

2025

Synergistic Effect of Alccofine as Partial Replacement of Cement and M-Sand as Sand Substitution in Concrete for the Assessment of Mechanical and Microstructural Properties

Yellinedi Madhavi

Research Scholar, Department of Civil & Structural Engineering, Annamalai University, Chidambaram-608001, Tamil Nadu, India, ymadhavi@rvrjc.ac.in

R.S. Ravichandran

Department of Civil & Structural Engineering, Annamalai University, Chidambaram-608001, Tamil Nadu, India, rsravichandran5589@gmail.com

J. Saravanan

Department of Civil & Structural Engineering, Annamalai University, Chidambaram-608001, Tamil Nadu, India, ausjs5070@gmail.com

N. VenkataSairam Kumar

Follow this and additional Works at: <https://commons.yildiz.edu.tr/jscmt>

Department of Civil Engineering, R.V.R & J.C College of Engineering, Guntur-522019, Andhra Pradesh, India, nvsairam52@gmail.com

 [ORCID](#), [ResearchGate](#), [Scopus](#), [Crossref](#), [Chemical Engineering Commons](#), [Civil and Environmental Engineering Commons](#), [Engineering Science and Materials Commons](#), [Materials Science and Engineering Commons](#), [Mechanical Engineering Commons](#), and the [Molecular, Cellular, and Tissue Engineering Commons](#)

Recommended Citation

Madhavi, Yellinedi; Ravichandran, R.S.; Saravanan, J.; and Kumar, N. VenkataSairam (2025) "Synergistic Effect of Alccofine as Partial Replacement of Cement and M-Sand as Sand Substitution in Concrete for the Assessment of Mechanical and Microstructural Properties," *Journal of Sustainable Construction Materials and Technologies*: Vol. 10: Iss. 2, Article 3.

<https://doi.org/10.29187/2458-973X.1181>

Available at: <https://commons.yildiz.edu.tr/jscmt/vol10/iss2/3>

This Research Article is brought to you for free and open access by YTU Press. It has been accepted for inclusion in *Journal of Sustainable Construction Materials and Technologies* by an authorized editor of YTU Press.



RESEARCH ARTICLE

Synergistic Effect of Alccofine as Partial Replacement of Cement and M-Sand as Sand Substitution in Concrete for the Assessment of Mechanical and Microstructural Properties

Yellinedi Madhavi^{a,*}, R.S. Ravichandran^b, J. Saravanan^b,
N. VenkataSairam Kumar^c

^a Research Scholar, Department of Civil & Structural Engineering, Annamalai University, Chidambaram-608001, Tamil Nadu, India

^b Department of Civil & Structural Engineering, Annamalai University, Chidambaram-608001, Tamil Nadu, India

^c Department of Civil Engineering, R.V.R & J.C College of Engineering, Guntur-522019, Andhra Pradesh, India

ABSTRACT

Using supplementary cementitious materials (SCMs) and traditional binder mass has revolutionized concrete production technology in the building industry. This study examines how Alccofine-1203 affects the microstructure and mechanical characteristics of concrete. The mechanical qualities of the mixtures were evaluated using six different mixes prepared for each M25 and M40 Grade. In the proposed mixes, cement is substituted with alccofine at 0 to 25% and M-Sand as fine aggregate. The Compressive strength and ultrasonic pulse velocity were assessed after 3, 7, 14, 28, 56, and 90 days of curing, and split tensile strength and flexure strength were evaluated after 28 and 90 days of curing. The samples prepared for SEM, EDS, and XRD tests were carried out to investigate the microstructure of the concrete matrix of M25 and M40 mixes after 28 days of curing. At the replacement level of AF20%, the 28-day compressive, split tensile, and flexural strength for M25 and M40 mixes are recorded as 40.44 MPa and 61.65 MPa, 3.18 MPa and 5.38 MPa, 4.93 MPa and 7.25 MPa, respectively. The quality of concrete is excellent for the replacement levels of M25-AF% and M40-AF% mixes. XRD analysis revealed a high concentration of Anorthite, Portlandite, and Quartz peaks. Concrete mixes containing 20% alccofine exhibited a more compact, resilient matrix and dense C-S-H gel formation, which is responsible for the improvement in strength properties of the mixes, was observed using scanning electron microscopy and energy dispersive spectroscopy (EDS).

Keywords: Alccofine, M-Sand, Mechanical properties, Scanning electron microscope, Energy dispersive spectroscopy (EDS), X-ray diffraction (XRD)

1. Introduction

Cement-related products are the most essential building materials. Concrete is often the most significant material element in the natural building environment. With increasing population and urbanization, the need for cement rises significantly [1–4]. Global concrete usage as a building material

is second only to water, spurring massive cement production, anticipated at approximately 5.2 billion metric tonnes in 2019. According to data, India's cement demand will exceed 550 million tonnes by 2030, with a 230 million tonne deficit. Approximately 94.76×10^6 Joules/ton of cement manufacturing contributes 5 to 7% of total CO₂ emissions, a major contributor to climate change [4]. Ordinary Portland

Received 2 December 2024; revised 24 March 2025; accepted 15 April 2025.
Available online 30 June 2025

* Corresponding author.

E-mail addresses: ymadhavi@rvjc.ac.in (Y. Madhavi), rsravichandran5589@gmail.com (R.S. Ravichandran), ausjs5070@gmail.com (J. Saravanan), sairam852@gmail.com (N. VenkataSairam Kumar).

<https://doi.org/10.29187/2458-973X.1181>

2458-973X/© 2025 Published by Yıldız Technical University Press, İstanbul, Türkiye. This is an open access article under the CC BY-NC 4.0 Licence (<https://creativecommons.org/licenses/by-nc/4.0/>).

Cement, also called OPC, manufacturing is predicted to use five percent of the world's natural resources and contribute to 1.35 billion tonnes, or 5–7% of the annual emissions of greenhouse gases [5, 6]. The cement industry is the second-largest emitter of greenhouse gases, specifically carbon dioxide (CO₂). Global cement production is predicted to reach over 4.38 billion tonnes by 2050, with a 5% annual growth rate [6]. With the fast expansion of infrastructure, cement utilization is inevitable. The construction industry needs to find a different, less harmful source of binding material for concrete to meet future demand and create a sustainable environment [7–9].

For the industries, it is not feasible to safely dispose of industrial wastes such as fly ash, silica fume, red mud, rice-husk ash, mining waste, Alccofine (AF), Ground granulated blast-furnace slag (GGBFs), and Metakaolin (MK). Green concrete may be produced using industrial wastes either as an addition to cement or as a substitute [10, 11]. Industrial by-products are produced annually, and landfills in the nearby fields contaminate the surroundings and water supplies [12–14]. Recent research has shown that Alccofine (AF), a microfine material generated from the iron ore industry in India, has pozzolanic properties and may be used as a partial substitute for cement in concrete [15]. Due to the overuse of natural resources, natural aggregates are rare worldwide, but the resulting shortage has raised building costs. The manufactured sand (M-Sand) has been researched in several directions for possible use in concrete. M-Sand is affordable and environmentally favorable, unlike real river sand. Since the produced sand is less expensive than river sand, the processing costs benefit more. The M-Sand particles are rough, angular, rounded, cubic, and have a smooth surface. However, additional cement may be required for M-Sand concrete to exhibit suitable workability. When M-Sand is added to concrete, its micro-fine particles improve its workability, strength, and durability. M-Sand has created high-strength and durable concrete [16].

Devinder Sharma et al. investigated how concrete's strength could be increased by partially substituting cement and fine aggregate with Alccofine (AF) and Foundry Slag (FD), respectively. Concrete specimens of the M100 grade were cast and tested at 7, 14, 28, 56, and 90 days to ascertain compressive, tensile, and flexural strength improvement. The percentage of FD varied from 0% to 50%, and the water/binder ratio was 0.239. The optimal percentage of AF was found to be 15%. When fine aggregates were substituted with up to 45% FD, CS, FS, and TS increased across all ages. However, these properties decreased when 50%

of FD was used. Based on the findings, high-strength concrete can be made using 10% to 45% FD as a fine aggregate substitute and 15% Alccofine as a cement substitute. Carbonation was also investigated using the alkalinity and rapid chloride permeability tests. The findings showed that at an optimal 15% substitution of alccofine for cement, the rise in FD levels increased the concrete's permeability and alkalinity [15]. K Thangapandiet et al examined the strength and behavior of alccofine and zinc oxide-containing manufactured sand concrete under extreme conditions, primarily emphasizing durability performance. The mixture was supplemented with 10% alccofine and 2% zinc oxide by weight of cement, respectively. Various percentages of manufactured sand (25, 50, 75, and 100 percent) replaced the natural river sand. The concrete compressive strength, flexural strength, and split tensile strength were determined following the conventional curing procedures. The concrete was also subjected to durability tests, including exposure to acid, seawater, sulphate attack, water absorption, rapid chloride penetration, and water permeability. The combination, including 0.5% Zinc Oxide Replacement, 50% M Sand, and 10% Alccofine, showed better durability than the others [16]. Bharat Bhushan Jindal et al. investigated the geopolymer concrete by adding fly ash, different proportions of alccofine, and sodium hydroxide, a sodium silicate-based alkaline activator. The concrete was then kept at ambient and high temperatures in an electric oven set at 90°C. This study examined the factors influencing geopolymer concrete's workability and compressive strength. These factors included the fly ash content, the curing temperatures, the curing time, and the percentage of alccofine. According to study findings, using alccofine in geopolymer concrete improves its properties both in its fresh and cured state. Alccofine generally enables geopolymer concrete to achieve compressive strength even at room temperature [17]. P. Narasimha Reddy et al. investigated the impact of incorporating calcium nitrate and the non-chloride hardening accelerator on the mechanical properties and durability of alccofine concrete. Concrete mixes were enhanced with a non-chloride accelerator at 0.65%, 0.85%, and 1.05% concentrations by cement weight. A reference concrete without the non-chloride accelerator was compared to evaluate the impact on alccofine concrete. Using an accelerator resulted in early-age strength improvements owing to the accelerated hydration of the phases of C3S and C3A. The non-chloride accelerator greatly improved the ability of the alccofine concrete to absorb water and withstand sulphates. A statistical technique predicts the empirical values belonging to concrete compressive strength.

The experimental data set was optimized using response surface methods, which involved developing an equation for regression that linked the input and response variables. This approach successfully predicted the experimental results with an acceptable margin of error. The results demonstrated a strong fit when the anticipated values were verified using the regression coefficient value and residual sum of squares. The study's findings demonstrated the inclusion of non-chloride hardening agents [18]. Saravanan J et al [19]. Investigated the compressive strength variance between river sand and Indian standard sand. Portland Pozzolana Cements (PPC) and Ordinary Portland Cement (OPC) are used. A further investigation into the effects of alccofine was carried out by replacing cement with alccofine in various quantities, including 5%, 10%, 15%, and 20%. The compressive strength of cement is determined by casting cubes with an area of 50 cm² using cement mortar with a 1:3 mix proportion, as per IS: 4031-1988 (Part-6 sand (Ennore Sand -ES). The cubes are manufactured using graded Indian Standard sand, also known as Ennore Sand -ES, which satisfies the requirements outlined in the Indian Standard 650-1991. To examine the difference in strength at compression between river sand and Indian standard sand, cubes of the same size are cast with the same mix proportion of river sand (RS). The laboratory test was conducted following Indian Standard 4301-1988 (Part 6) to determine the impact of Alccofine on cement mortar cubes. The results of the study were analyzed and presented through charts and diagrams. It was found that all combinations achieved early strength, but the strength of 10% Alccofine is greater than that of other concentrations [19]. Alccofine is an additive substance that can improve SCC properties while reducing the environmental impact of Portland cement production. This study examined the fresh, strength & durability characteristics of SCC by substituting with different percentages of alccofine (0%, 10%, 20%, 30%, 40%, 50%, and 60%) in cement. The fresh characteristics are evaluated utilizing slump flow, T50, V-funnel & L-box. The mechanical and durability characteristics, including its modulus of rupture, compressive strength test, water absorption, acid resistance, sorptivity, and sulphate resistance, were analyzed and contrasted with traditional SCC. Compared to other mixes, the results showed that the 30% alccofine substitution performed better in strength and durability [20]. Bharat Bhushan Jindal studied the effects of various mineral admixtures on the mechanical, durability, and microstructure properties of geopolymer concrete and mortar. The investigation results showed that, at room temperature, the mechanical properties

and durability qualities of geopolymer products, including these elements, were greatly improved. The findings imply that mineral compounds can create geopolymer combinations with the desired qualities under ambient temperature curing conditions, which could further advance their use as an eco-friendly building material [21]. Parveen et al. examined the characteristics of fly ash-based geopolymer concrete that included alccofine at room temperature. The binder was composed entirely of raw refuse material. As per Indian Standards, the workability, compressive, fracturing, tensile, flexural strengths, and water absorption of alccofine-activated geopolymer concrete have been investigated in its fresh and hardened stages. The prepared cubes' phase, composition, and microstructural properties were determined using X-ray diffraction (XRD) and scanning electron microscopy (SEM). The results suggested that the characteristics of geopolymer-based concrete produced with alccofine at the ambient temperature are significantly improved, but also recommended for use as a substitute for conventional concrete. At ambient temperature, the results indicated that the qualities of geopolymer-based concrete made with alccofine are greatly enhanced. Furthermore, it was recommended that this concrete be used as an alternative to traditional concrete. In addition, samples of geopolymer-concrete that have been produced with alccofine were made to check the densification process. The findings of this study show that alccofine has a major impact on the polymerization of geopolymer concrete, enhancing its strength and microstructural characteristics. In addition, the strength of all tested specimens was enhanced by the increased molarity and fly ash content [22]. BLN SaiSrinath et al. investigated the right use of alccofine for concrete compositions of all grades, including M20, M30, and M40. The strength of hardened concrete was tested for 5%, 10%, 15%, and 20% cement replacement with Alccofine. All of the design combinations established the acceptance criteria of test results. The highest test results were achieved for all the mixes when 15% of Alccofine was substituted. It was unexpected that the 28-day strength of M20 grade concrete was attained in the seven-day curing test results. According to the results, the Alccofine material might lower the level of carbon dioxide released into the air and the use of cement [23]. Wenkai Shen et al. [26] observed the performance of MS concrete during long-distance pumping and compared it to RS concrete of the same strength grade. Using a 348-m coiled pipeline for 12 batches of C30 and C60 concrete, pumping experiments were carried out at 2.5–18.9 liters per second. MS enhanced C30 concrete strength and lowered the thickness index, decreasing the C60

Table 1. Chemical composition of binders in %.

Materials	Cao	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	K ₂ O	MgO	Na ₂ O	Others
Cement	66.56	20.23	4.78	3.61	0.28	1.39	0.33	2.8
Alccofine	32.3	35.2	22.45	1.82	-	6.1	-	1.36

concrete viscosity coefficient. No predominant variation was observed between MS and RS concrete after pumping, but MS concrete showed less change in its plastic viscosity. MS did not substantially impact the loss of pumping pressure, but it did affect the variation in pumping pressure predictions via altering thixotropy.

As a result of the above background, this study aims to conduct an experimental investigation to confirm the possibility of developing environmentally friendly concrete by partially replacing cement with alccofine and M-Sand as fine aggregate. In this context, an effort was made to investigate the mechanical and microstructural properties of concrete using alccofine in conjunction with M-Sand to create an environmentally friendly concrete (EFC) that is sustainable.

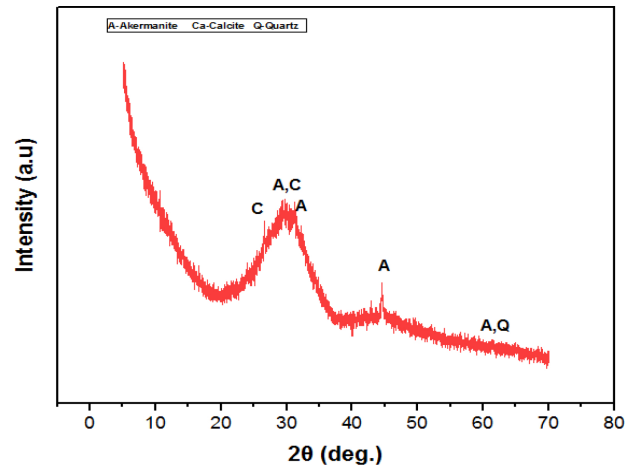
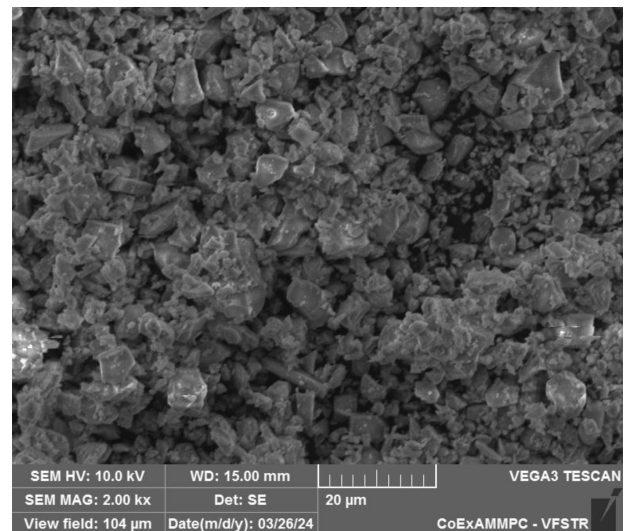
2. Materials and methods

2.1. Materials

Ordinary Portland cement 53 grade was used for all samples following IS:12269:1987 [29]. Alccofine(AF) is derived from blast furnace-based ultrafine slag with calcium silicate that has high reactivity. Alccofine has smaller particles than cement, fly ash, silica, etc. Alccofine reduces water use through controlled granulation and promotes workability while regulating high reactivity. Table 1 shows the chemical composition of binders. Table 2 represents the physical properties of binders for the study. Fig. 1 represents the XRD image of the Alccofine sample. The XRD image shows calcite as the primary phase and trace quantities of Akermanite and Quartz. Fig. 2 represents the SEM image of the Alccofine sample. Fig. 3 represents the EDS of the Alccofine sample. Crushed rocks readily available in the locality and having a specific gravity of 2.8 were utilized as coarse aggregate sizes of 20 mm and 12 mm. In contrast, M-Sand was used as fine aggregate in compliance with IS:383–2016 [30]. Table 3 represents the physical properties of aggregates for the study. Fig. 4 represents grading curves of M-Sand and coarse aggregate. According to IS 9103–1999 [31], a superplasticizer composed of polycarboxylic ether was utilized for the study. Portable water without chemicals and free from organic material is used to prepare the concrete matrix as per IS 456–2000 [32].

Table 2. Physical properties of the binder.

Item	Cement	Alccofine
Specific gravity	3.15	2.85
Colour	Grey	Grey
Average particle size(um)	90	6
Specific surface area(m ² /kg)	225	120

**Fig. 1.** XRD sample of alccofine.**Fig. 2.** SEM image of alccofine.

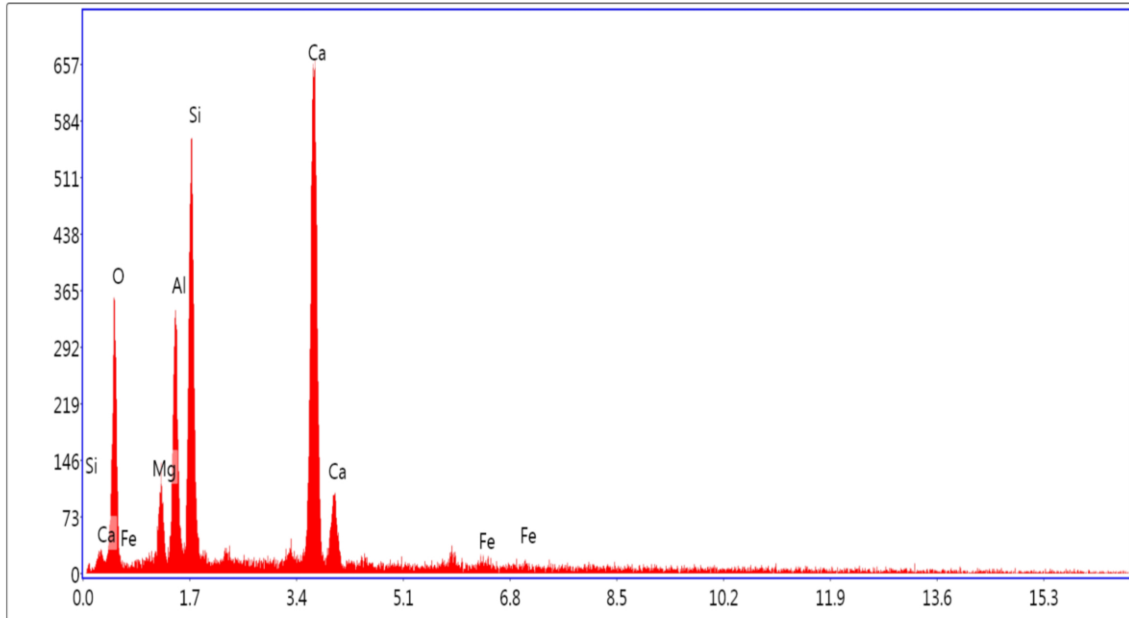
2.2. Methods

2.2.1. Methodology

To develop environmentally friendly concrete samples (EFC) that are sustainable, including using

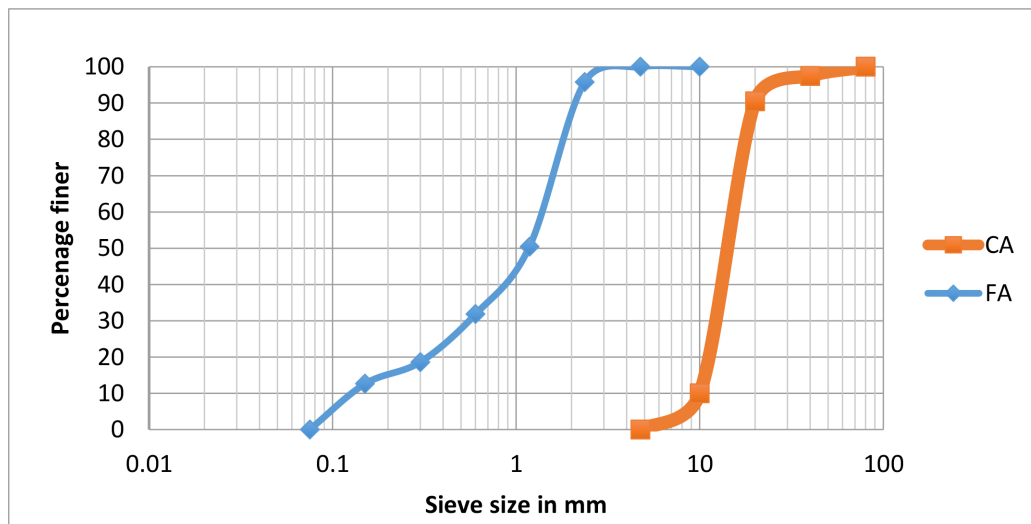
Table 3. Physical properties of aggregate.

Item	Specific gravity	Fineness modulus	Bulk Density (g/cu.cm)
Fine aggregate (M-Sand)	2.7	2.91	1.9
Coarse aggregate	2.8	6.86	1.7

**Fig. 3.** EDS of alccofine.

Alccofine to replace cement partly, and M-Sand to substitute sand. To investigate the influence of the inclusion of alccofine on the mechanical and microstructural qualities of concrete (M25 and M40) mixes, six different percentages (0, 5, 10, 15, 20, and

25%) of alccofine was used to partly replace the cement in the control mix that has 100% cement, 0% alccofine, and 100% M-Sand. An explanation of the EFC sample production process is presented in a flow chart, which may be seen in Fig. 5.

**Fig. 4.** Grading of curves of fine aggregate (M-Sand) and coarse aggregate.

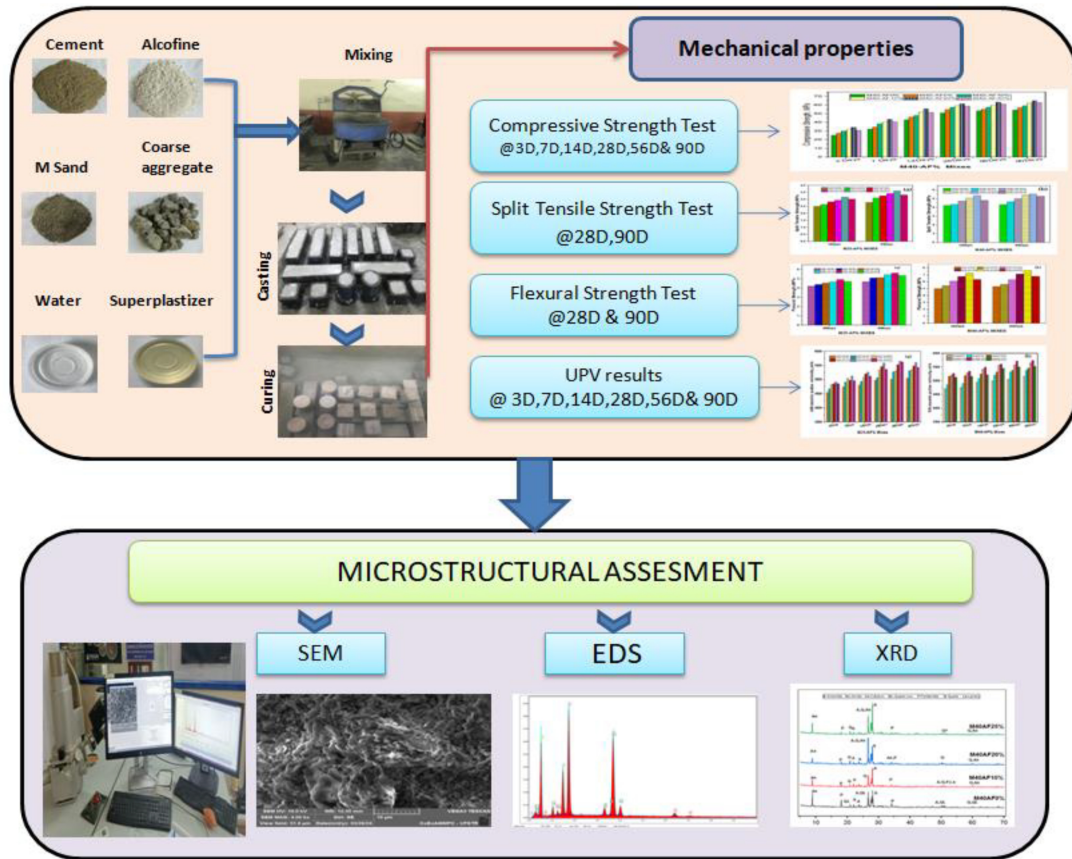


Fig. 5. Methodology of M25 & M40 concrete matrix.

2.2.2. Mix design and preparation

According to the concrete mix proportion criteria outlined in IS 10262–2019 [33], a mix design was developed for the M25 and M40 grades as shown in Table 4. Cement was partially replaced with alccofine. This study aimed to investigate the effects of alccofine incorporation on concrete's mechanical and microstructural characteristics by partly substituting cement in the control mix with six different percentages of alccofine (0, 5, 10, 15, 20, and 25%). Three identical specimens were analyzed for each mixture to evaluate the mechanical characteristics, and the average of the findings is shown. The control mix, M25-AF0% for the M25 grade and M40-AF0% for the M40 grade, had 100% M-Sand, 100% cement, and 0% alccofine. M25-AF5% for M25 grade and M40-AF5% for M40 grade represent 100% M-Sand and the alccofine replacement at 5%. Similarly, along with 100% M-Sand, cement replacement is carried out up to the alccofine 25%, which is denoted as M25-AF25% for M25 grade and M40-AF25% for M40 grade. The concrete was mixed following the parameters specified in IS 456–2000 [32]. Mixing was done with the help of a concrete mixer. At first, coarse and

fine aggregates are added into the mixer and mixed in a dry state. Then the components of the binder were mixed individually until they reached a colour that was consistent throughout. After that, they were moved to the concrete mixer, where they received further mixing for an additional minute. After thirty seconds of mixing, the dry mixer was given half of the water that had been measured. To guarantee that the combination was consistent and had the necessary level of workability, superplasticizer was added to the remaining water, then transferred to the wet mixture, and stirred for an additional sixty seconds. The mix was then transferred to the molds, which were prepared for casting specimens by applying oil onto the surface. The molds are subjected to vibration with the help of a table vibrator. Following 24 hours of casting, specimens were demoulded and cured in water at $27 \pm 2^\circ\text{C}$ until the test age.

2.2.3. Fresh and hardened concrete tests

To evaluate the impact of Alccofine and M-Sand on concrete, the Slump cone test, by IS 1199–1959 [34], was conducted to determine the workability

Table 4. Mix proportions of mixes in (kg/Cu. m).

Mix Id	Cement	M-Sand	Aggregate (20 mm)	Aggregate (12 mm)	Water	SP
M25	335.00	740.75	798.40	532.27	144.05	—
M40	380.00	703.24	791.56	527.71	144.44	3.80

**Fig. 6.** Hardened test of UTM mixes: (a) CPS, (b) STS, and (c) FTS.

of concrete. **Fig. 6** represents the hardened testing machines using the UTM for mixes. A compression testing machine (CTM) with a capacity of 2000kN was used to examine the mechanical characteristics of hardened concrete. According to IS 516–2015 [35], tests were conducted on 100mm × 100mm × 100 mm size specimens for compressive strength test (CPS) at 3,7,14,28,56 and 90 days curing and 500mm × 100 mm × 100 mm size specimens for flexural strength test (FST) at 28 and 90 days curing. The cylindrical specimens of 200 mm in height and 100 mm in diameter were subjected to split tensile strength (STS) tests after 28 and 90 days of curing. As part of the evaluation of the characteristics of EFC samples, an ultrasonic pulse velocity test is conducted on specimens measuring 100 × 100 × 100 mm at 3, 7, 14, 28, 56, and 90 days after curing as per IS 13311 (Part-1):1992 [36]. A microstructural examination uses X-ray diffraction, scanning electron microscopy, and EDS.

3. Results & discussion

3.1. Effect of alccofine and M-Sand on the workability of EFC samples

For fresh concrete, the workability was measured with a slump cone just after mixing the concrete. The slump cone test was done per IS 1199: 1959

[34]. The slump cone values of environmentally friendly concrete samples (EFC) with different AF% content are represented in **Table 5**. All of the alccofine-based mixes exhibited higher slump cone values than the control mix, and the test results indicated that the workability of EFC is substantially impacted by the partial replacement of the cement with alccofine. By comparing the control mix with the alccofine-included concrete mixes at a pre-determined water-binder ratio and superplasticizer dose, it was shown that the slump cone values increased as the proportion of alccofine increased up to AF20%. The increment of workability is observed for M25-AF% and M40-AF% mixes due to M-Sand as a fine aggregate. Also, alccofine positively influences flowability because of its better particle packing effect.

The cohesiveness of new concrete with aggregate sizes of 12 mm and 20 mm affects homogeneity and enhances the workability of the mixtures, including M-Sand and AF%. The slump first increased to AF20% and thereafter decreased to AF25%. The micro-aggregate filling action of M-Sand, along with the smaller particle size and surface characteristics of alccofine, provides ease of mixing, transporting, placing, and compacting concrete, without segregation and bleeding, which imparts the strength and durability to the concrete mixes [23–28].

Table 5. Slump cone values of M25-AF% and M40-AF% mixes, in mm.

Mix Id	M25-AF0%	M25-AF5%	M25-AF10%	M25-AF15%	M25-AF20%	M25-AF25%
Slump cone values, mm	76	77	80	81	85	82
Mix Id	M40-AF0%	M40-AF5%	M40-AF10%	M40-AF15%	M40-AF20%	M40-AF25%
Slump cone values, mm	74	75	78	80	81	76

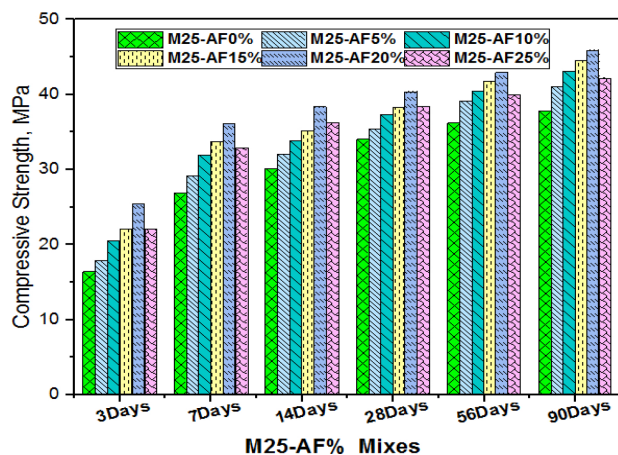


Fig. 7. Compressive strength of M25-AF% mixes at different curing ages.

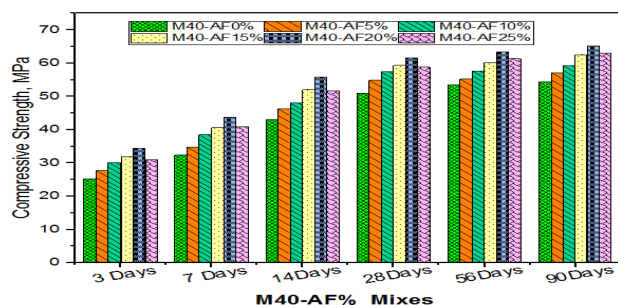


Fig. 8. Compressive strength of M40-AF% mixes at different curing ages.

3.2. Effect of alccofine and M-Sand in CPS test of EFC samples.

The findings of the tests performed for M25-AF% and M40-AF% concrete compressive strength at various curing ages are shown in Fig. 7 and Fig. 8. Figure .7 displays the range of compressive strength values after curing at 3, 7, 14, 28, 56, and 90 days. The values vary from 16.39 to 25.46 MPa at 3 days, 26.93 to 36.16 MPa at 7 days, 30.18 to 38.4 MPa at 14 days, 34.02 to 40.44 MPa at 28 days, 36.19 to 43.03 MPa at 56 days, and 37.84 to 45.98 MPa at 90 days. Fig. 8 depicts CPS test results variation due to the alccofine percentage (AF%) of various mixtures in M40 grade concrete after different curing durations, namely at 3, 7, 14, 28, 56, and 90 days. The compressive strength values range from 25.2 to 34.43 MPa, 32.38 to 43.71 MPa, 43.05 to 55.88 MPa, 50.92 to 61.65 MPa, 53.47 to 63.46 MPa, and 54.4 to 65.31 MPa, respectively, at 3, 7, 14, 28, 56, and 90 days of curing. The increment of compressive strength in the M25-AF% mixes at 5% replacement of cement with AF are 8.21%, 6.06%, 4.03%, 8.23% and 8.48%, at 10% replacement of cement with AF

are 18.72%, 12.29%, 9.67%, 11.63% and 13.93%, at 15% replacement of cement with AF are 25.44%, 16.70%, 12.52%, 15.58%, and 17.86%, at 20% replacement of cement with AF are 34.27%, 27.24%, 18.87%, 18.90% and 21.51% and at 25% replacement of cement with AF are 22.35%, 20.31%, 13.17%, 10.58% and 11.71 at 7, 14, 28, 56 and 90 days of curing. The increment in the M40-AF% mixes at 5% replacement of cement with AF are 7.32%, 7.50%, 7.72%, 3.22%, and 4.87%, at 10% replacement of cement with AF are 18.75%, 11.57%, 12.59%, 7.63% and 8.79%, at 15% replacement of cement with AF are 25.85%, 20.91%, 16.85%, 12.62% and 15.24%, at 20% replacement of cement with AF are 34.99%, 29.80%, 21.07%, 18.68% and 20.06% and at 25% replacement of cement with AF are 26.34%, 20.33%, 15.67%, 14.85% and 16.10 at 7,14, 28, 56 and 90 days of curing.

Based on the findings of the tests, all the mixes with alccofine exhibited enhanced compressive strengths when compared with the control mix (AF0%). Alccofine, as an alternative to cement, was shown to be suitable for up to AF20%. The increase in strength with AF% mixes pertains to the fine alccofine particles being distributed all over the concrete matrix due to the finer size and exhibiting an arrangement that is sub-round when compared to the cement [37, 38]. Additionally, the ultra-fine particles increase surface area and higher packing density and strengthen the blended cement's ability to react with additional compounds. The increase in reactivity makes it easier for the concrete microstructure to achieve early-age strength [39]. Apart from this, the incorporation of alccofine led to chemical changes in the aluminates and silicates of calcium via the pozzolanic process, which ultimately increased compressive strength. Scanning electron microscope (SEM) demonstrated the existence of a thick and uniform calcium silicate hydrate (C-S-H) gel formation up to AF20%. The unsoundness of the binder, which was caused by an increase in free lime (CaO), alumina (Al_2O_3), and magnesia (MgO), led to excessive expansion and micro-cracks in the concrete during the hydration process, which resulted in the concrete showing lower resistance against compression load. Furthermore, compressive strength was decreased at AF25% [40].

The findings of the mechanical and microstructural behavior of HSC were generated by the partial replacement of cement with different percentages of Alccofine-1203 and 20% fly ash. These percentages included 0%, 4%, 6%, 8%, 12%, and 14% with alccofine-1203. At the 28-day test of alccofine-1203, substituting thirty percent cement with twenty percent fly ash and ten percent alccofine-1203

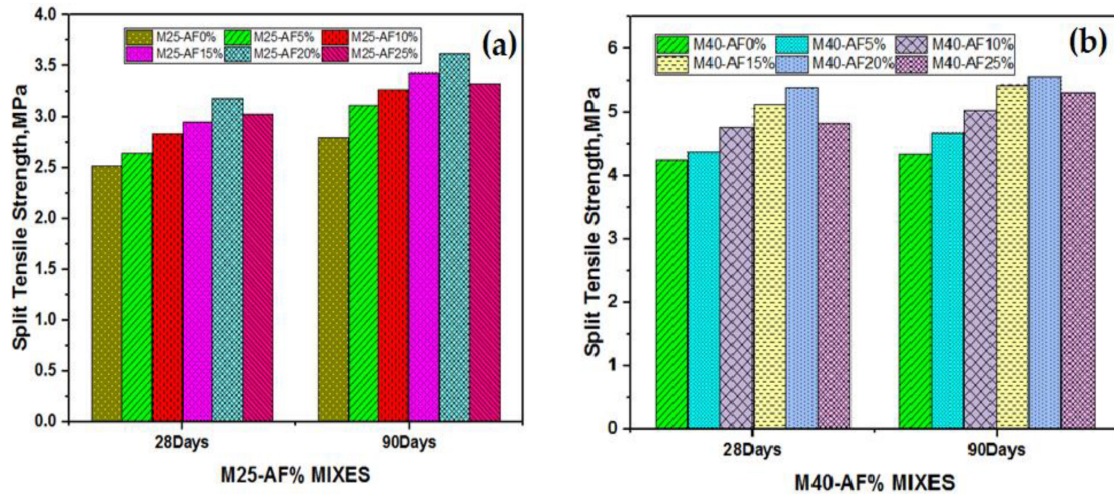


Fig. 9. STS of mixes: (a) M25-AF% mixes, (b) M40-AF% mixes.

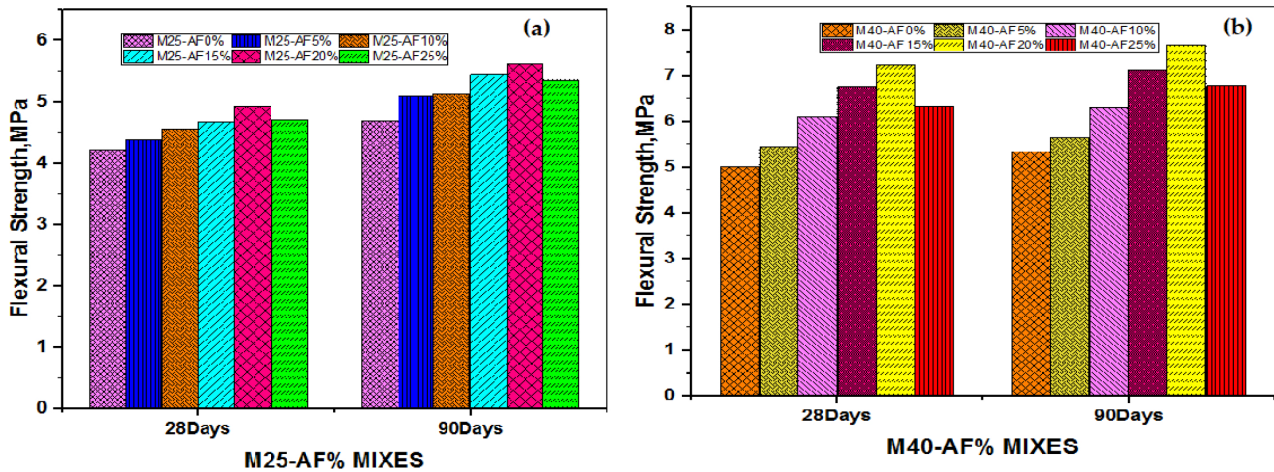


Fig. 10. FTS of mixes: (a) M25-AF% mixes, (b) M40-AF% mixes.

demonstrated the maximum compressive strength of eighty-three megapascals [40].

3.3. Effect of alccofine and M-Sand in STS test of EFC samples

The split strength test results of M25-AF% and M40-AF% concrete mixes at different curing ages are represented in Fig. 9. Fig. 9(a) illustrates the STS test result of AF% of mixes in M25 grade of concrete at 28 and 90 days of curing. Fig. 9(a) shows that split tensile strength values range from 2.52 MPa to 3.18 MPa and 2.8 MPa to 3.62 MPa at 28 and 90 days of curing. Fig. 9(b) represents the STS test result of AF% of mixes in M40 grade of concrete at 28 and 90 days of curing. The split tensile strength values range from 4.25 to 5.38 MPa and 4.34 to 5.56 MPa at 28 and 90 days of curing. The replacement of alccofine

at 0%, 5%, 10%, 15%, 20% and 25% in mixes shows an increment in the strength for M25 mixes at 28 and 90 days as follows: 1.68%, 1.93%, 2%, 2.38%, 2.18% and 2.2%, 2.4%, 2.62%, 2.84%, 2.47% respectively when compared with control mixture (M25-AF0%). The replacement of alccofine at 0%, 5%, 10%, 15%, 20%, and 25% mixes shows an increment in the strength for M40 mixes at 28 and 90 days as follows: 3.4%, 3.86%, 4.2%, 4.5%, 3.923% and 3.75%, 4.15%, 4.63%, 4.77%, 4.49% compared with control mixture (M40-AF0%).

3.4. Effect of alccofine and M-Sand in the FST test of EFC samples

The flexure strength test results of M25-AF% and M40-AF% mixes at distinct curing ages are represented in Fig. 10. Fig. 10(a) represents FST test results

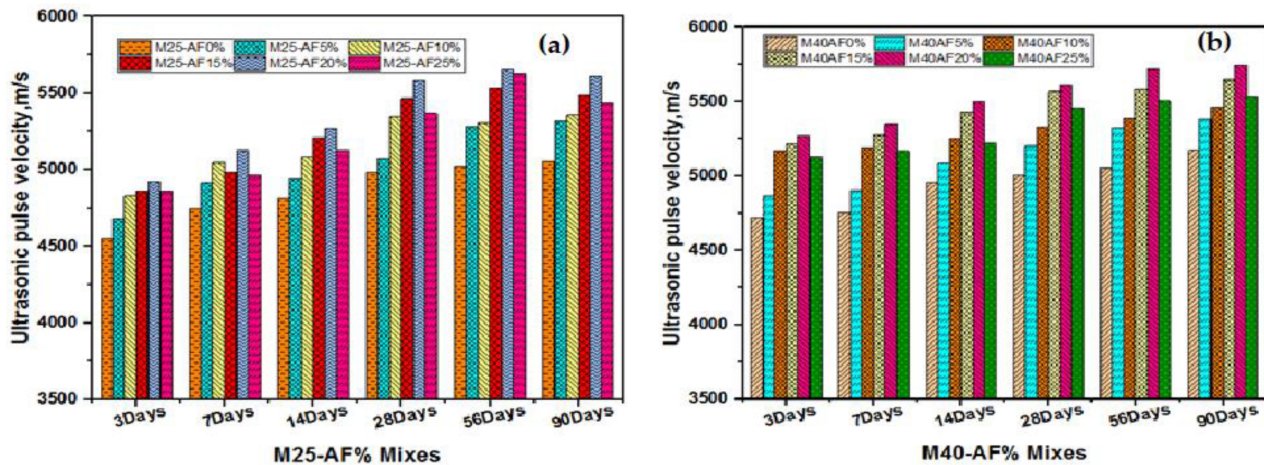


Fig. 11. UPV of mixes: (a) M25-AF% mixes, (b) M40-AF% mixes.

of the AF% of mixes in M25 grade of concrete at 28 and 90 days. The flexure strength values range from 4.21 to 4.93 MPa and 4.68 to 5.61 MPa at 28 and 90 days of curing. Fig. 10(b) represents the FST test results of the AF% of mixes in the M40 grade of concrete after 28 and 90 days. The flexure strength values range from 5.01 to 7.25 MPa and 5.35 to 7.68 MPa, respectively, at 28 and 90 days of curing at the replacement level of alccofine at 0%, 5%, 10%, 15%, 20%, and 25% mixes. The mixes with replacement of alccofine at 0%, 5%, 10%, 15%, 20%, and 25% show an increment in the strength for M25 mixes at 28 and 90 days as follows: 1.68%, 1.93%, 2%, 2.38% and 2.18%, 2.2%, 2.4%, 2.62%, 2.84% and 2.47% respectively when compared with control mixture (M25-AF0%). The replacement of alccofine at 0%, 5%, 10%, 15%, 20%, and 25% shows an increment in the strength for M40 mixes at 28 and 90 days as follows: 3.4%, 3.86%, 4.2%, 4.5% and 3.923%, 3.75%, 4.15%, 4.63%, 4.77% and 4.49% compared with control mixture (M40-AF0%).

3.5. Effect of alccofine and M-Sand in UPV test of EFC samples

The ultrasonic pulse velocity (UPV) test results of the concrete M25-AF% and M40-AF% mixes at different curing ages are represented in Fig. 11. Fig. 11(a) represents the UPV results of AF% of mixes in M25 grade of concrete at 3, 7, 14, 28, 56 and 90 days of curing. Fig. 11(a) shows the UPV test results of M25-AF% mixes at 3 days, the values are 4.5, 4.6, 4.8, 4.8, 4.9, 4.6 Km/s, at 7 days are 4.7, 4.9, 5.0, 4.9, 5.1 and 4.9 Km/s, at 14 days are 4.8, 4.9, 5.0, 5.2, 5.3 and 5.1 Km/s, at 28 days are 4.9, 5.0, 5.3, 5.4, 5.5 and 5.3 Km/s, at 56 days are 5.0, 5.2, 5.3, 5.5, 5.6

and 5.6 Km/s, at 90 days are 5.0, 5.3, 5.3, 5.4, 5.6 and 5.4 Km/s. Fig. 11(b) shows the UPV test results of M40-AF% mixes, at 3 days the values are 4.7, 4.8, 5.1, 5.2, 5.2, and 5.1 Km/s, at 7 days are 4.7, 4.9, 5.1, 5.2, 5.3 and 5.1 Km/s, at 14 days are 4.9, 5.0, 5.2, 5.4, 5.5 and 5.2 Km/s, at 28 days are 5.0, 5.2, 5.3, 5.5, 5.6 and 5.4 Km/s, at 56 days are 5.0, 5.3, 5.4, 5.5, 5.7 and 5.5 Km/s, at 90 days are 5.1, 5.3, 5.4, 5.6, 5.7 and 5.5 Km/s. The quality of the concrete is excellent [36].

4. Microstructural analysis

The microstructure of M25 and M40 mixtures is examined at the microstructure level with the help of SEM, EDS, and XRD analysis to evaluate the impact of alccofine and M-Sand in concrete to develop sustainable eco-friendly concrete samples (EFC).

4.1. X-ray diffraction analysis

An XRD diffractometer was used for the XRD analysis. This technique is very effective for characterizing materials and identifying the phase composition of elements and the crystal structure of particles inside a substance. XRD was performed at 2θ , ranging from 5 to 90 degrees, and is shown in Fig. 12 and Fig. 13. Fig. 12 and Fig. 13 shows the peaks of Anorthite (A), Annite (An), Calcite (Ca), Quartz (Q), Portlandite (P), Labradorite (L), Lamos (La) are the primary minerals found in all of the mix binders. Analysis of the patterns of XRD obtained for mix binders and identification of distinct mineralogical phases of the powder were performed using Match 3.0 software. Fig. 12 represents the X-ray diffraction of M25-AF% mixes. All of the test specimens exhibit the peak of

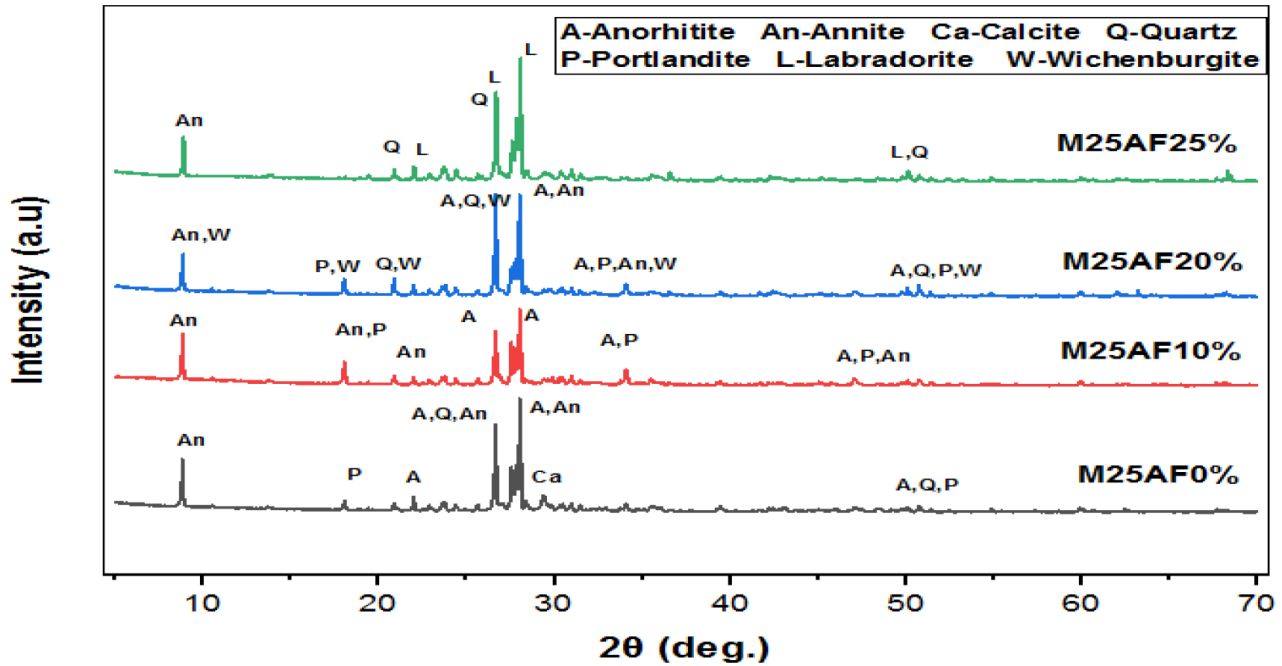


Fig. 12. X-ray diffraction of M25-AF% mixes.

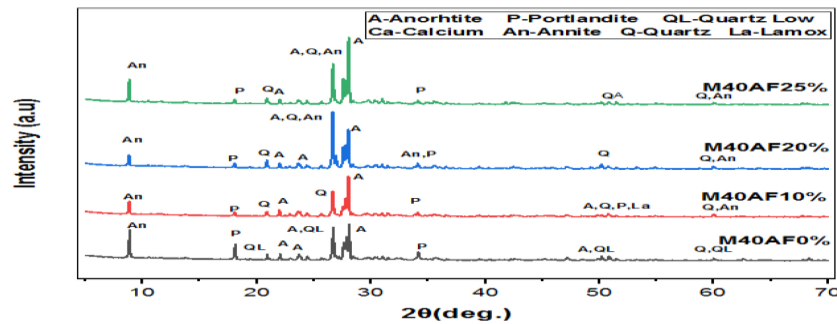


Fig. 13. X-ray diffraction of M40-AF% mixes.

Portlandite (P) ($\text{Ca}(\text{OH})_2$) at 18.067° [2 θ]. Fig. 12 at AF0% represents the Anorthite (A), Annite (An), and Portlandite (P); at AF10% shows the Anorthite (A), Annite (An), and portlandite (P); at AF20% shows Anorthite (A), Annite (An), Quartz (Q), Portlandite (P), at AF25% shows Anorthite (A), Annite (An), Quartz (Q), Portlandite (P) and Labradorite (L). Additionally, several prominent peaks were discovered around 2θ , ranging from 26.6° to 34.38° . These peaks include Anorthite (A), Annite (An), Calcite (Ca), Quartz (Q), Portlandite (P), Labradorite (L), and Lamox(La). Fig. 13 represents the X-ray diffraction of M40-AF% mixes. All of the test specimens exhibit the peak of Portlandite (P) ($\text{Ca}(\text{OH})_2$) at 18.067° [2 θ]. Additionally, several prominent peaks were discovered around 2θ , ranging from 26.6° to 34.38° . The Fig. 13 at AF0% represents the Anorthite

(A), Annite (An), Quartz Low (QL), Portlandite (P), at AF10% shows the Anorthite (A), Annite (An), Quartz (Q) and Portlandite (P), at AF20% shows Anorthite (A), Annite (An), Quartz (Q), Portlandite (P), at AF25% shows Anorthite (A), Annite (An), Quartz (Q) and Portlandite (P) Additionally, These peaks include Anorthite (A), Annite (An), Calcite (Ca), Quartz (Q), Portlandite (P) and Lamox(La).

Compared to the other mix binders, the AF20% mix exhibits a higher proportion of Anorthite, Portlandite, and Quartz, as demonstrated by quantifying the discovered minerals concerning AF0%. The quartz-synthetic phase ICSD-01-085-1053 had a hexagonal crystal morphology in the predominant peak phases across all mixes. The sample also contained anorthite and calcium hydroxide. The chemical formulae for anorthite and calcium hydroxide are

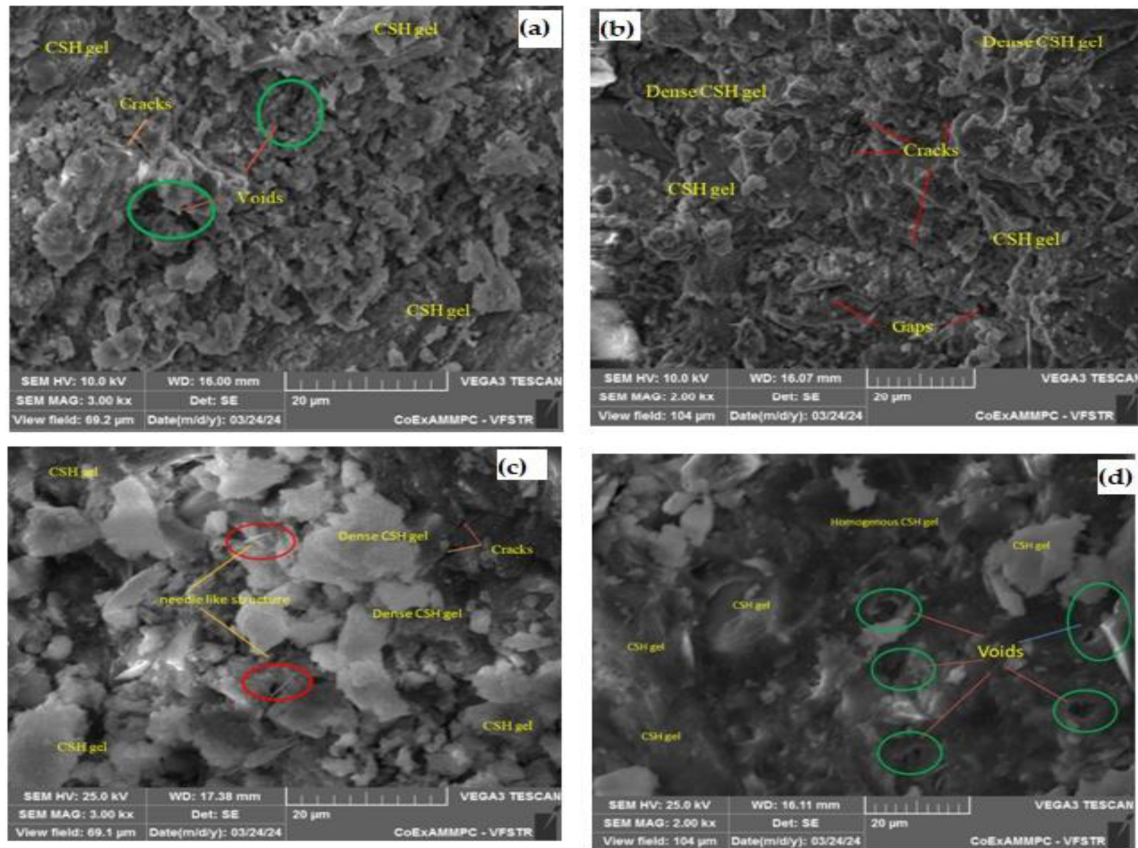


Fig. 14. SEM of mixes: (a) M25-AF0% mixes, (b) M25-AF10% mixes, (c) M25-AF20% mixes, (d) M25-AF25% mixes.

CaAlSi₂O₈ and Ca(OH)₂ [49, 50]. An increase in free lime (CaO), alumina (Al₂O₃), and magnesia (MgO) caused excessive expansion and micro-cracking in the concrete during hydration, resulting in reduced compressive strength [40]. A reduction in compressive strength intensity is noted in quartz, anorthite, portlandite, and calcium hydroxide, resulting in the mixtures.

4.2. SEM analysis

The effect of alccofine and M-Sand in the M25 and M40 mixes is studied by examining microstructure through SEM images and EDS at replacement levels of cement at 0%, 10%, 20%, and 25% with alccofine along with 100% M-Sand as fine aggregate. Fig. 12(a-d) depicts the SEM image of M25-AF% mixes after 28 days of curing. Fig. 14a,b represents an SEM image of dense calcium silicate hydrate (C-S-H) gel, gaps and cracks are observed at M25-AF0% and M25-AF10%. Fig. 14c represents an M25-AF20% mixture SEM image of dense calcium silicate hydrate (C-S-H) gel, and a needle-like structure is observed. SEM images demonstrated that the solid phase of the binders is composed of calcium hydroxide in the form of

portlandite during the initial stages of the hydration process. This Portlandite comprises hexagonal crystals in plates and columns, as Fig. 14(c) illustrates. Fig. 14d represents an M25-AF25 % mixture SEM image of homogenous calcium silicate hydrate (C-S-H) gel; voids are observed. According to the pictures obtained from the scanning electron microscope (SEM), a sequence of voids, in addition to a hexagonal crystal structure shaped like columns and plates, as shown in the Fig. 14d. Fig. 15(a-d) depicts the SEM image of M40-AF% mixes after 28 days of curing. Fig. 15a,b represents SEM image of C-S-H gel, and serious of gaps are observed at M40-AF0% and M40-AF10%. Fig. 15c, represents M40-AF20% mixture SEM image of dense homogenous C-S-H gel, and voids are observed. Fig. 15d represents an M40-AF25 % mixture SEM image of C-S-H gel; voids and serious cracks were observed. All mixes based on alccofine may have greater strengths when compared to the control mix because alccofine-based mix binders have large C-S-H gel properties due to the hydration process and the pozzolanic reaction of all the mix binders after 28 days. As a result of these features, greater strengths were attained by mixes consisting of alccofine than the control mix [37–42]. SEM

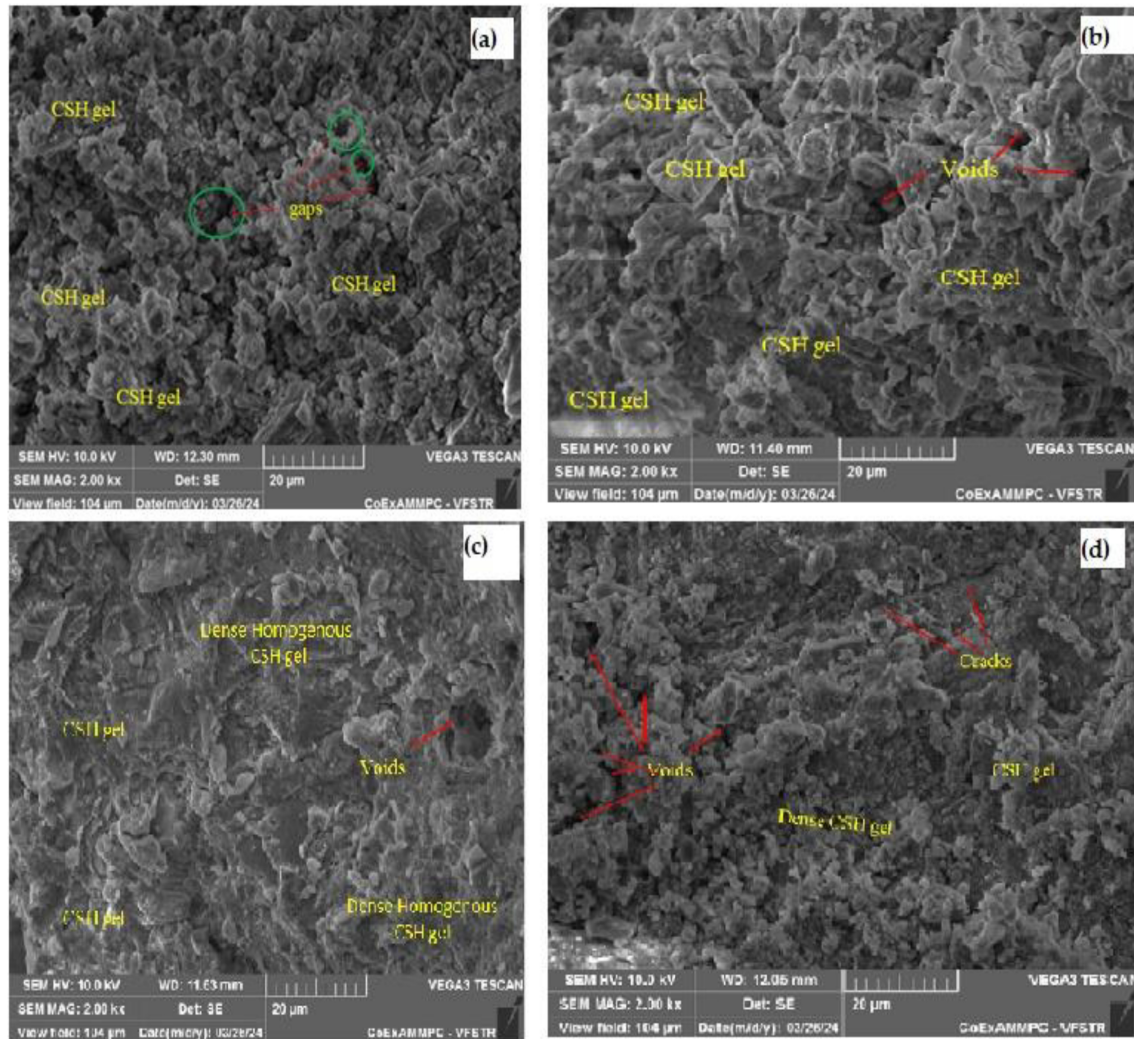


Fig. 15. SEM of mixes: (a) M40-AF0% mixes, (b) M40-AF10% mixes, (c) M40-AF20% mixes, (d) M40-AF25% mixes.

images of mixes containing AF20% revealed a dense calcium silicate hydrate C-S-H gel formation for M25 and M40 grades.

Figs. 14 and 15 clearly show that the mixtures of M25 and M40 have quite dense microstructures. Ultrafine alccofine and M-Sand, with a certain amount of fine powder, help the hydration process, filling the paste and decreasing open space in the concrete matrix [27]. Moreover, the interfacial zone between the aggregate and the paste shows a strong, complex matrix. This phenomenon happens in typical cement because the portlandite crystal and ettringite have an oriented development in the interfacial transition zone of the concrete. Conversely, when ultrafine alccofine is included in M25 and M40 mixtures, it might react with $\text{Ca}(\text{OH})_2$ and produce calcium silicate hydrate (C-S-H) gel. Furthermore, at a lower scale, polycarboxylate superplasticizer [43] has a nanoscale size. It becomes denser and more homogeneous with

interior structures from the dense packing of small-sized particles, which leads to improvement in the strength up to AF20% [43–47].

4.3. EDS analysis

EDS testing was used to conduct the microstructure investigation to understand better the impact of Alccofine and M-Sand on the microstructure of the M25 and M40 mixtures. Fig. 16(a-d) and Fig. 17(a-d) indicate the research findings that the substitution of 0, 10, 20, and 25% of cement with alccofine and hundred % sand with M-Sand as fine aggregate. The ratio of atomic calcium to silica was used to determine the amount of calcium silicate hydrate (C-S-H) gel produced by each binder mix. This ratio was considered appropriate based on the atomic percentages of Ca and Si acquired from the EDS analysis. Based on the results of the atomic Ca/Si

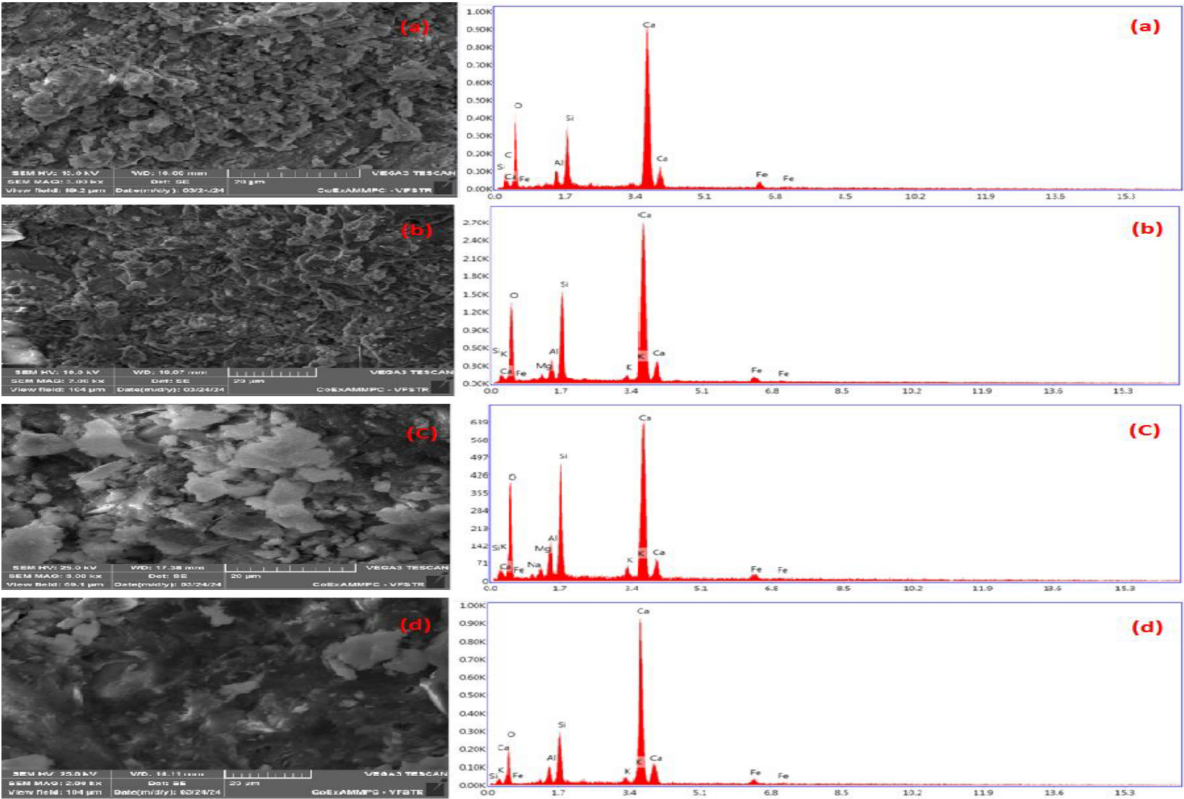


Fig. 16. EDS analysis: (a) M25-AF0% mixes, (b) M25-AF10% mixes, (c) M25-AF20% mixes, (d) M25-AF25% mixes.

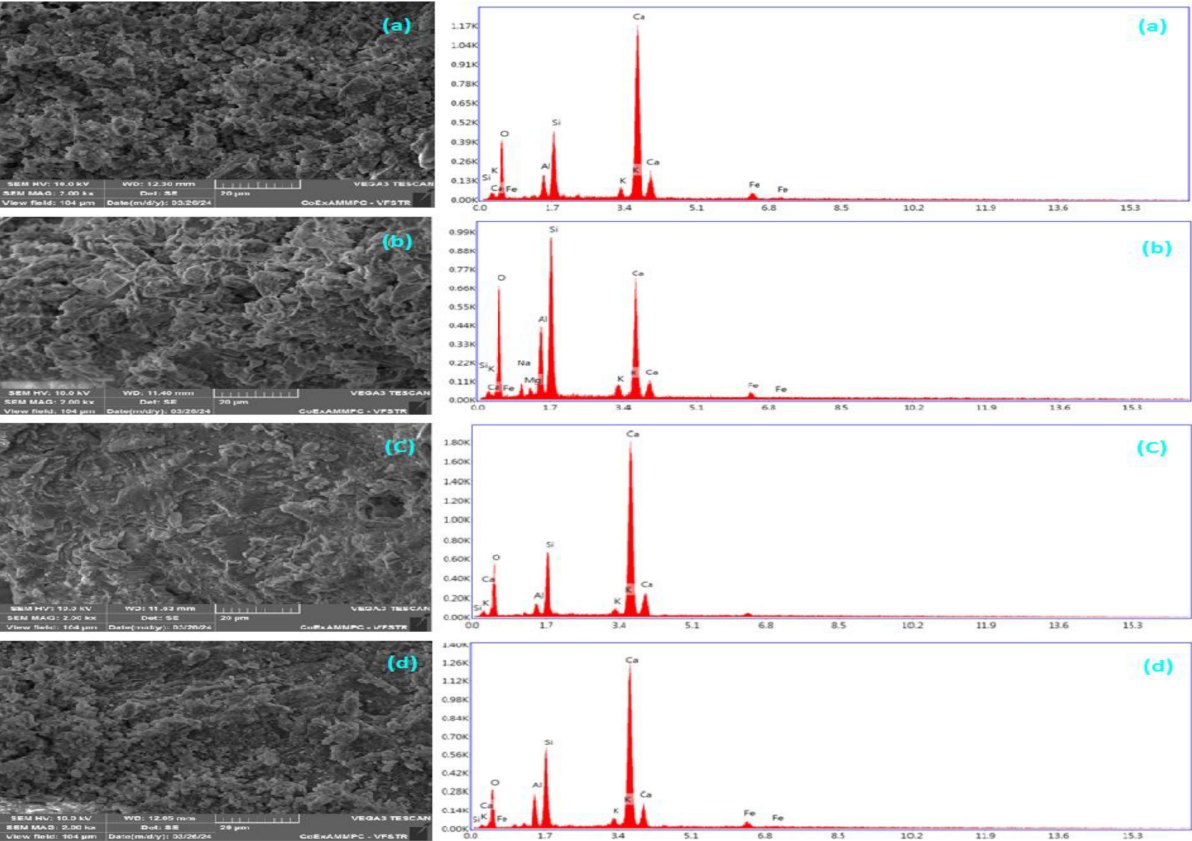


Fig. 17. EDS analysis: (a) M40-AF0% mixes, (b) M40-AF10% mixes, (c) M40-AF20% mixes, (d) M40-AF25% mixes.

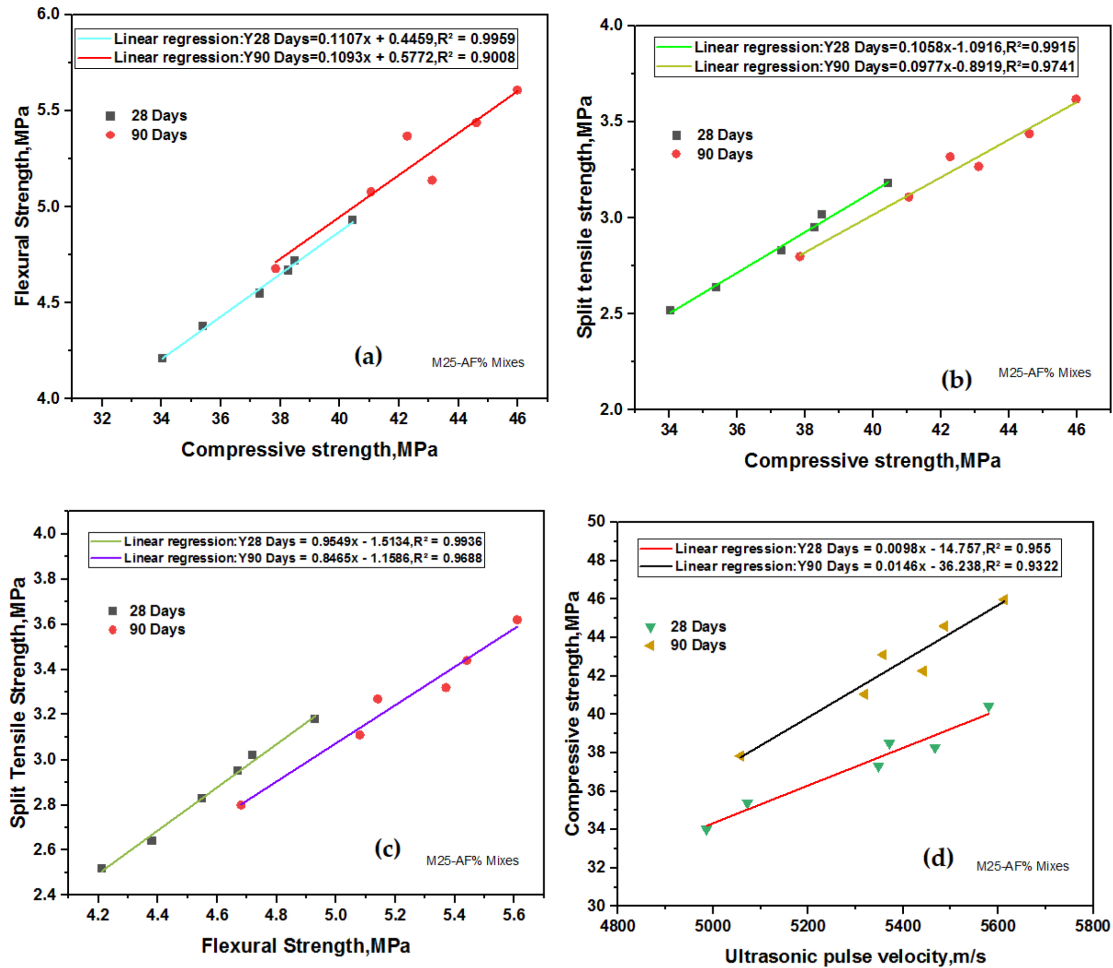


Fig. 18. Relation between M25-AF% mixes: (a) FST and CPS, (b) STS and CPS, (c) STS and FST, (d) CPS and UPV.

ratio analysis, it was discovered that the control mix had a Ca/Si ratio of 2.94, 3.03, 1.53, and 2.03, for the M25 mixes from the EDS analysis are depicted in Fig. 16(a-d) and 2.79, 2.92, 1.76, 2.175 for the M40 mixes from the EDS analysis are depicted in Fig. 17(a-d) respectively.

The AF20% mix has a high compressive strength of 40.44 MPa and 61.65 MPa for the M25 and M40 grades, respectively. This is in contrast to all other mixes, possessing a low atomic Ca/Si ratio of 1.53 and 1.76, and this mix also has a high compressive strength. Compared to the M25-AF% and M40-AF% mixes, the control mix has a low compressive strength of 34.02 MPa and 50.92 MPa, respectively, and a high atomic Ca/Si ratio of 2.94 and 2.79. Based on these results, it is possible to conclude that the compressive strength is increased due to the improved C-S-H gel formation, which is made possible by a lower atomic Ca/Si ratio. This conclusion allows for the possibility of a higher compressive strength. It has been shown that an increase in the atomic Ca/Si ratio decreases the compressive strength of the concrete, which in

turn leads to a reduction in the synthesis of calcium silicate hydrate (C-S-H) gel [37–42].

5. Statistical analysis

Regression analysis is a statistical technique employed to examine the correlation between various parameters. Various methods exist, including linear, power, exponential, logarithmic, and polynomial relationships among the properties. In this study, two grades of variations are observed concerning the effect of AF%.

The linear regression equations for the M25-AF% and M40-AF% mixes at 28 days and 90 days are illustrated in Fig. 18 and Fig. 19. Fig. 18 illustrates the correlation between CPS and FST in M25-AF% mixtures. Upon doing the regression analysis, the coefficients of determination (R^2) were recorded as 0.9959 (99.59%) and 0.9008 (90.08%). Fig. 18 illustrates the correlation between the CPS and STS, demonstrating a robust link across the various curing

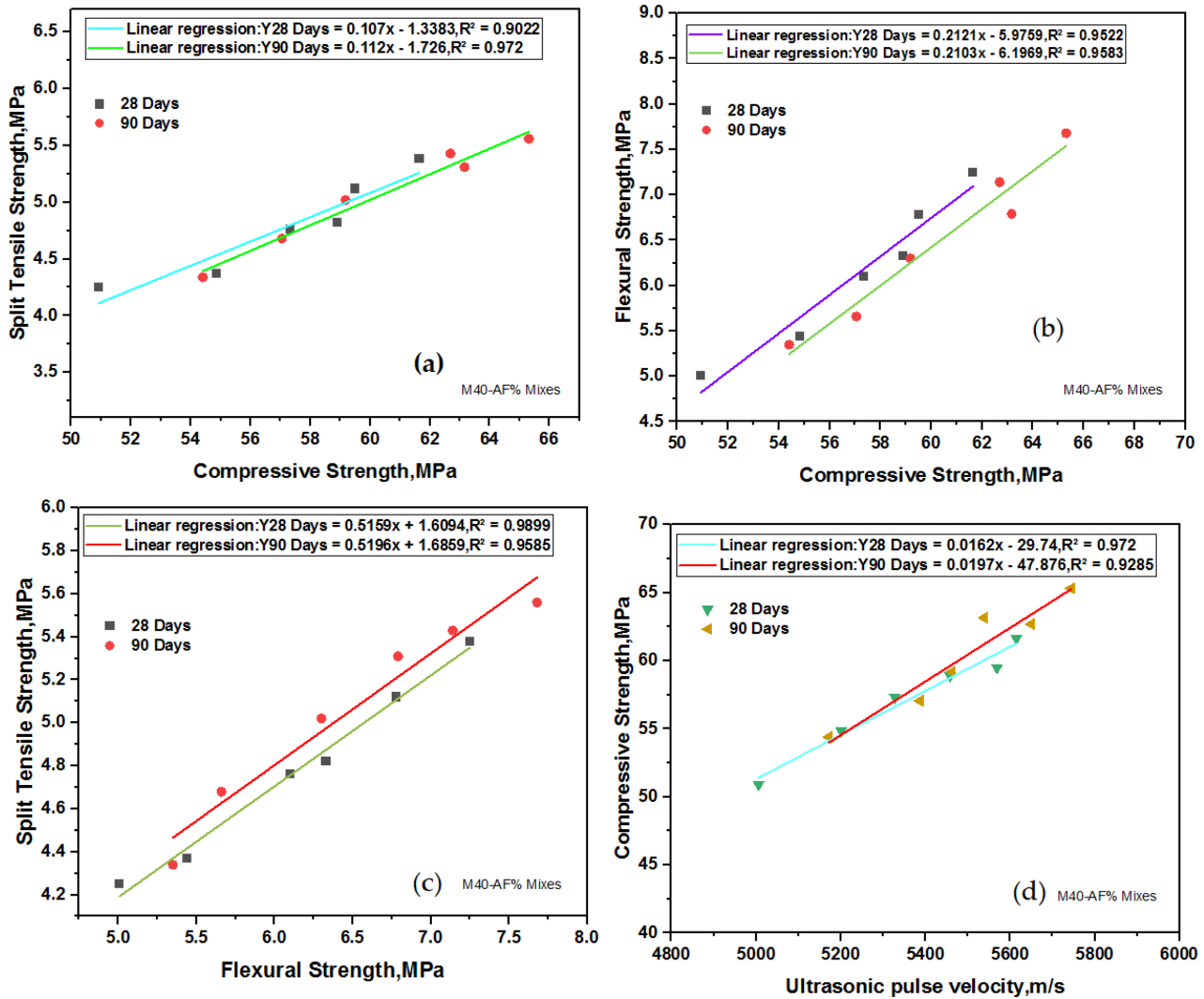


Fig. 19. Relation between M40-AF% mixes: (a) STS and CPS, (b) FST and CPS, (c) STS and FST, (d) CPS and UPV.

age groups. The linear regression yielded coefficients of determination (R^2) of 0.9915 (99.15%) at 28 days and 0.9741 (97.41%) at 90 days. Fig. 18c illustrates the correlation between FST and STS of M25-AF% mixtures at 28 days and 90 days of curing age. Upon doing the regression analysis, the coefficients of determination (R^2) are noted as 0.9936 (99.36%) and 0.9688 (96.88%). Fig. 18d illustrates the relationship between CPS and UPV. Following the execution of regression analysis on the UPV values for 28 and 90 days of curing of M25-AF% mixtures, the correlation (R^2) values for the direct models are 0.955 (95.5%) and 0.9322 (93.22%).

For samples of curing age, Fig. 19a shows the relationship between CPS and STS. At 28 days and 90 days, the R^2 value was 0.9022 (90.22%), while at both time points it was 0.972 (97.2%). The correlation between CPS and FST for M40-AF% blends is seen in Fig. 19b. Two coefficients of de-

termination (R^2), measuring 0.9522(95.22%) and 0.9583(95.83%) were noted. At both the 28-day and 90-day curing ages, Fig. 19c shows the relationship between FST and STS of M40-AF% blends. R^2 values of 0.9899 (98.99%) and 0.9585 (95.85%) are noted. Fig. 19d shows the relationship between UPV and CPS. For the direct models, the (R^2) values are 0.972 (97.2%) and 0.9285 (92.85%), respectively. The curing process, the ability of replacement samples to absorb water, and the amount of moisture in the concrete matrix are the primary factors determining the CMS [48].

6. Conclusion

The effect of alccofine (AF) in concrete is observed for the M25 and M40 mixes in cement replacement at 0%, 5%, 10%, 15%, 20%, and 25% with alccofine

and 100% of M-Sand. The following conclusions were drawn:

Using alccofine as a mineral admixture and M-Sand as fine aggregate increased the compressive strength, split tensile strength, flexure strength, and ultrasonic pulse velocity for the M25 and M40 mixes. Alccofine at 20% replacement showed the best performance for M25-AF% mixes, increasing 28,56 and 90-day strength by up to 37%, 40.7%, and 44.62%, and for M40-AF% mixes, increasing 28,56 and 90-day strength by up to 44.2%, 45.75%, and 47.2% compared to the control mixes of AF0% for M25 and M40. All the mixes show that the quality of the concrete is excellent. Using alccofine allows for filling the voids between the cement particles, lowering the permeability of the M25 and M40 mixes. In addition to enhancing the workability of concrete, the cohesiveness of new concrete with aggregate sizes of 12 mm and 20 mm affects homogeneity and improves the workability of the mixtures, including M-Sand and AF%. The slump first increases to AF20% and then decreases at AF25% mixtures. The micro-aggregate filling action of M-Sand, the smaller particle size, unique chemical composition, and surface characteristics of AF% particles, minimize segregation and bleeding by decreasing the needed water content. According to the findings of the microstructural investigation, the zone of interfacial transition in concrete was enhanced by the addition of AF% mixes in M25 and M40. This was accomplished by increasing the density of the particle packing and allowing pozzolanic products, such as more C-S-H, to fill gaps. In the EDS analysis, the M25-20%AF and M40-20%AF mixes had a lower atomic Ca/Si ratio of 1.53, 1.76, and exhibited high compressive strength of 40.44 MPa and 61.65 MPa. On the other hand, the control mix had a high atomic Ca/Si ratio of 2.94 and 2.79, and it demonstrated lower compressive strengths of 34.02 MPa and 50.92 MPa for the M25-AF0% and M40-AF0% control mixes, respectively. Based on these findings, it can be inferred that a lower atomic Ca/Si ratio leads to greater C-S-H gel formation and, hence, a higher compressive strength. If the atomic Ca/Si ratio is greater, then the production of CSH gel will be reduced, which will decrease the compressive strength of the concrete. Because of the presence of a significant quantity of calcium (CaO) and silica (SiO₂) in AF%, the rate of the hydration process is increased, and the pozzolanic reaction is improved.

This confirms the formation of even more hydrated C-S-H gel, eventually leading to a dense core matrix structure in concrete, resulting in greater strength during the early curing stages. Consequently, this occurs throughout the whole curing process. After

careful consideration, it has been determined that employing Alccofine as a replacement for cement in concrete mixes of M25 and M40 is beneficial. All M25 and M40 concrete mixes tested at AF20% exhibited positive results compared to the control mix test findings. There were absolutely no adverse results found in any of the mixes. In this context, it is beneficial to mix AF20% with M-Sand to produce environmentally friendly concrete (EFC) samples for sustainable infrastructure development.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Funding

The authors declared that this study has received no financial support.

Author contribution

Yellinedi Madhavi: Written original article, Materials Collection, Experimentation, Results analysis, R. S. Ravichandran: supervisor, Edited the manuscript, J. Saravanan: Edited the manuscript, N. Venkata Sairam Kumar: Edited the manuscript.

Ethics

There are no ethical issues with the publication of this manuscript.

References

1. Venkatesh C, Rao MVS, Kumar MP, Sonali Sri Durga C. Effect of mineral admixtures and curing regimes on properties of self-compacting concrete. *J Sustain Const Mater Technol*. 2024;9(1):25–35.
2. Sonali Sri Durga C, Venkatesh C, Priyanka M, Krishna Chaitanya B, Rao BNM, Rao TM. Synergistic effects of GGBFS addition and oven drying on the physical and mechanical properties of fly ash-based geopolymer aggregates. *J Sustain Const Mater Technol*. 2024;9(2):93–105.

3. Chaitanya BK, SaiMadupu LNK, Satyanarayana SV. Experimental Study on Fresh and Mechanical Properties of Crimped Steel Fibers in Self Compacting Concrete. *J Polym Compos.* 2023;11:S65–75.
4. KanthCh L, Kumar PR, Chaitanya BK, Kumar NVS, Thati NSRK, Kumar NSV, Ravi B, Rao AN. Prediction of mechanical and tensile properties of self-compacting concrete incorporating fly ash and waste copper slag by artificial neural network-ANN. *Annales de Chimie - Science des Matériaux.* 2024;48(5):655–65. doi:10.18280/acsm.480506.
5. Kuunreddy S, Murugan S. Effect of Alccofine 1203 on setting times and strength of ternary blended geopolymer mixes with M-Sand cured at ambient temperature. *Revista Romana de materiale = Romanian journal of materials = RRM.* 2019;49:527–34.
6. Saxena SK, Gautam M, Singh NB. Effect of Alccofine powder on the properties of Pond fly ash based Geopolymer mortar under different conditions. *Environmental Technology & Innovation.* 2018;9. doi:10.1016/j.eti.2017.12.010.
7. Chaitanya BK, Kumar IS. Effect of waste copper slag as a substitute in cement and concrete-a review. In IOP Conference Series: Earth and Environmental Science; IOP Publishing: Bristol, UK, 2022. Volume 982, p. 012029.
8. Krishna Chaitanya B, Sivakumar I. Influence of waste copper slag on flexural strength properties of self compacting concrete. *Mater Today Proc.* 2021;42:671–6.
9. Raj P, Prithivi J. Influence of W/B Ratio and Chemical Admixture on Fresh and Hardened Properties of Self Compacting Concrete using Alccofine. *Xi'an DianziKejiDaxueXuebao/Journal of Xidian University.* 2020;14:4906–15. doi:10.37896/jxu14.5/537.
10. Chaitanya BK, Sivakumar I, Madhavi Y, Cruze D, Venkatesh C, Naga Mahesh Y, Sri Durga CS. Microstructural and Residual Properties of Self-Compacting Concrete Containing Waste Copper Slag as Fine Aggregate Exposed to Ambient and Elevated Temperatures. *Infrastructures.* 2024;9(5):85. doi:10.3390/infrastructures9050085.
11. Muralikrishnan B, Saravanan J. Study on Bond Strength of Alccofine-Based Normal and High-Strength Concrete. *Civil Engineering Journal.* 2019;5:679. doi:10.28991/cej-2019-03091278.
12. Chaitanya BK, Sivakumar I. Experimental investigation on bond behaviour, durability and microstructural analysis of self-compacting concrete using waste copper slag. *J Build Rehabil.* 2022;7:85.
13. Raj P, Saravanan J. Characteristics of Self-Compacting Concrete with Different Size of Coarse Aggregates and Alccofine. 2022;19:3042. doi:10.48048/tis.2022.3042.
14. Chaitanya BK, Sivakumar I. Flow-behaviour, microstructure, and strength properties of self-compacting concrete using waste copper slag as fine aggregate. *Innov Infrastruct Solut.* 2022;7:181.
15. Sharma D, Sharma S, Goyal A. Utilization of Waste Foundry Slag and Alccofine for Developing High Strength Concrete. *International Journal of Electrochemical Science.* 2016; 11(4):3190–205. doi:10.1016/S1452-3981(23)16174-8.
16. Thangapandi K, Anuradha R, Awoyera PO, et al. Durability Phenomenon in Manufactured Sand Concrete: Effects of Zinc Oxide and Alccofine on Behaviour. *Silicon.* 2021;13:1079–85. doi:10.1007/s12633-020-00494-2.
17. Jindal B, Singhal D, Sanjay S, Ashish D, Jangra P. Improving compressive strength of low calcium fly ash geopolymer concrete with alccofine. *Advances in Concrete Construction.* 2017;5:17–29. doi:10.12989/acc.2017.5.1.17.
18. Reddy PN, Naqash JA. Development of high early strength in concrete incorporating alccofine and non-chloride accelerator. *SN Appl Sci.* 2019;1:755. doi:10.1007/s42452-019-0790-z.
19. Muralikrishnan B, Saravanan J. Effect of Addition of Alccofine on the Compressive Strength of Cement Mortar Cubes. *Emerging Science Journal.* 2021;5:155–70. doi:10.28991/esj-2021-01265.
20. Prithiviraj C, Saravanan J, Ramesh Kumar D, Murali G, Vatin NI, Swaminathan P. Assessment of Strength and Durability Properties of Self-Compacting Concrete Comprising Alccofine. *Sustainability.* 2022;14(10):5895. doi:10.3390/su14105895.
21. Jindal BB. Investigations on the properties of geopolymer mortar and concrete with mineral admixtures: A review. *Construction and Building Materials.* 2019;227:116644. doi:10.1016/j.conbuildmat.2019.08.025.
22. Parveen DS, TalhaJunaid M, Jindal BB, Mehta A. Mechanical and microstructural properties of fly ash based geopolymer concrete incorporating alccofine at ambient curing. *Construction and Building Materials.* 2018;180:298–307. doi:10.1016/j.conbuildmat.2018.05.286.
23. Bln SS, Srinath, Patnaikuni D, Baswa S, Venkata K, Kvgd B. Balaji Strength effect of alccofine on ordinary and standard grade concrete mixes. *International Journal of Advanced Technology and Engineering Exploration.* 2022;9:47–60. doi:10.19101/IJATEE.2021.874698.
24. Sagar B, Sivakumar MVN. Use of alccofine-1203 in concrete: review on mechanical and durability properties. *International Journal of Sustainable Engineering.* 2021;14(6):2060–73. doi:10.1080/19397038.2021.1970275.
25. Ding X, Li C, Xu Y, Li F, Zhao S. Experimental study on long-term compressive strength of concrete with manufactured sand. *Construction and Building Materials.* 2016;108:67–73.
26. Shen W, Jin Z, Yuan Q, Ji Y, Zeng R, Wu Y, Lao L, Shi C. Comparative study on the performance of fresh concrete comprising manufactured sand vs. river sand during full-scale long-distance pumping. *Construction and Building Materials.* 2024;452:138953. doi:10.1016/j.conbuildmat.2024.138953.
27. Nguyen DT, Nguyen DL, Ngoc-TraLam M. An experimental investigation on the utilization of crushed sand in improving workability and mechanical resistance of concrete. *Construction and Building Materials.* 2022;326:126766. doi:10.1016/j.conbuildmat.2022.126766.
28. Li N, Zhang Z, Hu D, Pang G, Wang Q, Si W. Economic and Carbon Emission Analyses of C50 Manufactured Sand Concrete Considering Workability and Compressive Strength. *Buildings.* 2025;15(1):77. doi:10.3390/buildings15010077.
29. IS:12269:1987: Specification For 53 Grade Ordinary Portland Cement. Bureau of Indian Standard: New Delhi, India, 1987.
30. IS 383-2016: Specification for Coarse and Fine Aggregates from Natural Sources for Concrete. Bureau of Indian Standard: New Delhi, India, 2016.
31. IS 9103:1999: Concrete Admixtures-Specification (First Revision). Bureau of Indian Standard: New Delhi, India, 1999.
32. IS 456:2000: Indian Standard Plain And Reinforced Concrete-Code of Practice. Bureau of Indian Standard: New Delhi, India, 2000.
33. IS 10262:2019; Concrete Mix, Proportioning Guidelines (First Revision). Bureau of Indian Standard: New Delhi, India; 2019.
34. IS 1199-1959: Method of Sampling and Analysis of Concrete. Bureau of Indian Standards, New Delhi, India, 1959.
35. IS 516:2015: Methods of Tests for Strength of Concrete. Bureau of Indian Standard: New Delhi, India, 2015.

36. IS:13311 (Part-1):1992: Non-Destructive Testing of Concrete—Methods of Test—Part 1 Ultrasonic Pulse Velocity. Bureau of Indian Standard: New Delhi, India, 1992.
37. Zanni H, Cheyrezy M, Maret V, Philippot S, Nieto P. Investigation of hydration and pozzolanic reaction in reactive powder concrete (RPC) using ^{29}Si NMR. *CemConcr Res.* 1996;26:93–100. doi:[10.1016/0008-8846\(95\)00197-2](https://doi.org/10.1016/0008-8846(95)00197-2).
38. Muralikrishnan B, Saravanan J. Effect of Alccofine and GGBS Addition on the Durability of Concrete. *Civil Engineering Journal.* 2019;5:1273–88. doi:[10.28991/cej-2019-03091331](https://doi.org/10.28991/cej-2019-03091331).
39. Sagar B, MVN S. Mechanical and microstructure characterization of alccofine based high strength concrete. *Silicon.* 2022;14:795–813. doi:[10.1007/s12633-020-00863-x](https://doi.org/10.1007/s12633-020-00863-x).
40. Sagar B, MVN S. An Experimental and Analytical Study on Alccofine Based High Strength Concrete. *International Journal of Engineering.* 2020;33(4):530–8.
41. Kjellsen KO, Wallevik OH, Fjällberg L. Microstructure and microchemistry of the paste-aggregate interfacial transition zone of high-performance concrete. *AdvCem Res.* 1998;10:33–40. doi:[10.1680/adcr.1998.10.1.33](https://doi.org/10.1680/adcr.1998.10.1.33).
42. Ng KM, Tam CM, Tam VWY. Studying the production process and mechanical properties of reactive powder concrete: a Hong Kong study. *Mag Concr Res.* 2010;62:647–54. doi:[10.1680/mac.9.00063](https://doi.org/10.1680/mac.9.00063).
43. Zhu YC, Ma BG, Tan HB. Effect of Side-chain structure of polycarboxylic acid type water-reducer on hydration of C3A. *Adv Mater Res.* 2012;50:807–12.
44. Song TH, Lee SH, Kim B. Recycling of crushed stone powder as a partial replacement for silica powder in extruded cement panels. *Constr Build Mater.* 2014;52(52):105–15.
45. Mouret M, Bascoul A, Escadeillas G. Microstructural features of concrete in relation to initial temperature—SEM and ESEM characterization. *Cem Concr Res.* 1999;29(3):369–75.
46. Mo KH, Alengaram UJ, Jumaat MZ, et al. Assessing some durability properties of sustainable lightweight oil palm shell concrete incorporating slag and manufactured sand. *J Clean Prod.* 2016;112:763–70.
47. Zhou Y, Zhang Z. Effect of fineness on the pozzolanic reaction kinetics of slag in composite binders: Experiment and modelling. *Constr Build Mater.* 2021;273:121695. doi:[10.1016/j.conbuildmat.2020.121695](https://doi.org/10.1016/j.conbuildmat.2020.121695).
48. Sreenivasulu C, Guru Jawahar J, Sashidhar C. Effect of copper slag on micro, macro, and flexural characteristics of geopolymer concrete. *J Mater Civ. Eng.* 2020;32(5):04020086. <https://doi.org/10.1016/j.conbuildmat.2020.121695>.
49. Gupta N, Siddique R. Strength and micro-structural properties of self-compacting concrete incorporating copper slag. *Constr Build Mater.* 2019;224:894–908.
50. Tangadagi RB, Manjunatha M, Seth D, Preethi S. Role of mineral admixtures on strength and durability of high strength self compacting concrete: An experimental study. *Materialia.* 2021;18:101144.