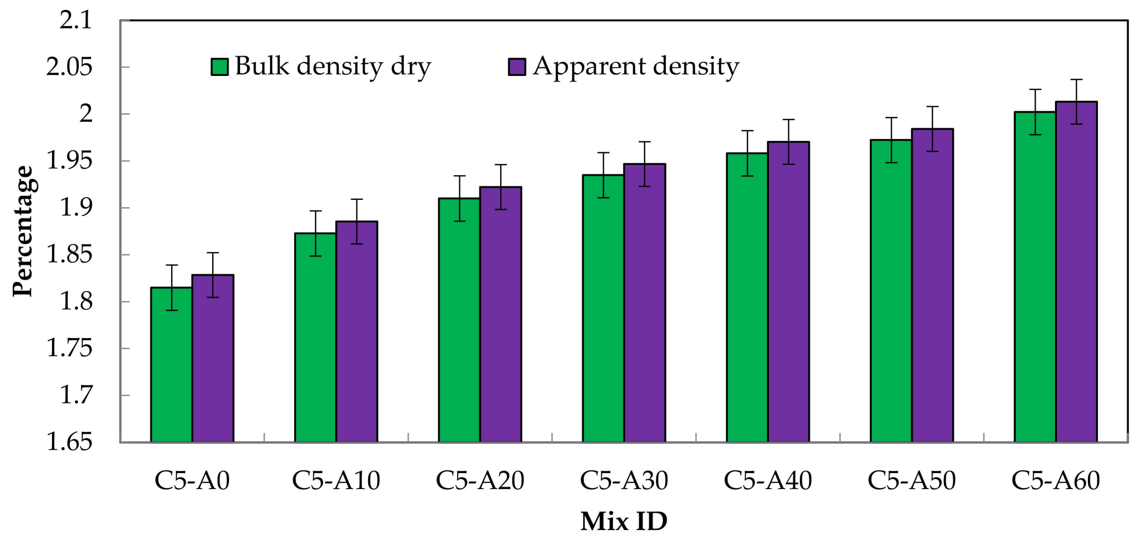


Figure 16. Density variations of SCC mixes.

3.5. Sorptivity Test

Capillary absorption is the movement of liquids through unsaturated porous materials owing to exterior tension acting on capillaries. Researchers examined the sorptivity of several SCC mixes in contrast to CVC of a related strength grade to scientifically analyze the capillary inclusion of SCC mixes of varied compositions and strengths [48]. Sorptivity is a measure of dampness transfer into unsaturated materials, and it has lately been acknowledged as an essential sign of concrete durability [52]. Sorptivity testing is also more accurate in simulating real field circumstances. The approach, according to some experts, may also be used to calculate the total pore volume of capillary and gel pores in concrete [53]. The test results for this test are graphically plotted in Figure 17. The graph is plotted for the absorption (I) and the square root of time ($s^{1/2}$) using the primary rate of water absorption that is observed for the duration of 1 min to 6 h. The initial rate of water absorption is defined as the regression line that fits best when plotted against the square root of time. The slope values (sorptivity-S) are obtained using linear regression analysis of the plot, and the values follow the linear relationship based on the references [54,55]. From the graph, it can be observed that incorporation of an increased percentage of alccofine reduced the sorptivity. Because of the dispersion effect of the superplasticizer and the packing of particles by the extra fine fillers, the improved pore structure would lower sorptivity. The values of the initial rate of water absorption (S_i) and the correlation coefficient (R^2) are obtained for all mixes from the graph that are displayed in Table 7. The values of S_i varied between 0.004 and 0.016, and R^2 varied between 0.98 and 0.99. In ASTM C1585-13, it is given that the correlation coefficient value of less than 0.98 cannot be used to find the initial rate of absorption. Generally, the variation in sorptivity may be due to many factors like mix proportions, use of chemical admixture and SCMs, composition and physical characteristics, air content, curing, degree of hydration, presence of cracks and casting method [25].

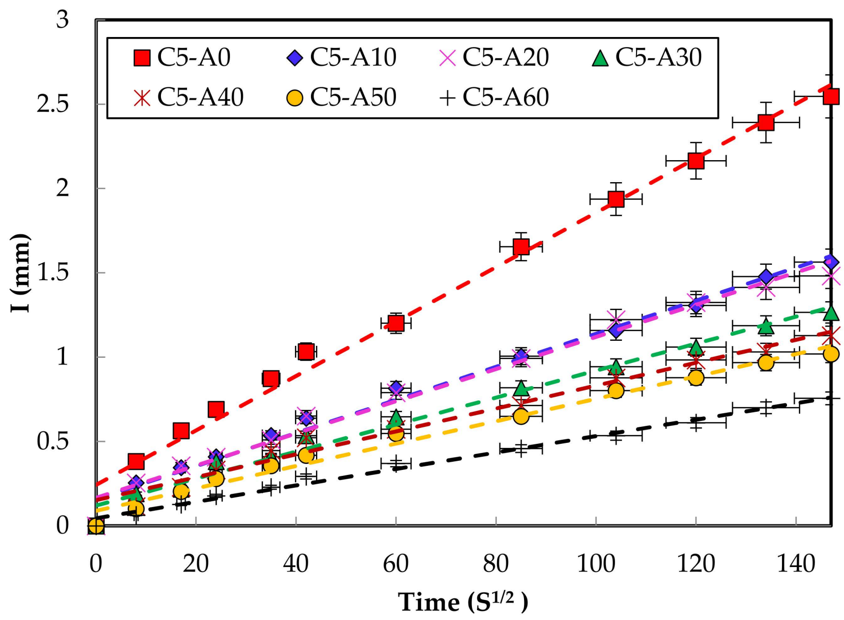


Figure 17. Initial rate of absorption of SCC mixes.

Table 7. Sorptivity results of SCC mixes.

Description	Mix ID						
	C5-A0	**C5-A10**	**C5-A20**	**C5-A30**	**C5-A40**	**C5-A50**	**C5-A60**
Initial rate of absorption ($mm/s^{1/2}$)	0.016	0.009	0.009	0.008	0.006	0.006	0.004
Correlation coefficient R^2	0.99	0.99	0.98	0.98	0.98	0.98	0.99

Based on the findings of permeation characteristics, it was observed that the mix C5-A60 had less water absorption and sorptivity compared to other mixes due to the presence of more fineness of alccofine. The presence of a higher amount (beyond 30%) of alccofine could reduce the pore space, but effective hydration was not achieved since the excess amount of alccofine acted as filler only instead of being a binder. When compared to the conventional mix, all the alccofine-based mixes showed better performance. However, the excess filler material could control only the permeability but could not contribute to strength improvement.

3.6. Sulphate Resistance Test

Sulphate attack can cause concrete to expand, crack, lose strength, and disintegrate. Sulphate attack is caused by sulphate ions reacting with calcium aluminate hydrate and calcium hydroxide to produce ettringite and gypsum. Ettringite production results in an increase in solid volume, which causes expansion, fracturing, and weight loss, especially while restricted. Gypsum progress can cause softening and a reduction in weight and strength. The percentage of strength loss and weight loss of all the mixes after the examination of this test is represented as a bar chart and line graph, which is shown in Figure 18. From the test findings, it is observed that the percentage of weight loss had variation between 0.22 to 1.89 and 0.29 to 1.98 for 28 days and 56 days, respectively, and the percentage of strength loss had variation between 1.3 to 6.8 and 10.9 to 16.1 for 28 days and 56 days, respectively. The reduction in compressive strength is listed in Table 8. All the alccofine-based mixes had lower weight reduction and strength reduction when compared to the conventional mix. The lower reduction in alccofine mixes was due to pozzolanic processes that utilize calcium hydroxide, rendering it unavailable to combine with sulphate to form ettringite, as well as decreased permeability, which helped to prevent harmful sulphate ions from penetrating the concrete. Mineral admixtures, in general, can reduce the effect of sulphate attack [56,57]. The higher reduction in the conventional mix was due to more permeability since there were no additional fillers, resulting in the passage of more sulphate ions into it. $MgSO_4$ solutions have been shown to be more aggressive on cement paste because they can attack and dissolve calcium silicate hydrates, C-S-H, as well as aluminate phases [58].

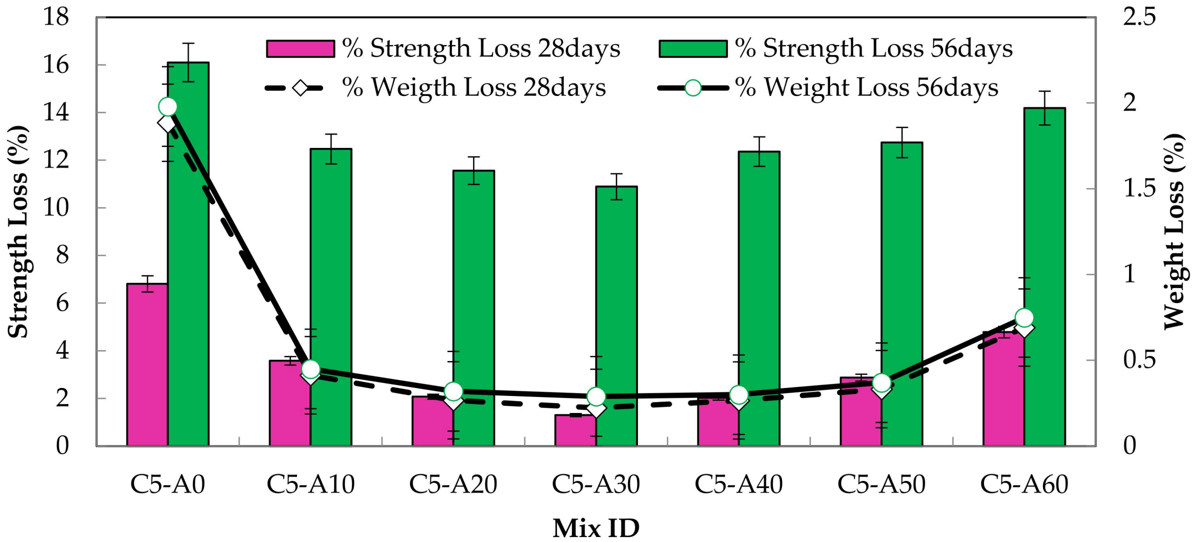


Figure 18. Percentage of strength and weight loss due to sulphate attack.

Table 8. Compressive strength after sulphate attack (N/mm^2).

Description	Mix ID						
	C5-A0	C5-A10	C5-A20	C5-A30	C5-A40	C5-A50	C5-A60
$MgSO_4$ Solution at 28 days	28.60	32.87	44.85	47.51	42.96	36.17	33.02
$MgSO_4$ Solution at 56 days	25.75	29.84	40.48	42.93	38.42	32.47	29.76

3.7. Acid Resistance Test

An acid resistance test is performed with the hydrochloric acid solution and the change in weight loss and strength loss after 28 days and 56 days of immersion are displayed as a percentage in Figure 19. From the test findings, it is observed that the percentage of weight loss had a variation between 7.2 to 11.7 and 16.1 to 23.3 for 28 days and 56 days, respectively, and the percentage of strength loss had variation between 9 to 17 and 21.5 to 29.6 for 28 days and 56 days, respectively. The reduction in compressive strength is listed in Table 9. In that, the conventional mix C5-A0 was more affected by the HCl solution compared to other mixes. This is due to the formation of calcium chlorides, particularly water-soluble salts, as a result of the reaction of HCl with cement, which is more significant in the occurrence of calcium-containing fillers. The occurrence of a high calcium concentration enhances cement's (OPC 53) ability to absorb more hydrochloric acid [59,60]. In the alccofine-based SCC blends, the mix C5-A30 was found to be better in acid resistance. This is due to the incorporation of an optimum dosage of alccofine in SCC that could reduce the size of capillary pores through the better formation of C-S-H gel as a result of improved hydration, thus reducing the acid attack. A similar observable fact was found with the natural pozzolans in SCC [61]. At the same time, the rich fineness of the alccofine also enhances the acid's aggressiveness in leaching the paste quickly, especially on the exposed surface of the cube, thus resulting in more weight loss and strength loss (beyond 30%). Another reason for the loss in weight and strength was that the main hydrated products such as calcium, silica, and alumina were leached away by the low pH value of HCL and deteriorated easily.

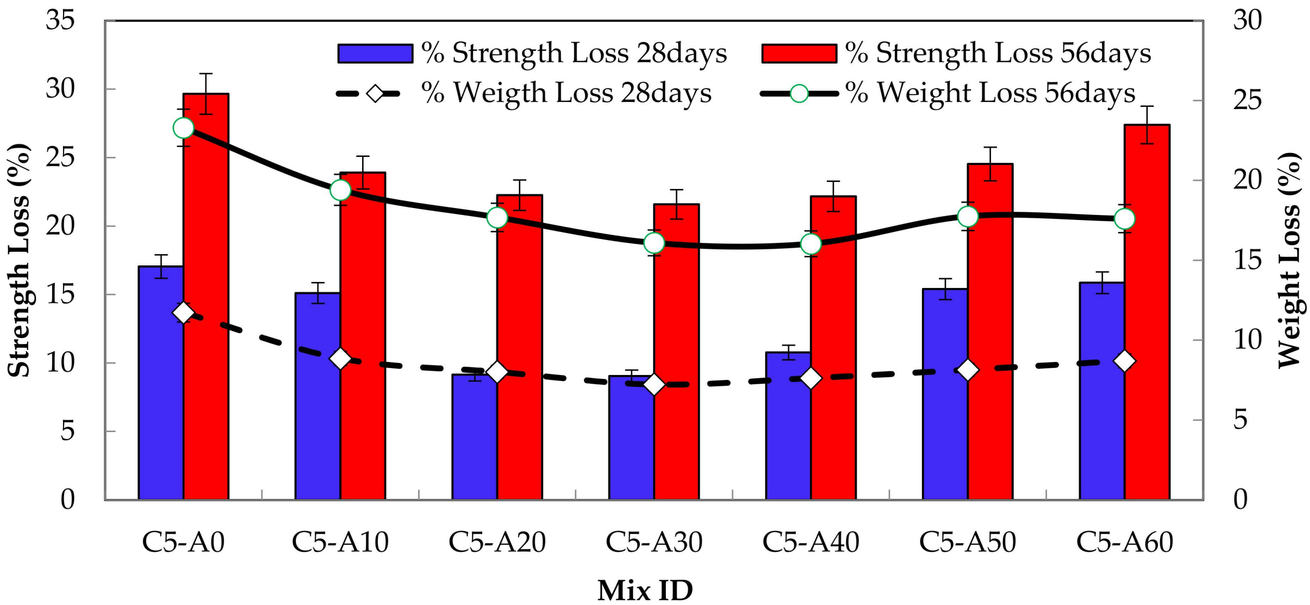


Figure 19. Percentage of strength and weight loss due to acid attack.

Table 9. Compressive strength after acid attack(N/mm^2).

Description	Mix ID						
	C5-A0	**C5-A10**	**C5-A20**	**C5-A30**	**C5-A40**	**C5-A50**	**C5-A60**
HCl Solution at 28 days	25.46	28.94	41.58	43.78	39.12	31.48	29.18
HCl Solution at 56 days	21.59	25.94	35.58	37.74	34.12	28.08	25.18

4. Conclusions

This experimental work was carried out to determine the fresh and hardened characteristics of SCC with varying percentages of alccofine from 0% to 60%. Based on the findings, the following conclusions were made:

- The fresh properties of alccofine-based SCC mixes are increased from 10 to 30% due to the enhanced lubrication effect for the selected W/B ratio and SP dosage. However, it has considerably decreased from 40 to 60% due to the superior surface area produced by slag addition and increased water demand;
- The mechanical properties are gradually increased for the mixes C5-A10 to C5-A30 and decreased further. The increase in strength is due to the increased total specific surface area, denser particle packing, and high pozzolanic reactivity that resulted in an enhanced hydration process. The occurrence of a higher amount of calcium, silica, and alumina in alccofine is one reason for the enhancement of the compressive strength;
- The improved flexural strength and Young's modulus of concrete are due to its pozzolanic reaction, which improved the bond between binder material and aggregate and resulted in improved strength at the Interfacial Transition Zone;
- The water absorption percentage, voids, and sorptivity of the mixes C5-A0 to C5-A60 are decreased gradually. The increase in the replacement percentage of alccofine in the SCC mix considerably reduced water absorption capacity, voids, and sorptivity due to the presence of rich fineness, which leads to fewer pores and higher density in the concrete;
- The percentage of strength loss for the mixes C5-A0 to C5-A30 is gradually reduced for sulphate and acid resistance tests, respectively. Furthermore, it is increased for C5-A40 to C5-A60. Overall, the mix C5-A30 showed better resistance against chemicals in the durability examination. This enhanced resistance is due to lower permeability, better formation of C-S-H gel by improved hydration, and a reduction in the size of capillary pores.

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