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TECHNICAL PAPER

# Studies on the concrete with composite cement and alccofine: from use of OPC towards low-carbon quaternary binder

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## Abstract
In recent days, there is an increased interest in using alternative materials in cement to produce concrete with improved properties. Supplementary cementitious materials (SCMs), which are the alternative materials used in the production of cement, are mainly industrial wastes like fly ash (FA), ground-granulated blast furnace slag (GGBS) and silica fume, giving rise to sustainable construction practices. Numerous investigations have been performed on the utilisation of alternate materials in the production of cement that is used in concrete, and an enhancement in the performance of concrete has been reported. Composite cement, a novel material, finds application in construction in which a certain percentage of cement clinker is replaced by GGBS, FA and silica fume during its production. The drawback of the composite cement containing GGBS and FA is that it attains a lower strength at earlier ages. Alccofine, an ultrafine slag-based material collected as a residue from the iron industry, has also been utilised as an SCM in the production of cement. In this study, the effect of a partial replacement of composite cement (COC) with alccofine is examined. It was observed that 10% replacement of COC by alccofine increases the maximum compressive strength (CS), modulus of elasticity (MOE), split tensile strength (STS) and flexural strength (FS) of concrete, respectively, by 12.67%, 16.95%, 11.4% and 21.42% at 28 days. The formation of closely packed structure due to the finer particles of alccofine contributes to an improvement in the strength of concrete.

**Keywords** Supplementary cementitious materials (SCMs) · Composite cement (COC) · Alccofine · Mechanical properties · Microstructural characterisation

## Introduction

Cement manufacturing is an energy-intensive and resource-exhausting process that releases a large amount of greenhouse gases into atmosphere. It was reported that around 2.8 tonnes of raw material, including fuel and other materials, are needed to produce 1 tonne of Portland cement (PC) [1, 2]. Moreover, the production of 1 tonne of PC releases 1 tonne of greenhouse gases as a result of decarbonisation of limestone [3, 4]. The cement industry faces a number of challenges including scarcity of raw materials, leading to lower availability of concrete in construction [5, 6]. As of now, efforts have been made to promote the utilisation of pozzolans as a replacement for PC in concrete. The pozzolans are either artificial or natural materials with silica in the reactive formation. ASTM C618 describes pozzolana as a siliceous or aluminous material that possess little or no cementitious value, but it will automatically react with calcium hydroxide in the chemical form in the presence of moisture at ambient temperature to develop hydrated cementitious properties [7]. The reaction of pozzolanic material with lime is known as "pozzolanic reaction," which is usually slow at ordinary temperature. The utilisation of pozzolanic material as a blended component of cement production results in huge energy savings and lowers the amount of solid wastes needed [8, 9]. The use of different kinds of waste materials like fly ash (FA) [10], clay brick wastes [11] and metakaolin [12] as pozzolans in concrete results in better chemical resistance, high strength and better durability. Among various industrial waste materials, fly ash (FA) and ground-granulated blast furnace slag (GGBS) are the commonly used pozzolanic materials because of their pozzolanic properties. The amount of fly ash and GGBS generated from industries are increasing on a daily basis, necessitating

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their disposal. GGBS and FA form an additional C–S–H gel after the reaction with portlandite, whose structure is similar to hydrated cement. FA is one of the most widely used pozzolans obtained as a by-product from the combustion of powdered coal. Among the significant advantages of using FA are better workability, decreased water needs and increased strength properties [13]. The major drawbacks of using FA are that its replacement percentage with cement is lower and early strength gain is minimum [14]. The low strength gain is due to the formation of $Ca(OH)_2$ during the cement hydration process [15], whereas GGBS obtained from steel industry as a by-product can be replaced with cement up to 70% [16]. The oxides of $SiO_2$, CaO, $Al_2O_3$ and MgO present in GGBS undergo hydration upon reaction with water [17]. Due to its denser microstructure, using an optimum amount of GGBS, the durability and strength characteristics of concrete can be improved [18]. However, the carbon footprint is higher than when FA alone is used as more processing time is needed for GGBS, which consumes more energy [19].

Alccofine is an ultrafine slag-based material which possesses high strength and durability characteristics than other SCMs used in the construction industry [20]. It is the most refined material obtained from steel industry as a waste material. The particle size distribution is one of a kind due to the granulation process. The individual particle size in alccofine is up to 6 µm. The particles of alccofine are very finer than cement, rice husk and FA, which leads to enhanced hydraulic properties, pozzolanic reactivity and packing density of paste [21, 22]. Two commercially available forms of alccofine are 1101 and 1203 [23] with specific surface area greater than 12,000 $cm^2/g$ and with specific gravity in the range of 2.8–2.9 [24, 25]. $SiO_2$ plays a major role in enhancing the strength properties [26]. Alccofine is inert in nature, but once it is combined with cement, it possesses greater binding properties. This property leads to a significant improvement in strength and durability properties of concrete [27, 28]. Due to pozzolanic reaction, alccofine modifies the interfacial transition zone (ITZ), thus reducing porosity. Balamuralikrishnan and Saravanan [29] replaced cement with alccofine at 0%, 5%, 10%, 15% and 20% to examine its impact on the compressive strength (CS) of cement mortar and reported that replacement of cement with 10% of alccofine increases the CS by 18.73%. Srinath et al. [30] stated that replacement of cement with 15% of alccofine leads to 40.71%, 41.5% and 125% increase in CS, split tensile strength (STS) and flexural strength (FS), respectively. Rajesh Kumar et al. [31] noted that the replacement of cement with 10% of alccofine increases the FS by 27.6%. Venkatesan et al. [32] reported that replacement of cement with 10% alccofine increases the CS by 20.52%. Gautam and Sood [33] found that the replacement of cement with 10% alccofine increases the FS by 25.5%. Srinivasan [34], on the other hand, found FS to increase by 22% on replacing cement with 10% alccofine. Harish et al. [35] tested the mechanical properties of concrete in which cement was replaced by 5–20% of alccofine and concluded that the addition of alccofine in concrete yielded promising results as compared to conventional concrete. Chakravarthy and Raj [36] observed that the replacement of cement with 16% of alccofine increases the CS by 60.95%. Even high-performance concrete is more durable with the addition of alccofine along with other SCMs [37]. Due to microfiller effect and pozzolanic reaction of GGBS, the cement paste has a lower number of pores [38]. It was also noted that concrete developed with 88.3% alccofine and 16.3% FA possessed substantial CS and FS [39]. From the previous studies, it was demonstrated that 8–12% of alccofine as a replacement for cement produces higher strength in the relevant concrete grades [40]. Thus, cement in concrete can be partially replaced with alccofine, FA and GGBS. The addition of alccofine with GGBS improves the workability of concrete because of its high fineness and glassy surface characteristics and low calcium silicate chemical composition [41]. Kavitha and Kala [41] replaced cement with 5–20% of alccofine in combination with 30% of GGBS in concrete and noted that CS and STS increase by 17.7% and 107%, respectively, for the combination of 10% alccofine with 30% GGBS. Kavyateja et al. [42] replaced cement with 5–15% of alccofine combined with 25% of FA in concrete and reported that the CS and STS are increased by 17.49% and 39.25%, respectively, for the combination of 10% of alccofine with 25% of FA. Soni et al. [39] reported that the CS and FS increase by 6% and 1.76% when cement is replaced by 16% FA and 8% of alccofine. Ansari et al. [43] studied the behaviour of concrete by partially replacing cement with alccofine in combination with FA for the M30 grade concrete. They found that the strength of concrete is improved on replacement up to 15%. Reddy et al. [44] replaced cement with

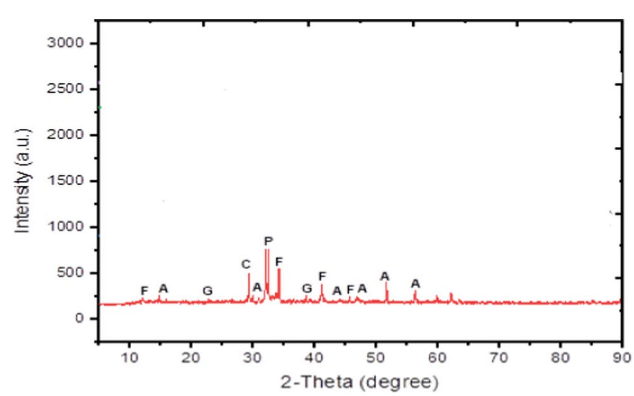



**Fig. 1** XRD of cement

**Table 1** Physical properties of OPC

| Description | Fineness ($m^2$/kg) | Normal consistency (%) | Setting time | | Compressive strength (MPa) | | |
|---|---|---|---|---|---|---|---|
| | | | Initial (min) | Final (min) | 3 days | 7 days | 28 days |
| Results | 309 | 28 | 50 | 460 | 35.4 | 45.7 | 62.4 |

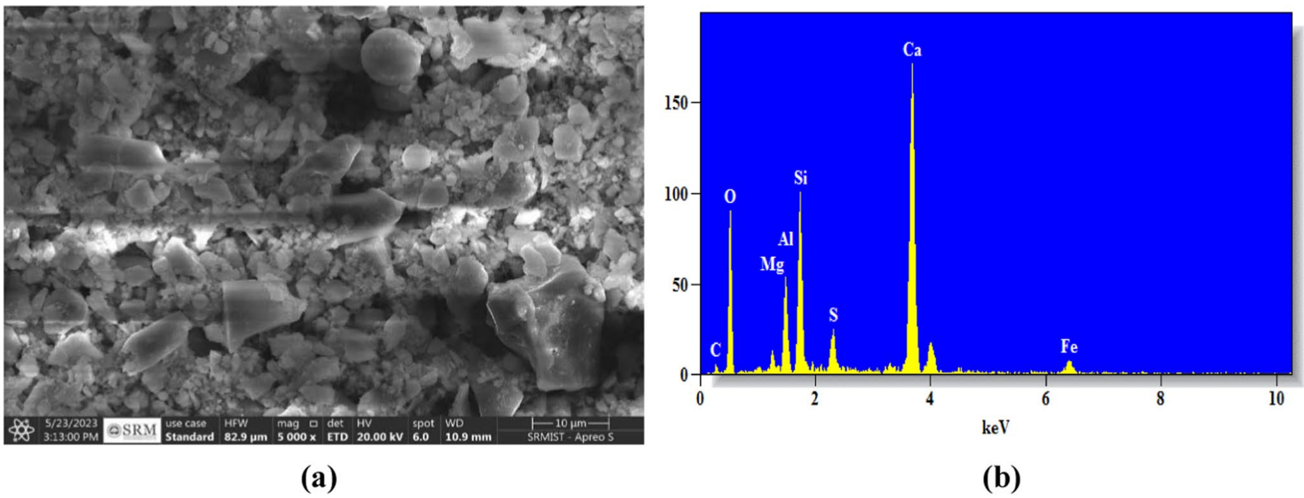



**Fig. 2** SEM images and EDX of OPC

**Table 2** Chemical composition of OPC

| Composition | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $K_2O$ | $Na_2O$ | LOI |
|---|---|---|---|---|---|---|---|---|---|
| % | 21.31 | 5.71 | 5.55 | 61.20 | 1.35 | 2.17 | 0.59 | 0.12 | 2 |

**Table 3** Physical properties of COC

| Description | Fineness ($m^2$/kg) | Normal consistency (%) | Setting time | | Compressive strength (MPa) | | |
|---|---|---|---|---|---|---|---|
| | | | Initial (min) | Final (min) | 3 days | 7 days | 28 days |
| Values | 332 | 32 | 75 | 535 | 20.9 | 31 | 42.6 |

**Table 4** Chemical composition of COC

| Composition | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $K_2O$ | $Na_2O$ | LOI |
|---|---|---|---|---|---|---|---|---|---|
| % | 31.93 | 11.49 | 5.78 | 42.66 | 2.59 | 2.73 | 0.50 | 0.10 | 2.22 |

5–20% of alccofine in combination with 5–20% of FA in concrete and achieved a maximum CS of 52 MPa for the combination of 20% of FA with 20% of alccofine. Similarly, Sambangi et al. [45] replaced cement with 5–20% of alccofine in combination of 5–20% of FA in concrete and achieved a maximum CS of 62.74 MPa for the combination of 15% of FA with 15% of alccofine. Reddy and Ramadoss [46] developed ultra-high-performance concrete (UHPC) using alccofine with GGBS and found that UHPC attains 80% of the characteristic CS within 7 days itself. Upadhyay and Jamnu [47] also reported that the strength gain of the concrete produced from alccofine and FA was excellent between 3 and 7 days, whereas strength gain between 7 and 28 days was comparatively lower. Saiya et al. [48] compared the performance of FA–alccofine concrete mix and GGBS–alccofine concrete mix and concluded that the FA–alccofine mix has better flowability than the GGBS–alccofine mix, whereas FA–alccofine mix possesses better CS than the GGBS–alccofine mix. Hence, it is essential to optimise the mix that produces better mechanical properties with better flow properties. So, an attempt has been made to replace alccofine in composite cement (COC) concrete in various proportions. COC is prepared using waste materials such as FA, slag and silica fume. COC is the cement in which a proportion of the cement clinker is replaced by industrial waste materials such as FA and slag. These industrial waste materials react with the hydration products of the cement forming additional hydrates, which contribute to the development of strength in concrete [49–51]. The hydration reaction of the composite cement based on the combination of cement with FA conforms to BS:3892 (Part-I) [52] or GGBS conforms to BS: 6699 [53] and is generally slower than the cement that conforms to BS:12–1996 [54], which results in a low rise in temperature. COC is developed accordance with Indian standards IS-16415–2015 [55], which

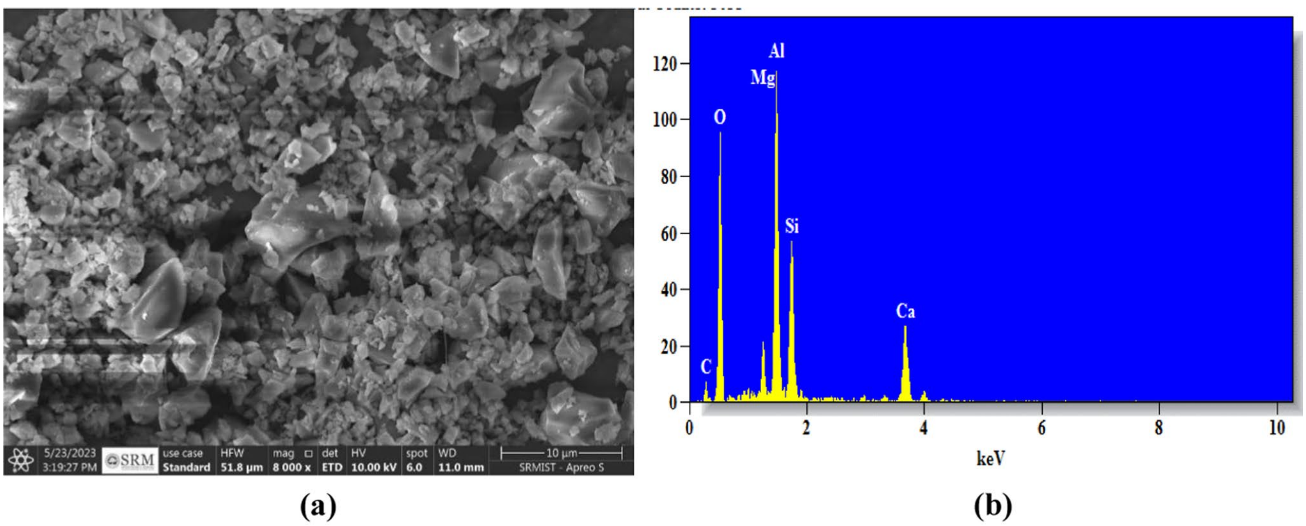



**Fig. 3** SEM images and EDX of COC

**Table 5** Chemical composition of ALC

| Composition | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | LOI |
|---|---|---|---|---|---|---|
| % | 35.30 | 21.4 | 1.20 | 32.20 | 8.20 | 1.7 |

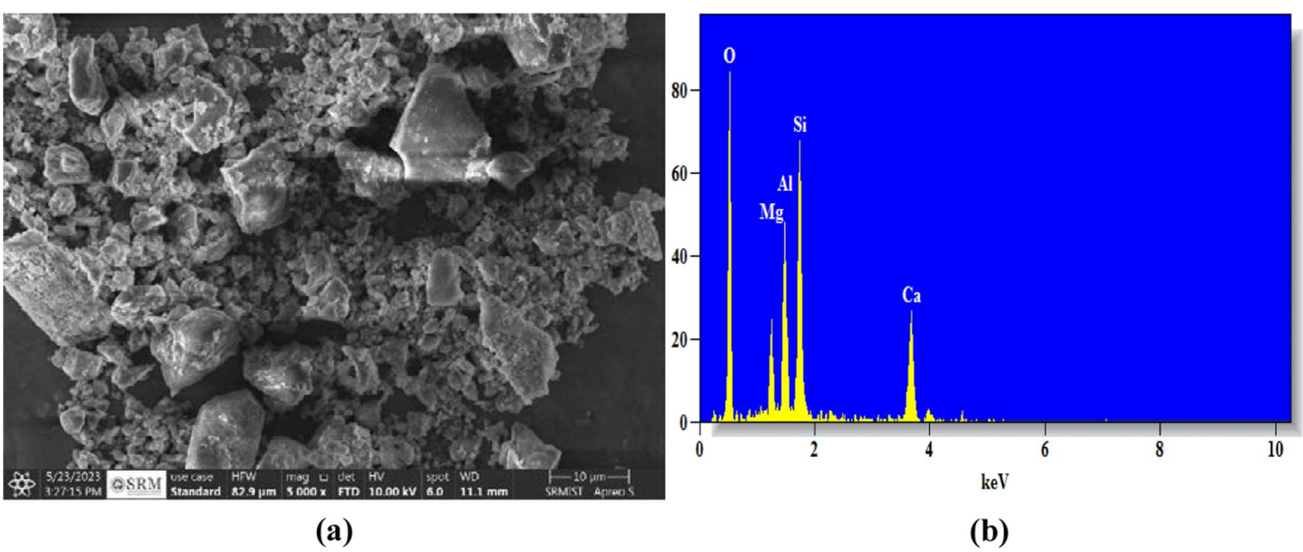



**Fig. 4** SEM and EDX of ALC

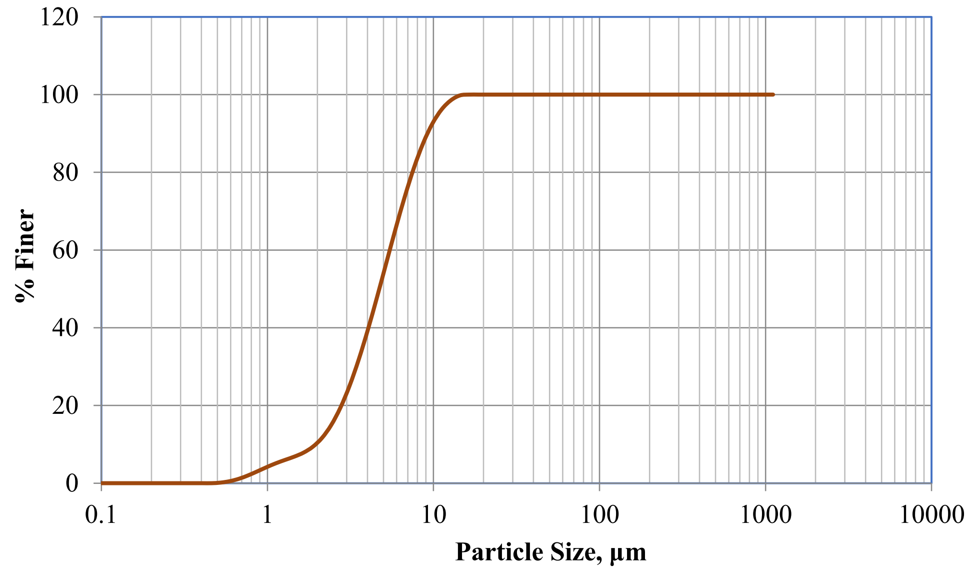



**Fig. 5** Particle size distribution of alccofine

pertain to COC. COC is the combination of 35–65% of OPC, 12–35% of FA and 20–50% of GGBS [56]. COC is one of the recent innovations in construction material research. Therefore, only a limited number of reports are available on the properties of COC concrete using alccofine as an SCM [57]. On the other hand, the utilisation of alccofine is limited due to lack of proper code for its utilisation. For example, the Indian Standard (IS) concrete design mix guidelines IS-10262:2019 [58] recommends the use of GGBS, FA and silica fume as a partial replacement for cement but does not advocate the usage of the ultrafiner materials like alccofine [59, 60]. The aim of this study is to examine the mechanical properties and undertake the microstructural characterisation of COC concrete in which COC is partially replaced by alccofine. This study will prove highly beneficial to the construction industry. Alccofine's potential as a game changer in concrete is undeniable. The use of alccofine marks a stride towards sustainability, as industrial waste materials are used in construction. Embracing industrial waste materials like alccofine in COC leads to stronger, greener structures, which reduce carbon footprint.

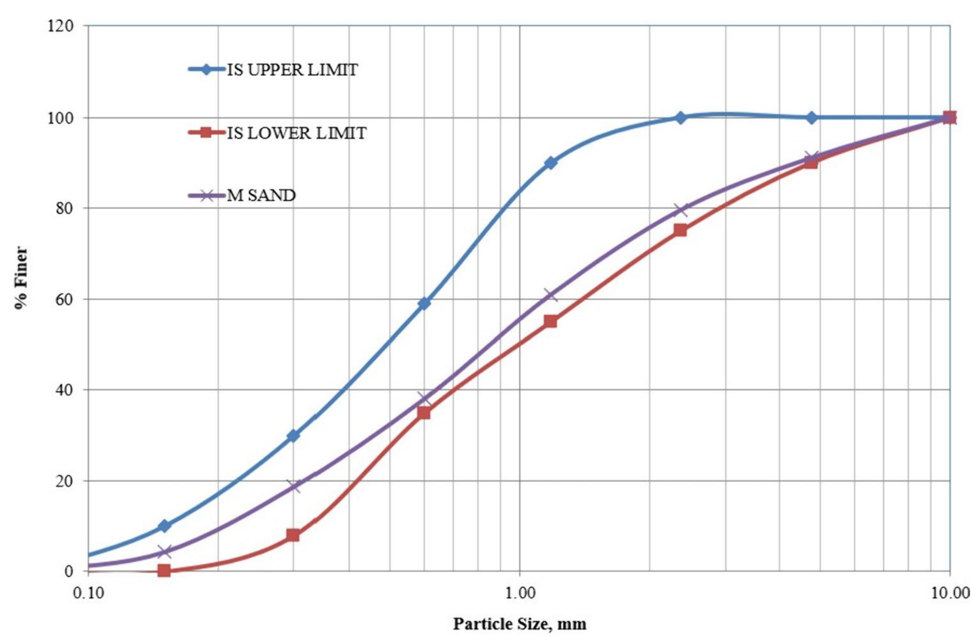



**Fig. 6** Gradation curve of fine aggregate

# Materials and methodology

The current study examines the effect of SCMs such as alccofine on the mechanical properties and microstructure of COC. Comprehensive experimental tests such as slump cone, CS, STS, FS and modulus of elasticity (MOE) test have been conducted to examine the effect of SCM (alccofine) on the mechanical properties of COC.

## Materials

### Ordinary Portland cement (OPC)

The cement utilised was Coromandel King OPC 53 grade, which conforms to IS:12,269–1987 [61]. The characteristic composition of the Ordinary Portland cement was determined using XRD analysis, and the XRD images are shown in Fig. 1. The presence of alite, belite, aluminate periclase and calcite can be observed at peaks of 56.385°, 32.514°, 34.281° and 29.350°, respectively. The physical properties are given in Table 1, and the chemical composition of OPC as determined for EDX analysis is displayed in Fig. 2 and Table 2.

### Composite cement (COC)

The Chettinad composite cement containing 60% OPC clinker, 20% GGBS and 20% fly ash according to IS-16415:2015 [55] is used in this study. The physical properties of this cement are given in Table 3. The chemical compositions and the amount of COC are listed in Table 4 with reference to the peak positions and intensities ascertained from the EDX pattern. The chemical composition of COC as determined for EDX analysis is displayed in Fig. 3.

### Alccofine

Alccofine is the slag residue produced from the iron ore industries in India. Alccofine 1100 series has a low amount of calcium silicate, whereas alccofine 1200 series has a high amount of calcium silicate. The fine, microfine and ultrafine particle sizes of alccofine are represented as 1201, 1202, and 1203 in alccofine 1200 series. Alccofine-1101, Alccofine-1203 and Alccofine-1206 are the most commercially available alccofine compositions in the market [62]. Alccofine-1203 used in this study as a partial replacement material for composite cement conforms to ASTM-C989-99 [63]. Because of the granulation process, Alccofine-1203 contains ultrafine particles with a fineness of 12,000cm$^2$/gm with a unique chemistry. The chemical compositions of the alccofine with reference to the peak positions and intensities as determined from the EDX pattern are given in Table 5. Alccofine interacts synergistically with ground-granulated blast furnace slag (GGBS) and fly ash, both of which are supplementary cementitious materials in the composite cement. These materials undergo pozzolanic reactions themselves, reacting with calcium hydroxide and contributing to the formation of additional C-S–H gel during hydration process. Alccofine presence intensifies these reactions, augmenting the overall pozzolanic activity and enhancing the durability and strength of the concrete. The chemical composition of composite cement (COC) suggests a favourable environment for C-S–H (calcium silicate hydrate) formation, particularly


**Fig. 7** Modulus of elasticity test setup

**Table 6** Optimised mix for OPC 53, COC and COC + 10% ALC

| Description | OPC 53 | | | COC | | | COC + 10% ALC | | |
|---|---|---|---|---|---|---|---|---|---|
| | M25 | M40 | M60 | M25 | M40 | M60 | M25 | M40 | M60 |
| Cement (kg/m$^3$) | 300 | 410 | 500 | – | – | – | – | – | – |
| Composite cement (kg/m$^3$) | – | – | – | 330 | 450 | 550 | 297 | 405 | 495 |
| Alccofine (kg/m$^3$) | – | – | – | – | – | – | 33 | 45 | 55 |
| M-Sand (kg/m$^3$) | 857 | 847 | 809 | 831 | 814 | 765 | 831 | 814 | 765 |
| Coarse Aggregate (kg/m$^3$) | 1085 | 1002 | 958 | 1044 | 963 | 905 | 1044 | 963 | 905 |
| W/C ratio | 0.55 | 0.39 | 0.33 | 0.51 | 0.36 | 0.30 | 0.51 | 0.36 | 0.3 |
| Superplasticizer (%) | 0.35 | 0.5 | 0.55 | 0.5 | 0.5 | 0.7 | 0.70 | 1 | 1.1 |

due to the high CaO content (42.66%). Both $Al_2O_3$ (11.49%) and $SiO_2$ (31.93%) contribute to C–S–H formation. The presence of ground-granulated blast furnace slag (GGBS) and fly ash acts as supplementary cementitious materials (SCMs). They participate in hydration reactions, consuming CaO and forming additional C–S–H gel. Alccofine, though primarily considered an inert filler, possesses some pozzolanic activity. It can react with CaO released during hydration to form additional C–S–H gel, contributing further to strength and durability. The SEM image of alccofine as shown in Fig. 4 indicates that the particles are irregular in shape and have sharp edges. The particle size distribution of alccofine is presented in Fig. 5. The graph shows that the majority of the particles are between 1 and 10 µm in diameter. This indicates that alccofine is a very fine material, which could contribute to providing beneficial effects on the properties of concrete.

### Fine aggregates

The fine aggregate used is locally available manufactured sand, which passes through sieve of 4.75 mm, conforming to grading zone II of IS: 383–1970 [64] with water absorption of 0.67%, specific gravity of 2.71 and fineness modulus of 2.57. Figure 6 presents the gradation curve of fine aggregate.

### Coarse aggregates

The coarse aggregate with maximum size of 12.5 mm, conforming to IS: 383–1970 [64], was used. Its fineness modulus was 7.2, specific gravity 2.7 and water absorption 0.62%.

### Superplasticizer

The commercially available SP is based on the copolymer of acrylic acid and polyethylene glycol (PEG) referred to as polycarboxylate ether (PCE). A commercially available SP known as Master Glenium ACE 30 from BASF chemical company is used as the chemical admixture. The admixture has a specific gravity of 1.82 and solid content of 25% and was added to concrete.

## Mix proportioning

The concrete mixture was designed aiming for the target strength using the conceptual proportioning strategy by keeping the binder to total aggregate and fine to coarse aggregate ratio proportioned as per IS:10,262–2019 [58]. A total of nine trial mixes were developed for the M20, M40 and M60 grade concrete mixes by replacing COC by 5%, 10% and 15% of alccofine. Finally, three optimised mixes with 10% of alccofine were selected for M20, M40 and M60 grade concrete mixes, respectively, which offer between workability and mechanical properties as presented in Table 6. The workability and mechanical properties of these optimised mix are compared with the OPC and COC mixes.

Initially, the coarse aggregate and fine aggregate were fed into the mixer and mixed for 2 min. Then, the required amount of cement was introduced into the mixture and mixed for 2 min in the dry condition. Then, the water and accelerator mix were added in the mixer containing cement, coarse and fine aggregate and mixed for the period of 4 min.

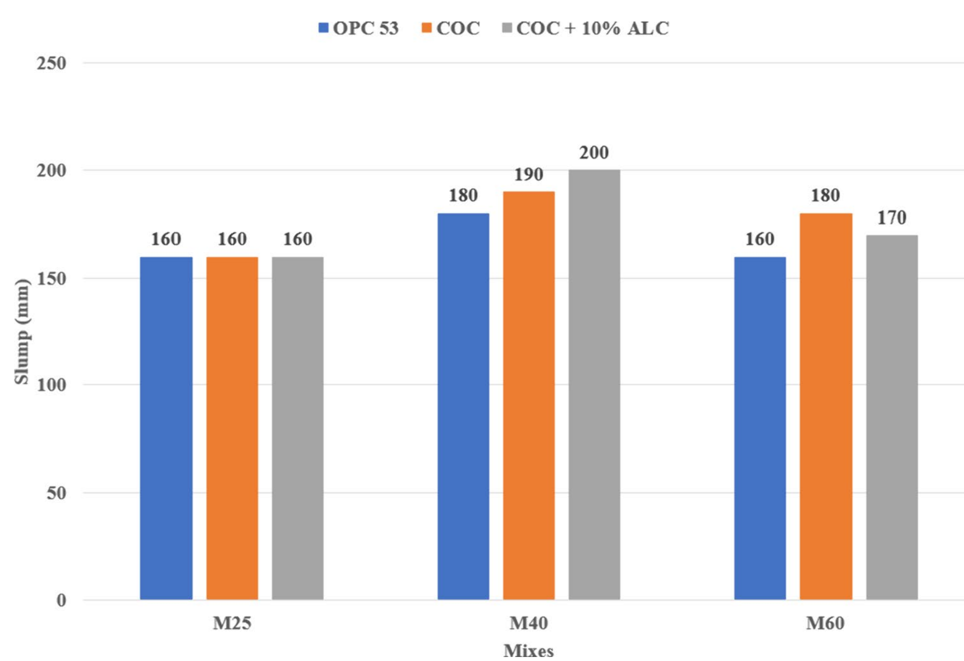



**Fig. 8** Workability of different grades of concrete

## Experimental investigation

The primary aim of this study is to examine the effect of the partial replacement (10%) of composite cement by alccofine. In order to achieve the objective of this study, various tests (slump cone test, CS test, elastic modulus test, STS and FS test) were conducted. Three samples are tested to compute the average CS value for each concrete mix.

### Workability

The prepared fresh concrete was tested to determine the workability properties using slump cone, and the slump value was noted. The slump cone test was performed using the apparatus called slump cone with height of 300 mm, with top diameter and bottom diameter of 100 m and 200 mm as per IS-1199:1959 [65] standards.

### Compressive strength test

The CS test was conducted as per IS: 516–1959 with a 100-mm cube [66]. After 24 h of curing, the specimens were demoulded and cured in water. After 28 days of water curing, the specimens were tested for its properties. The test was done by loading the test specimen using the compressive testing machine (CTM) of 1000 kN capacity having a least count of 1 kN.

### Modulus of elasticity

As per IS:5816–1959 [67], cylindrical specimens of 100 mm diameter and 200 mm height were cast and tested to determine the modulus of elasticity. All the specimens were demoulded after 24 h of moist curing and then introduced into the water tank for curing. After 28 days of curing, the specimens were tested for its properties. The test was done as per IS:516-1959 [66] standards using the universal testing machine (UTM) of 1000 kN capacity having a least count of 1 kN as shown in Fig. 7.

### Split tensile strength test

In order to study the tensile strength, cylinder specimens of height 200 mm and diameter 100 mm were cast for testing. All the specimens were demoulded after 24 h and then immersed in water for curing. After 28 days of curing, the specimens were tested for its properties. The test was done as per IS: 5816-1959 [68] standards using the universal testing machine (UTM) of 1000 kN capacity having a least count of 1 kN.

### Flexural strength test

A prism specimen of size 100 mm × 100 mm × 500 mm specimen was cast for testing FS or modulus of rupture. All the specimens were demoulded after 24 h of moist curing and then introduced into water tank for curing. After 28 days of curing, the specimens were tested for its properties. The test was done as per IS:516-1959 [66] standards using the

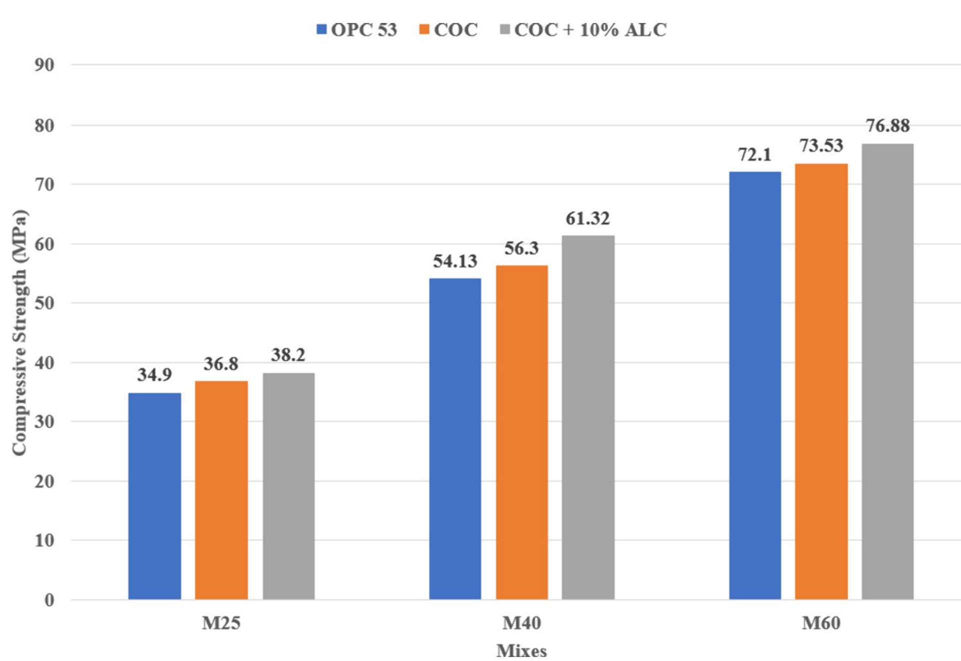



**Fig. 9** Compressive strength of different grades of concrete

universal testing machine (UTM) of 1000 kN capacity having a least count of 1 kN.

## Results and discussion

### Workability

The slump flow value of the M25, M40 and M60 COC concrete mixes was 5.55–12.5% higher than the slump flow value of the M25, M40 and M60 OPC concrete mixes. The slump flow value of the M25, M40 and M60 COC + 10% ALC concrete mix was 5.25–12.5% higher than the slump flow value of the M25, M40 and M60 COC concrete mixes. For the M25 mix, there was no change in the slump flow value when OPC was replaced with COC and COC + 10% ALC. Generally, the addition of FA into concrete increases the slump value due to the spherical shape of the FA particles. This shape causes the ball bearing effect, resulting in the improvement in slump value of the concrete. However, the combined addition of FA and GGBS as COC in the concrete mix does not lower the slump value. This may be due to the elongated shape of the GGBS particles and also high surface area of GGBS, thus requiring more water for wetting. However, the amount of the superplasticiser was increased to 0.5 kg/m$^3$ without affecting the mechanical properties. Similarly, the addition of ALC into the COC reduces the slump flow value. However, the amount of the superplasticiser was increased to 0.7 kg/m$^3$ without affecting the mechanical properties. Figure 8 presents the slump flow of the OPC 53, COC and COC + 10% ALC for M25, M40 and M60 grades of concrete.

For the M40 mix, there was an improvement in the slump flow value when OPC was replaced with COC and COC + 10% ALC. The slump flow value of the COC of M40 grade concrete is 5.55% higher than the OPC mix. The slump flow value of COC with 10% ALC mix of M40 grade concrete is 5.25% higher than the COC mix. The partial replacement of COC by alccofine produces a high volume of paste due to its lower density, and this high volume of paste reduces the friction between binder–aggregate interface, improves the cohesiveness and plasticity and thus prompts increased workability. For the M60 mix, there was an improvement in the slump flow value when OPC was replaced by COC. For the M60 mix, there was a reduction in slump flow value when COC was replaced with 10% ALC, though the addition of 1.1 kg/m$^3$ of superplasticiser does not lead to any improvement in the slump flow value. The slump flow value of the COC with 10% ALC mix of M60 grade concrete is 6.25% lower than the OPC mix. This may be because of high water absorption, surface area and fineness of alccofine materials. A higher amount of alccofine will absorb more water due to its finer particle size and also as a result of its increased surface area [69].

### Compressive strength

It was observed that the replacement of OPC by COC cement in concrete increases the CS by 5.30%, 3.93% and 1.96%, respectively, for M25, M40 and M60 grade concretes. Also, it was observed that the partial replacement of COC cement with 10% of ALC increases the CS by 9.02%, 12.46% and 6.42% for M20, M40 and M60 grade concretes,

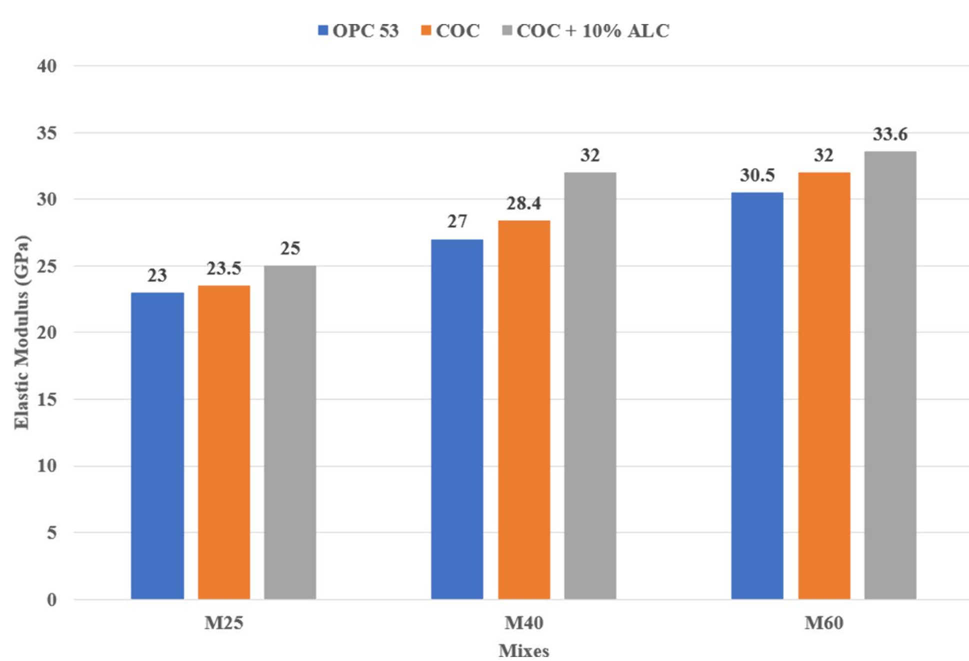
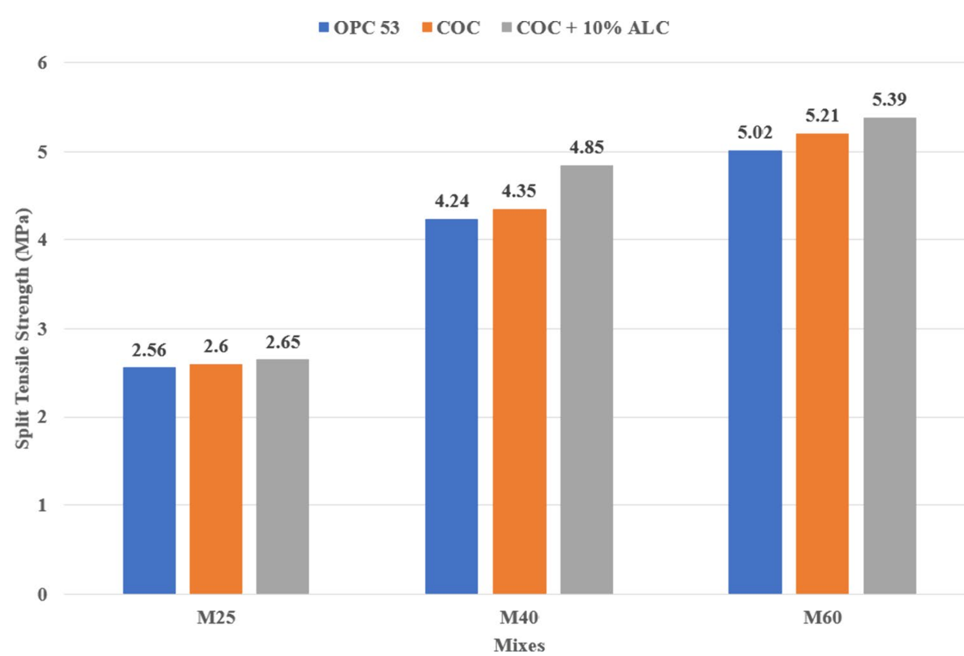



**Fig. 10** Elastic modulus of different grades of concrete

respectively. For the M25 grade concrete, the replacement of OPC with COC cement in concrete increases the CS by 5.30% and the partial replacement of COC cement with 10% of ALC increases the CS by 9.02%. For the M40 grade concrete, the replacement of OPC with COC cement in concrete increases the CS by 3.93%, while the partial replacement of COC cement with 10% of ALC increases the CS by 12.46%. For the M60 grade concrete, the replacement of OPC with COC cement in concrete increases the CS by 1.96%, whereas the partial replacement of COC cement with 10% of ALC increases the CS by 6.42%. Figure 9 shows the variation of CS of OPC 53 concrete, COC concrete and COC + 10% ALC concrete at 28 days of curing.

It was concluded that the addition of 10% alccofine into the composite cement (60% of OPC + 20% GGBS + 20%FA) increases the CS. Reddy and Ramadoss [46] also achieved an improvement in the CS of concrete with the addition of alccofine into the concrete mix containing FA and GGBS. They achieved a 6.69% improvement in CS on the addition of alccofine of 160 kg/m$^3$; in this study, a maximum of 9.2% improvement in CS was achieved with the addition of 45 k/m$^3$ of alccofine. This improvement in CS is due to the homogeneity of the concrete matrix, where materials with the same chemical composition display a stronger bonding. The higher production of CSH gel also contributes to an improvement in CS. The chemical composition of COC offers a favourable environment for C–S–H formation, especially due to the presence of high $CO_2$ content (42.66%) along with $Al_2O_3$ (11.49%) and $SiO_2$ (31.93%). GGBS and FA in the COC participate in the hydration reactions, consuming CaO and forming additional C–S–H gel. Alccofine, though primarily considered an inert filler, possesses some pozzolanic activity. It can react with CaO released during hydration to form additional C–S–H gel, contributing further to strength and durability. Srinath and Patnaikuni [70] reported that the replacement of cement with 10% alccofine can increase the CS by 8%. However, in this study, more than 8% improvement in CS was achieved when composite cement (60% of OPC + 20% GGBS + 20%FA) was replaced by 10% alccofine. However, some studies reported that the addition of high amount of alccofine decreases the CS. Kavyateja et al. [42] realised a reduction in CS on the addition of 15% alccofine into the concrete mix containing 72% OPC and 15% FA. The decrease in strength with the addition of alccofine beyond 10% is due to the increased water demand by alccofine, which prompts a reduction in the pore bonding strength [71]. Reddy and Meena [72] obtained a reduction in CS on the addition of 8% of alccofine into the concrete mix containing 72% of OPC with 20% of GGBS. In line with the outcomes of Reddy and Meena [72], a partial replacement of COC with alccofine is more beneficial than the replacement of OPC with a combined addition alccofine and GGBS in concrete. Reddy et al. [73] obtained the maximum CS of 55.21 N/mm$^2$ for M40 grade concrete when OPC cement was partially replaced by 15% alccofine. Qureshi et al. [74] noted a maximum CS of 59.56 N/mm$^2$ on the partial replacement of OPC cement by 18% FA and 12% alccofine. In this study, the maximum CS of 61.32 N/mm$^2$ was achieved for M40 grade concrete on the partial replacement of COC cement by only 10% alccofine at 28 days. This demonstrates the beneficial effect of mechanical properties on partially replacing COC cement with alccofine in concrete for construction applications.

**Fig. 11** Split tensile strength of different grades of concrete



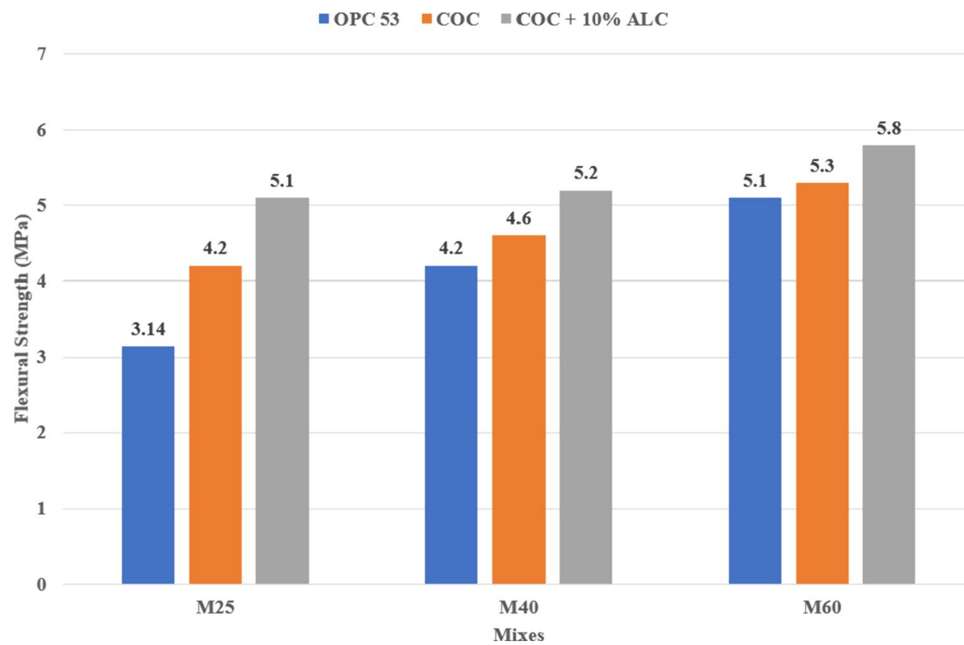



**Fig. 12** Flexural strength of different grades of concrete

## Modulus of elasticity (MOE)

The replacement of OPC with COC cement in concrete results in an increase of MOE by 2.15%, 5.05% and 4.8% for M25, M40 and M60 grade concretes, respectively. Similarly, the partial replacement of COC cement with 10% of ALC results in the increase of the MOE by 8.33%, 16.95% and 9.67% for M20, M40 and M60 grade concretes, respectively. For M25 grade concrete, the replacement of OPC with COC cement in concrete increases the MOE by 2.15%, whereas the partial replacement of COC cement with 10% of ALC increases the MOE by 8.33%. For the M40 grade concrete, the replacement of OPC with COC cement in concrete increases the MOE by 5.05%, while a partial replacement of COC cement with 10% of ALC increases the MOE by 16.95%. For the M60 grade concrete, the replacement of OPC with COC cement in concrete increases the MOE by 4.8%, whereas the partial replacement of COC cement with 10% of ALC increases the MOE by 9.67%. Figure 10 shows the variation of MOE of OPC 53 concrete, COC concrete and COC + 10% ALC concrete at 28 days of curing.

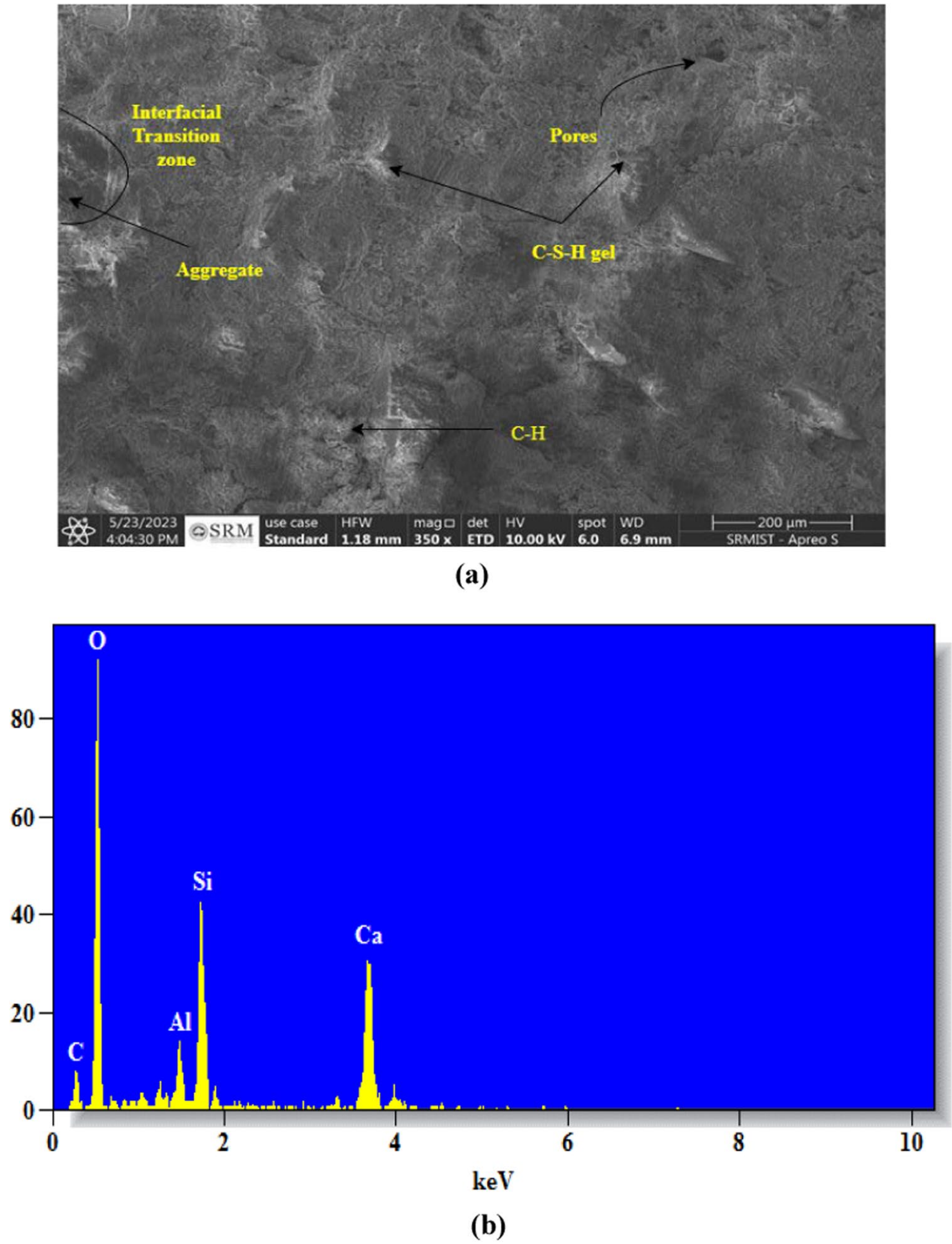
The alccofine particles are much finer than the other cementitious materials like fly ash, GGBS and cement. Hence, the voids that are formed in the concrete between the FA, GGBS and cement are filled by the alccofine particles, resulting in a closely packed structure. During testing, the load transfer from one grain to another as a result of strain increases eventually at the rate of stress, thereby contributing to an improvement of elastic modulus.

## Split tensile strength

It was observed that the replacement of OPC with COC cement in the concrete increases the STS by 1.56%, 2.59% and 3.7% for M25, M40 and M60 grade concretes, respectively. Also, it was observed that the partial replacement of COC cement with 10% ALC increases the STS by 1.9%, 11.4% and 3.45% for M20, M40 and M60 grade concretes, respectively. For the M25 grade concrete, the replacement of OPC with COC cement in the concrete increases the STS by 1.56%, while a partial replacement of COC cement with 10% of ALC increases the STS by 1.9%. For the M40 grade concrete, the replacement of OPC with COC cement in concrete increases the STS by 2.59%, while a partial replacement of COC cement with 10% of ALC increases the STS by 11.4%. For the M60 grade concrete, that replacement of OPC with COC cement in the concrete increases the STS by 3.7%, whereas a partial replacement of COC cement with 10% of ALC increases the STS by 3.45%. Figure 11 shows the variation of STS of OPC 53 concrete, COC concrete and COC + 10% ALC concrete at 28 days of curing.

The improvement in tensile strength might be due to the improved properties of the concrete matrix and strong interphase bond between the binders (i.e., COC and alccofine) and aggregates [75]. Therefore, an interfacial transition zone (ITZ) plays a significant part in the improvement of STS. By utilising microparticles like FA in COC and alccofine, the ITZ becomes denser, resulting in an improvement in STS. Sagar and Sivakumar [76] achieved a 2.5% improvement in STS of concrete containing 420 kg/m$^3$ of OPC, 120 kg/m$^3$ of FA and 84% kg/$^3$ of alccofine at 28 days. In this study, a 11.4% improvement in STS was achieved with the addition

Fig. 13 SEM images and EDX of M25 OPC concrete

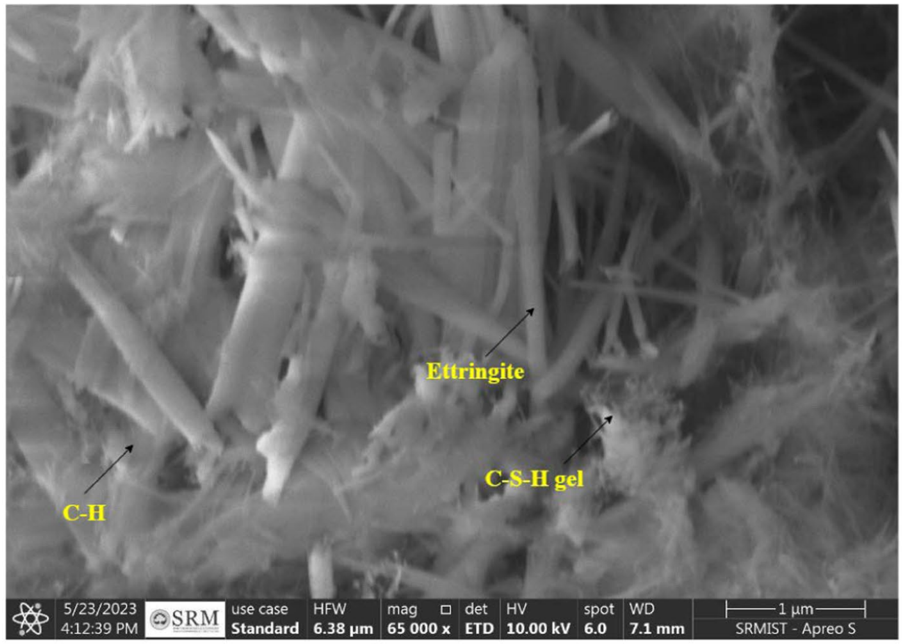



of 45 kg/m$^3$ of alccofine to the concrete containing 405 kg/m$^3$ of COC at 28 days. This demonstrates the beneficial effect of using alccofine as a partial replacement to COC cement in concrete production with regard to STS.

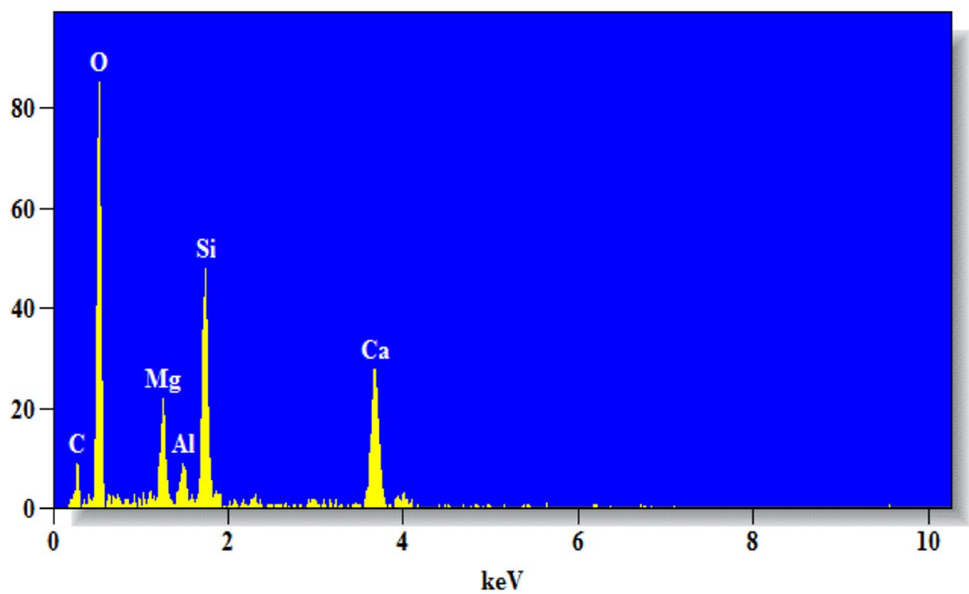
## Flexural strength

The replacement of the OPC with COC cement in concrete results in an increase of FS of 33.76%, 9.52% and 3.92% for M25, M40 and M60 grade concretes, respectively. Similarly, the partial replacement of COC cement with 10% of ALC results in an increase of FS by 21.42%, 13.04% and 9.43% for M20, M40 and M60 grade concretes, respectively. For the M20 grade concrete, the replacement of OPC with COC cement in the concrete increases the FS by 33.76%, whereas a partial replacement of COC cement with 10% ALC increases the FS by 21.42%. For the M40 grade concrete, the replacement of OPC with COC cement in concrete increases the FS by 9.52%, while a partial replacement of COC cement with 10% ALC increases the FS by 13.04%. For the M60 grade concrete, the replacement of OPC with COC cement in the concrete increases the FS by 3.92%, whereas a partial replacement of COC cement with 10% ALC increases the

**Fig. 14** SEM images and EDX of M40 OPC concrete




**(a)**

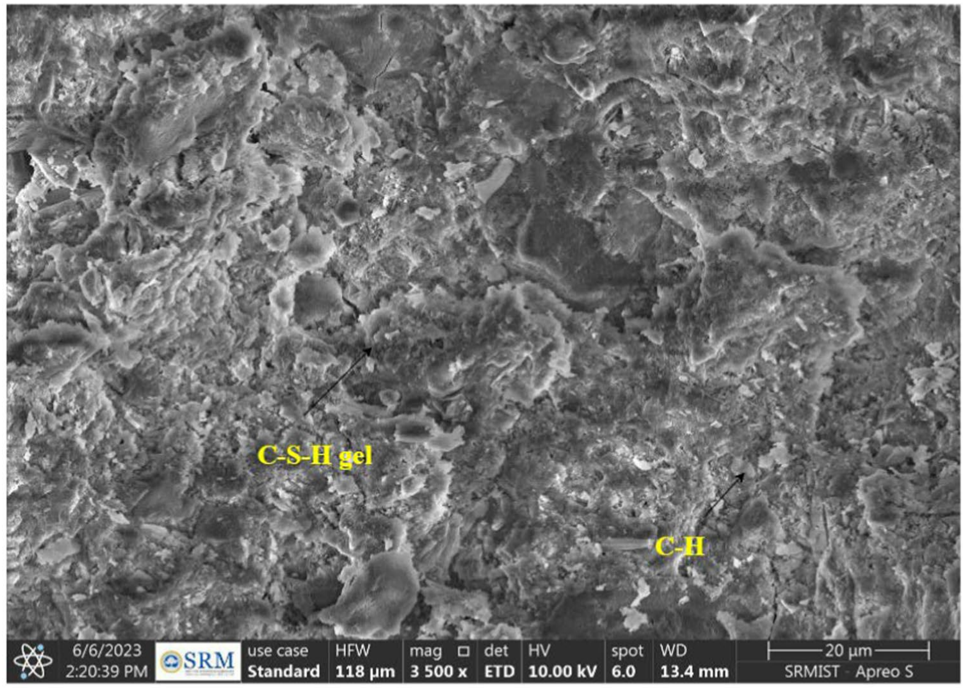



**(b)**

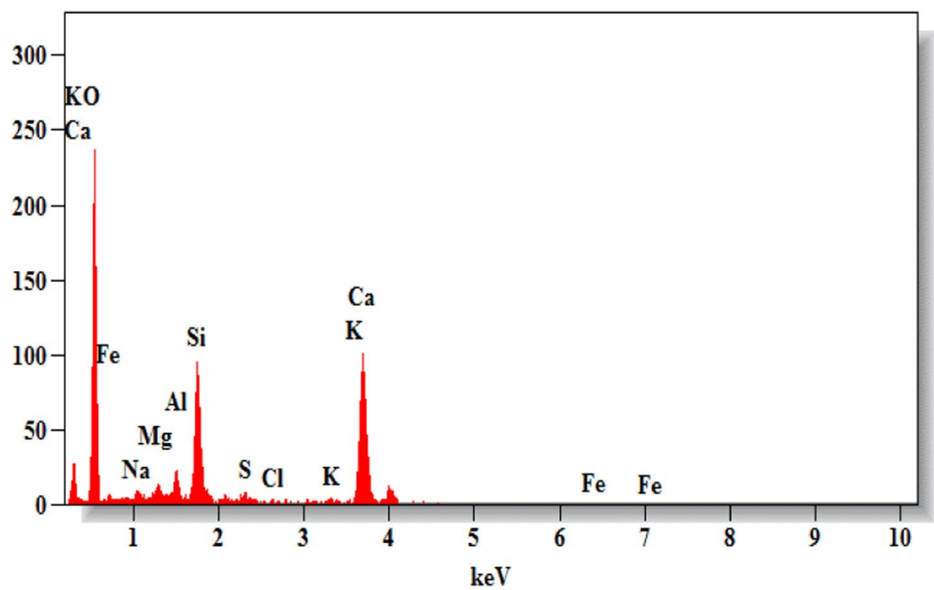
FS by 9.43%. Figure 12 shows the variation of FS of OPC 53 concrete, COC concrete and COC + 10% ALC concrete at 28 days of curing.

This improvement in flexural strength occurs because of high specific area and high pozzolanic activity of the alccofine resulting in the high production of C–S–H gel, which helps in the formation of compact structure, thus improving the strength. Also, the various oxide compounds present in the GGBS and FA (which are present in COC) contribute to improving strength by pozzolanic or hydraulic activity [77]. Sagar and Sivakumar [76] achieved a 18% improvement in FS of the concrete containing 420 kg/m$^3$ of OPC, 120 kg/m$^3$ of FA and 60% kg/$^3$ of alccofine at 28 days. In this study, a 21.42% improvement in FS was achieved with the addition of 33 kg/$^3$ of alccofine to concrete containing 297 kg/m$^3$ of COC at 28 days. This demonstrates the beneficial effect of using alccofine as a partial replacement to COC cement in concrete production with regard to FS. The failure of the specimen is

**Fig. 15** SEM images and EDX of M60 OPC concrete




(a)



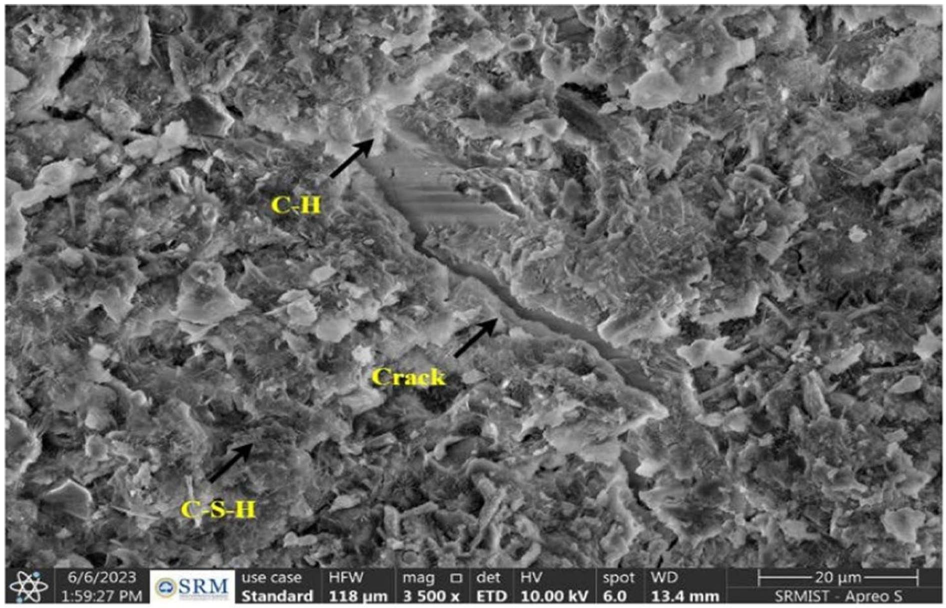

(b)

associated with the sudden break of the specimen without any initial cracks.

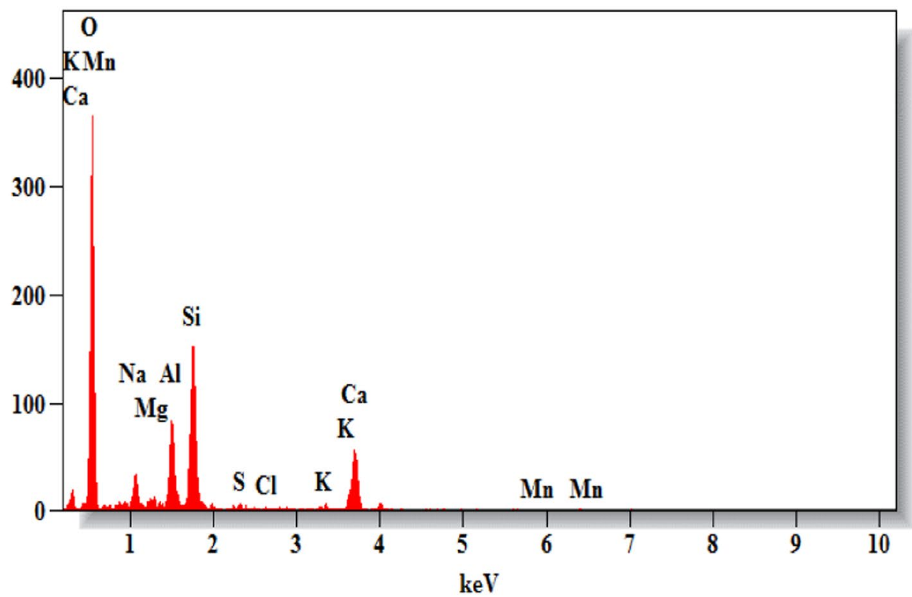
## Microstructural analysis

The surface morphology in concrete is examined using SEM images [78]. The calcium–silicate–hydrate (C–S–H) gel is a major non-crystalline phase present in the hydrated OPC that provides strength and durability to the concrete. SEM and EDX were employed to determine the C–S–H phase in the composite sample as the hydrated sample has various other phases. Elemental analysis that is spatially resolved is possible with EDX and SEM imaging. When the electron beam strikes the sample surface, EDX identifies the emitted backscattered electrons and provides the elemental composition of the sample surface. As a result, EDX can identify the existence of elements in a scanned area. The presence of an element in the total scan area of the image is indicated by

**Fig. 16** SEM images and EDX of M25 COC concrete




(a)

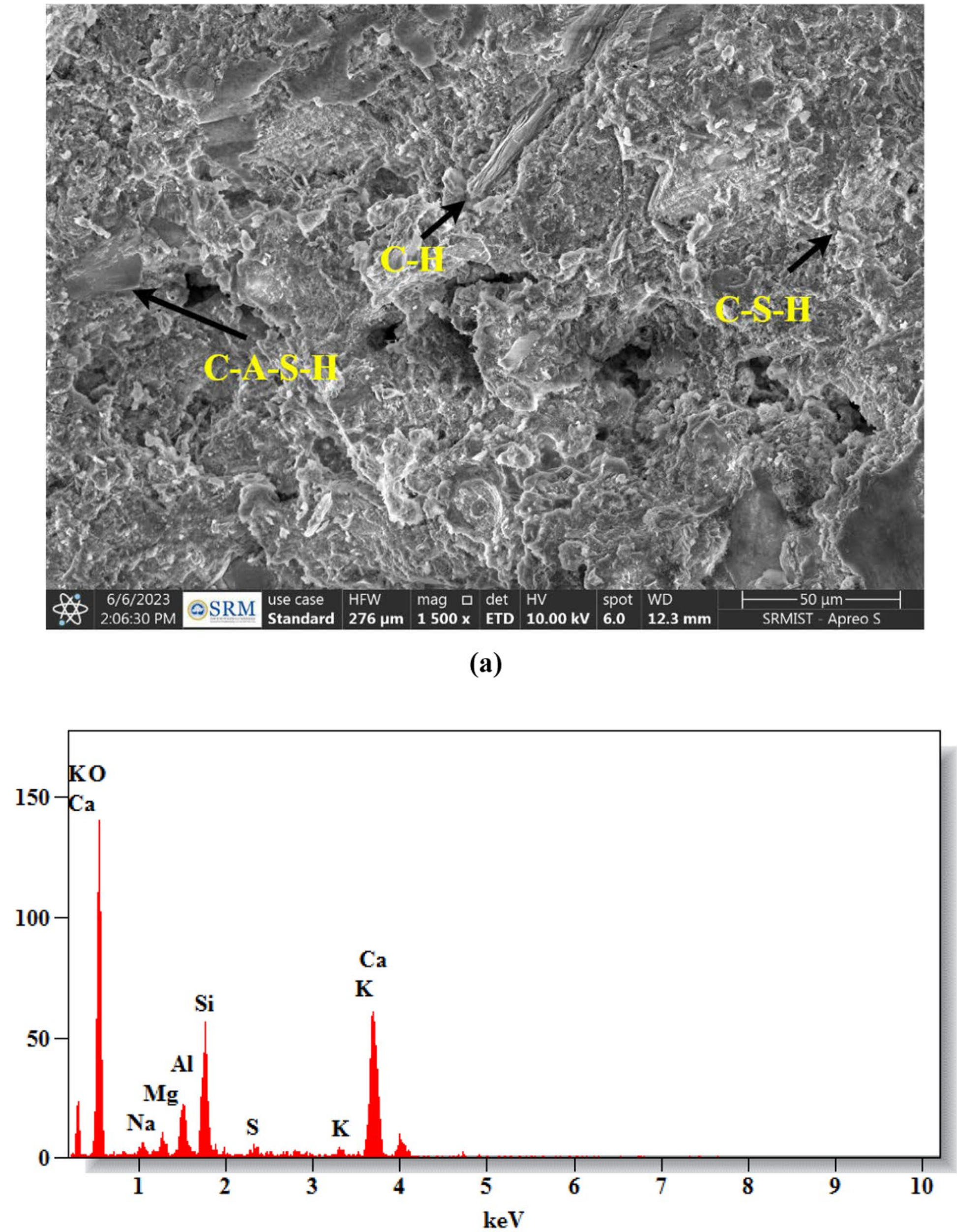



(b)

each peak in the spectrum. To identify the C–S–H gel, three components such as oxygen (O), silica (Si) and calcium (Ca) are to be located. The C–S–H phase is represented by regions with high concentrations of Si, Ca and O. Similarly, calcium hydroxide (CH) is represented by regions with the presence of Ca and O. The SEM and EDX techniques were used to analyse the elemental composition of the OPC, COC and COC + 10% ALC powder and concrete mix using the tested samples after 28 days of curing.

The morphology of C–S–H phase formation varies from poorly crystalline fibres to clusters and rectangular networks. When Portland cement paste is fully hydrated, it is the most important phase in a network of C–S–H clusters, amounting to 50–60% of the solids volume, which determines the properties of the paste. Figures 13a, 14 and 15a show only the clusters and reticular networks and ettringite is not observed. The formation of primary ettringite during early stages is essential and a beneficial component for the Portland cement system [79]. The formation of ettringite is typically associated with peak intensities of Al, S, Si and Ca as observed in Figs. 17b, 18 and 19b. Within a few minutes or hours of cement hydration, a needle-shaped

**Fig. 17** SEM images and EDX of M40 COC concrete




calcium trisulphoaluminate hydrate crystals, also known as ettringite, started to form as a result of interactions between calcium, sulphate, aluminate and hydroxyl ions. Later, the long and slender ettringite formed earlier was transformed into fibrous crystals as shown in Fig. 16a, where there are some long prismatic crystals indicating the formation of calcium hydroxide (CH) and very small fibrous crystal showing the formation of the C–S–H phase. The hexagonal plate-like structure of calcium hydroxide was found in all M25, M40 and M60 grade concretes. However, its presence was found to be higher in M60 grade. This phenomenon is primarily due to the higher cement content used in higher-grade concrete mixes. This observation is found to be in line with Srinath et al. [80], who reported that the presence of calcium hydroxide was found to be in a higher grade of concrete. SEM micrographs of the M25 OPC mix revealed wide shear cracks and interfacial cracks, whereas no cracks were observed for the M40 and M60 OPC mixes.

The SEM images and elemental peaks as obtained from the EDX analysis for COC concrete of M25, M40 and M60

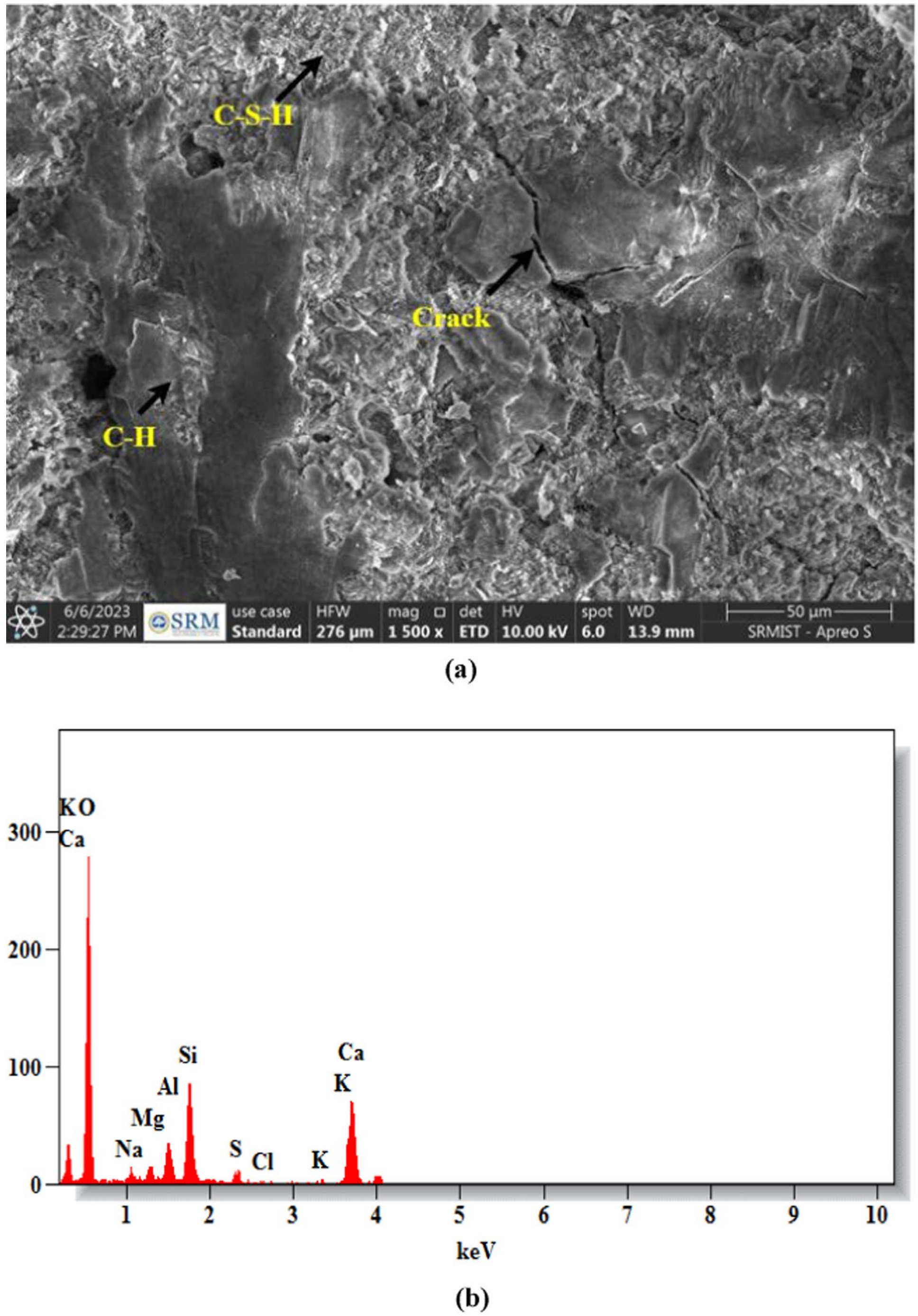
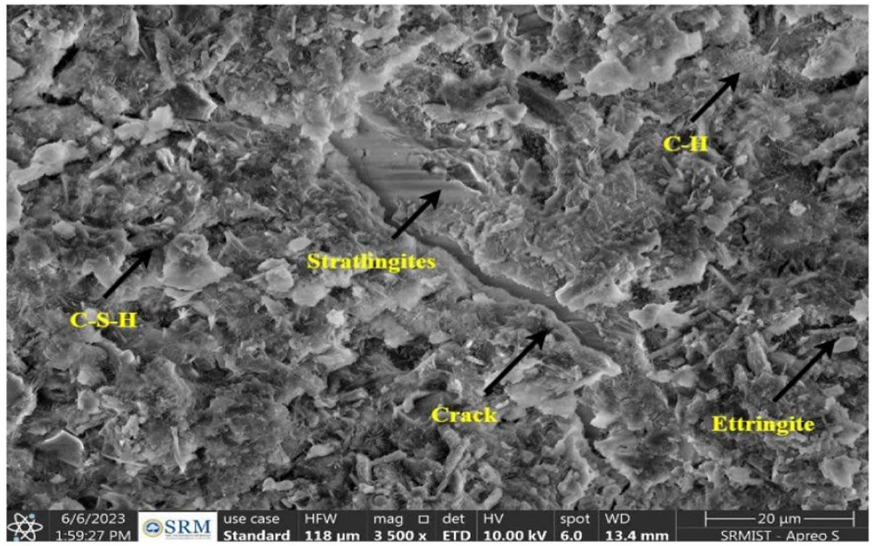
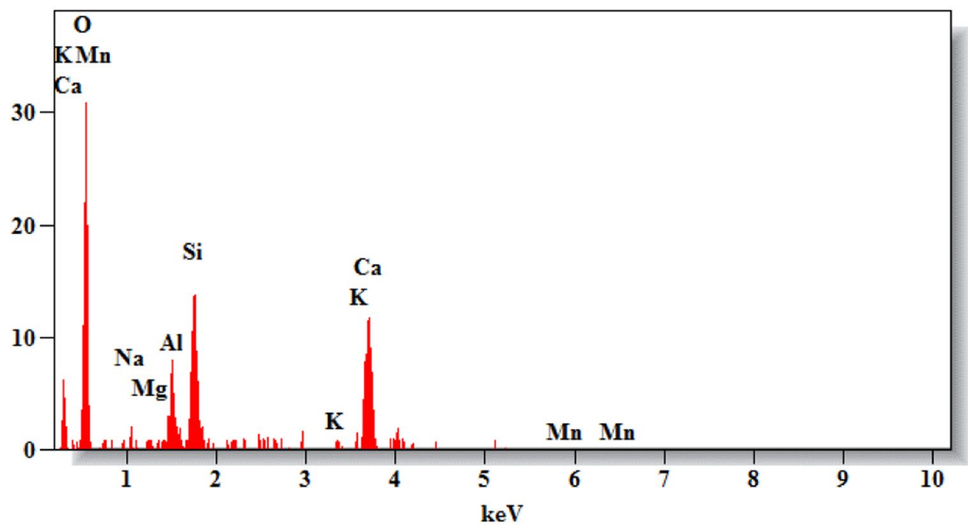



**Fig. 18** SEM images and EDX of M60 COC concrete

grades are presented in Figs. 16, 17 and 18. At increased magnification, the samples show distinguished microstructures with a slag content that further produces a denser matrix. The formation of CSH is evident. The EDX analysis confirms the presence of calcium of about 19.28%, 39.79% and 38.61% in the COC of M25, M40 and M60 grade concretes leads to the formation of the C–S–H gel. The FA particles fill in the space and begin reacting with the GGBS, which improves the characteristics. Due to the presence of FA particles, the region of crack initiation on the surface of the concrete was reduced. The elements such as Na, S, and K are formed in the hydration process, which are not seen in the OPC concrete samples. This makes a more compact gel structure and improves the mechanical




(a)




(b)

**Fig. 19** SEM images and EDX of M25 COC + 10% ALC concrete

capabilities. For M25 and M40 concretes, stratified layer-like structures, most likely made of C–A–S–H and C–S–H gels, can be detected. For M60, hydration products in the form of denser clusters can be seen. Microcracks along with small void places are observed for some specimens. Such denser morphologies prompt improvement in mechanical and durability properties.

Figures 19, 20 and 21 show the SEM images of the COC concrete added with 10% of ALC of M25, M40 and M60 grade concretes. It was observed that the solid phase of the binders consists of C–H, primarily in the form of portlandite at the early stage of the hydration process. The SEM images showed that portlandite structures are prevalent when using concrete mix with alccofine. This may have happened as a result of the pozzolanic reaction between alccofine and tricalcium and dicalcium silicates in cement. The formation of stratlingite was also observed from the SEM images of alccofine-mixed concrete. The formed stratlingite and portlandite crystal, which reacts with FA in the composite cement, formed a honeycomb structure called C–S–H gel at the lateral stages of the hydration process. Stratlingite has a primary composition of aluminium due to the availability of higher amount of alumina in alccofine. This is in line with Senff et al. [81]. Because of the formation of the C–S–H gel, the alccofine-added concrete mix possesses high strength than other mixes considered in this study, that is, the FS of the COC + 10% ALC concrete was around 21.42% higher than COC concrete mix. Table 7 presents the elemental compositions and the percentages of O, Ca, Si, Na, and Al based on the findings of the EDX study. These elemental atomic

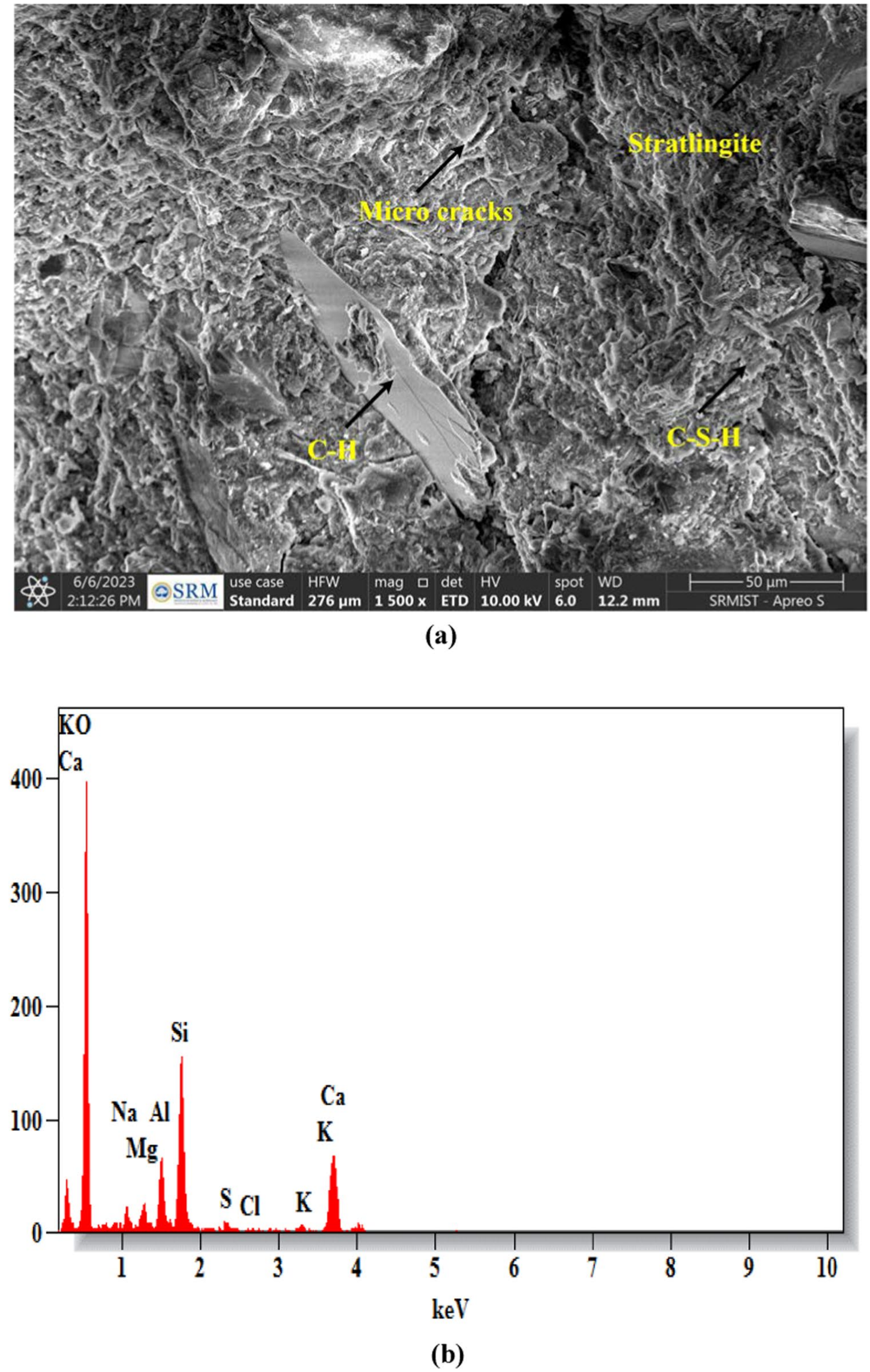



**Fig. 20** SEM images and EDX of M40 COC + 10% ALC concrete

ratios such as CA/Si, Na/Si and Al/Si are significant factors affecting the strength and durability of the COC + ALC mixes. Table 7 displays the values of this ratio for Ca/Si, Na/Si, and Al/Si ratios. These ratios are primarily in the narrow ranges of 1.12–1.83, 0.01–0.11 and 0.12–0.43 in the current set of COC + 10% ALC mix. Thus, it may be concluded that the primary elements indeed appear in the COC + 10% ALC mixtures in the following order: Ca > Si > Al > Na, possibly as constituents of C–A–S–H and C–S–H gels.

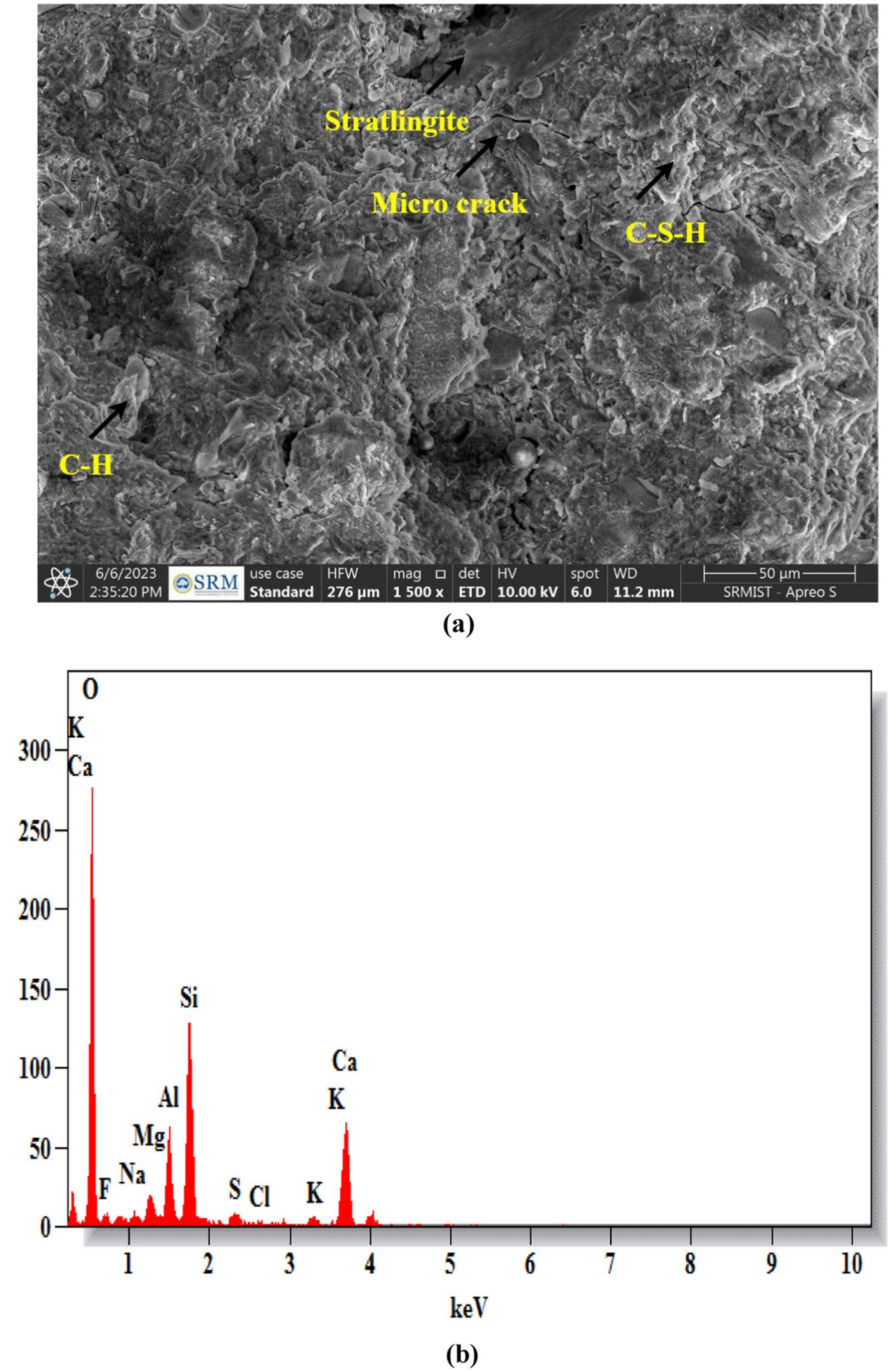



**Fig. 21** SEM images and EDX of M60 COC + 10% ALC concrete

**Table 7** Atomic (%) of COC + 10% mix using EDX analysis

| Mix | O | Na | Mg | Al | Si | Ca | Ca/Si | Na/Si | Al/Si |
|---|---|---|---|---|---|---|---|---|---|
| M25 COC + 10%ALC | 58.28 | 0.87 | 0.77 | 4.79 | 10.93 | 20.06 | 1.83 | 0.07 | 0.43 |
| M40 COC + 10%ALC | 68.74 | 1.26 | 1.53 | 3.60 | 10.74 | 12.74 | 1.18 | 0.11 | 0.33 |
| M60 COC + 10%ALC | 64.67 | 0.22 | 1.61 | 4.53 | 12.44 | 13.94 | 1.12 | 0.01 | 0.12 |

## Conclusions

The supplementary cementitious materials (SCMs), which can partially replace cement, represent a new technological innovation in concrete manufacturing in the construction industry. This paper aimed to examine the beneficial effect of using alccofine as partial replacement to composite cement. The conclusions derived from the experimental results are as follows:

- The partial replacement of COC by alccofine leads to an improvement in the mechanical characteristics of concrete. But due to the presence of finer alccofine, which has a higher surface area, it absorbs higher water, leading to a decrease in the workability of concrete.
- As the percentage of alccofine used instead of cement increases, the CS of concrete increases. However, the percentage increase in strength is lower because of lesser pozzolanic nature at later ages. The maximum CS of 61.32 N/mm$^2$ was achieved for M40 grade concrete when COC cement was partially replaced by only 10% of alccofine at 28 days.
- The partial replacement of COC with 10% of alccofine to COC results in a 11.4% and 21.42% increase in STS and FS at 28 days. This improvement is due to the strong interphase bond between the binders (i.e., COC and alccofine) and aggregates. Therefore, an interfacial transition zone (ITZ) plays a significant part in the improvement of STS.
- Around 16.95% improvement in the modulus of elasticity of concrete was achieved when COC was partially replaced with 10% of alccofine. The finer particles of alccofine fill the gap formed between the COC particles and the closely packed structure formed, thus having the ability to withstand higher load.
- The microstructural characterisation of the COC with the addition of alccofine using SEM and EDX shows that the addition of alccofine can contribute to the formation of hydration products, especially stratlingite, which was formed as a result of the addition of alccofine.

This study primarily focused on determining the mechanical and microstructural properties of the concrete in which alccofine is added as a partial replacement to composite cement. However, this study has a limitation of not assessing the durability properties of concrete. In the future, the durability performance of alccofine-modified concrete would be taken up for investigation. The practical implications might involve using alccofine in concrete mix designs to create stronger and more resilient structures.

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**Author contributions** BS contributed to conceptualization; data curation; methodology; investigation; roles/writing—original draft; and writing—review and editing. PRKR contributed to conceptualization; data curation methodology; supervision; validation; and writing—review and editing.

**Data availability** The data that has been used are confidential.

## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

**Ethical approval** This manuscript has not been published and is not under consideration for publication elsewhere.

**Informed consent** For this type of study, informed consent statement is not applicable.

## References

1. Venkatakrishnaiah R, Sakthivel G (2015) Bulk utilization of fly-ash in self compacting concrete. KSCE J Civ Eng 19:2116–2120
2. Assi LN, Carter K, Deaver E, Ziehl P (2020) Review of availability of source materials for geopolymer/sustainable concrete. J Clean Prod 263:121477
3. Worrell E, Price L, Martin N et al (2001) Carbon dioxide emissions from the global cement industry. Annu Rev Energy Environ 26:303–329
4. Khozin V, Khokhryakov O, Nizamov R (2020) A «carbon footprint» of low water demand cements and cement-based concrete. In: IOP conference series: materials science and engineering. IOP Publishing, p 12105
5. Imbabi MS, Carrigan C, McKenna S (2012) Trends and developments in green cement and concrete technology. Int J Sustain Built Environ 1:194–216
6. Miah MJ, Huaping R, Paul SC et al (2023) Long-term strength and durability performance of eco-friendly concrete with supplementary cementitious materials. Innov Infrastruct Solut 8:255
7. Astm (2010) Standard specification for coal fly ash and raw or calcined natural pozzolan for use. Annu B ASTM Stand 3–6
8. Wang H, Liu X, Zhang Z (2023) Pozzolanic activity evaluation methods of solid waste: a review. J Clean Prod 402:136783
9. Singh GVPB, Subramaniam KVL (2019) Production and characterization of low-energy Portland composite cement from post-industrial waste. J Clean Prod 239:118024
10. Abdellatief M, Abd Elrahman M, Elgendy G, Bassioni G, Tahwia AM (2023) Response surface methodology-based modelling and optimization of sustainable UHPC containing ultrafine fly ash and metakaolin. Constr Build Mater 388:131696
11. Abdellatief M, Elemam WE, Alanazi H, Tahwia AM (2023) Production and optimization of sustainable cement brick incorporating clay brick wastes using response surface method. Ceram Int 49(6):9395–9411

12. Abdellatief M, Al-Tam SM, Elemam WE, Alanazi H, Elgendy GM, Tahwia AM (2023) Development of ultra-high-performance concrete with low environmental impact integrated with metakaolin and industrial wastes. Case Stud Constr Mater 18:e01724
13. Radwan MKH, Onn CC, Mo KH, et al (2020) Eco-mechanical performance of binary and ternary cement blends containing fly ash and slag. In: Proceedings of the institution of civil engineers-engineering sustainability. Thomas Telford Ltd, pp 23–36
14. Zou F, Hu C, Wang F et al (2020) Enhancement of early-age strength of the high content fly ash blended cement paste by sodium sulfate and C-S–H seeds towards a greener binder. J Clean Prod 244:118566
15. Fanghui H, Qiang W, Jingjing F (2015) The differences among the roles of ground fly ash in the paste, mortar and concrete. Constr Build Mater 93:172–179
16. Mo KH, Ling T-C, Alengaram UJ et al (2017) Overview of supplementary cementitious materials usage in lightweight aggregate concrete. Constr Build Mater 139:403–418
17. Özbay E, Erdemir M, Durmuş Hİ (2016) Utilization and efficiency of ground granulated blast furnace slag on concrete properties—a review. Constr Build Mater 105:423–434
18. Łukowski P, Salih A (2015) Durability of mortars containing ground granulated blast-furnace slag in acid and sulphate environment. Procedia Eng 108:47–54
19. Feiz R, Ammenberg J, Baas L et al (2015) Improving the $CO_2$ performance of cement, part I: utilizing life-cycle assessment and key performance indicators to assess development within the cement industry. J Clean Prod 98:272–281
20. Sharma P, Sharma SK, Rambabu D, Reddy BSP (2023) A detailed laboratory investigation on evolving the mix design of roller compacted concrete containing RAP aggregates and SCMs. Innov Infrastruct Solut 8:284
21. Rather SA, Sharma N, Najar IA (2019) Effects of rice husk ash (RHA) and alccofine-1101 on stabilization of clay soil. Int Res J Eng Technol 6:474–478
22. Dutta RK, Yadav JS (2021) The impact of alccofine inclusion on the engineering properties of bentonite. Clean Eng Technol 5:100301
23. Srinath BLNS, Patnaikuni CK, Balaji K et al (2021) A prospective review of alccofine as supplementary cementitious material. Mater Today Proc 47:3953–3959
24. Ramkrishnan R, Abilash B, Trivedi M et al (2018) Effect of mineral admixtures on pervious concrete. Mater Today Proc 5:24014–24023
25. Jayswal SD, Mungule M (2022) Performance assessment of Alccofine with silica fume, fly ash and slag for development of high strength mortar. Front Struct Civ Eng 16:576–588
26. Suthar Sunil B, Shah BK (2013) Study on strength development of high strength concrete containing alccofine and fly-ash. Indian J Res 2:102–104
27. Swaroop AHL, Venkateswararao K, Kodandaramarao P (2013) Durability studies on concrete with fly ash & Ggbs. Int J Eng Res Appl 3:285–289
28. Rout MKD, Biswas S, Sinha AK (2021) Mechanical and durability properties of alccofine used in reclaimed asphalt concrete pavements (RACP). In: Advances in sustainable construction materials: select proceedings of ASCM 2020. Springer, pp 131–142
29. Balamuralikrishnan R, Saravanan J (2021) Effect of addition of alccofine on the compressive strength of cement mortar cubes. Emerg Sci J 5:155–170
30. Srinath BLNS, Patnaikuni CK (2022) Concrete properties evaluated by replacing cement with alccofine. Int J Eng Sci Technol 6(1):91–97
31. Rajesh Kumar S, Samanta AK, Roy DKS (2015) An experimental study on the mechanical properties of alccofine based high grade concrete. Int J Multidiscip Res Dev 2:218–224
32. Venkatesan B, Venuga M, Dhevasenaa PR, Kannan V (2021) Experimental study on concrete using partial replacement of cement by Alccofine fine aggregate as iron powder. Mater Today Proc 37:2183–2188
33. Gautam M, Sood H (2017) Effect of alccofine on strength characteristics of concrete of different grades—a review. Int Res J Eng Technol 4:2854–2857
34. Srinivasan G (2020) Study on alccofine based high performance concrete. In: IOP conference series: materials science and engineering. IOP Publishing, p 12040
35. Harish B, Dakshinamurthy NR, Sridhar M, Rao KJ (2022) A study on mechanical properties of high strength concrete with alccofine as partial replacement of cement. Mater Today Proc 52:1201–1210
36. Chakravarthy PRK, Raj RR (2017) Analysis on compressive strength of concrete with partial replacement of cement with alccofine. ARPN J Eng Appl Sci 12(8):2392–2395
37. Suthar S, Shah BK, Patel PJ (2013) Study on effect of alccofine & fly ash addition on the mechanical properties of high performance concrete. Int J Sci Res Dev 1:464–467
38. Kumar R, Muthupriya P, Venkatsubramani R (2013) The experimental investigating on durability characteristics of high performance concrete. Int J Sci Tech Res 3:239–250
39. Soni D, Kulkarni S, Parekh V (2013) Experimental study on high-performance concrete, with mixing of alccofine and flyash. Indian J Res 3:84–86
40. Sagar B, Sivakumar MVN (2021) Use of alccofine-1203 in concrete: review on mechanical and durability properties. Int J Sustain Eng 14:2060–2073
41. Kavitha S, Kala TF (2016) Evaluation of strength behavior of self-compacting concrete using alccofine and GGBS as partial replacement of cement. Indian J Sci Technol 9:1–5
42. Kavyateja BV, Jawahar JG, Sashidhar C (2020) Effectiveness of alccofine and fly ash on mechanical properties of ternary blended self compacting concrete. Mater Today Proc 33:73–79
43. Ansari US, Chaudhri IM, Ghuge NP, Phatangre RR (2015) High performance concrete with partial replacement of cement by alccofine and fly ash. Indian Res Trans 5:19–23
44. Reddy MVS, Ashalatha K, Surendra K (2016) Studies on eco-friendly concrete by partial replacement of cement with Alccofine and fine Fly Ash. ARPN J Eng Appl Sci 11:3445–3448
45. Sambangi A, Kundeti N, Srimani R, Nadukuditi A (2023) Effect of fly ash and alccofine as cementitious materials on M40 grade concrete. Mater Today Proc
46. Reddy GGK, Ramadoss P (2020) Influence of alccofine incorporation on the mechanical behavior of ultra-high performance concrete (UHPC). Mater Today Proc 33:789–797
47. Upadhyay SP, Jamnu MA (2014) Effect on compressive strength of high performance concrete incorporating alccofine and fly ash. Int J Innov Res Dev 3:124–128
48. Saiya J, Tiwari A, Jagtap S (2018) Experimental investigation on effect of alccofine with flyash and GGBS on high performance concrete. Int Res J Eng Technol 5:2734–2739
49. Massazza F (1998) Pozzolana and pozzolanic cements. Lea's Chem Cem Concr 4:471–631
50. Moranville-Regourd M (1998) Cements made from blast-furnace slag, Lea's Chemistry of Cement and Concrete Ed. PC 633:674
51. Desha C, Robinson D, Sproul A (2015) Working in partnership to develop engineering capability in energy efficiency. J Clean Prod 106:283–291

52. BS 3892 (Part 1) Pulverized-fuel ash part 1: specification for pulverized-fuel ash for use with portland cement
53. BS: 6699-1992 Ground granulated blastfurnace slag for use with portland cement
54. BS 12/1996 Specification of ordinary portland cement british standard
55. IS 16415:2015 BIS certification for composite cement
56. Teja VP, Brahma Chari KJ, Rao VR (2019) Experimental research on composite cement with glass fibers. Int J Recent Technol Eng 7:278–283
57. Zajac M, Skocek J, Durdzinski P et al (2020) Effect of carbonated cement paste on composite cement hydration and performance. Cem Concr Res 134:106090
58. IS-10262:2019 Concrete mix proportioning—guidelines
59. Khan AA, Al Kheraif AAA, Jamaluddin S, et al (2017) Recent trends in surface treatment methods for bonding composite cement to zirconia: a review. J Adhes Dent 19
60. Türkel S, Alabas V (2005) The effect of excessive steam curing on portland composite cement concrete. Cem Concr Res 35:405–411
61. IS: 12269-1987 Ordinary portland cement, 53 grade—specification
62. Jamenraja MCK, Ravichandran K (2023) Structural performance of polypropylene fibre-reinforced concrete beams incorporating nanosilica and alccofine. Innov Infrastruct Solut 8:191
63. ASTM C989-99 Standard specification for ground granulated blast-furnace slag for use in concrete and mortars
64. IS:383 (1970) Specification for coarse and fine aggregates from natural sources for concrete. Indian Stand 1–24
65. IS-1199-1959 Slump test of fresh concrete to measure workability
66. IS 516 (2021) Method of tests for strength of concrete. Bur Indian Stand 1–30
67. IS 456 (2000) Plain concrete and reinforced. Bur Indian Stand Dehli 1–114
68. IS-5816:1959 Splitting tensile strength of concrete—method of test
69. Amarkhail N (2015) Effects of silica fume on properties of high-strength concrete. Int J Tech Res Appl 32:13–19
70. Srinath BLNS, Patnaikuni CK, Santhosh KB et al (2022) Strength effect of alccofine on ordinary and standard grade concrete mixes. Int J Adv Technol Eng Explor 9:47
71. Vijayan DS, Arvindan S, Janarthanan TS (2020) Evaluation of ferrock: a greener substitute to cement. Mater Today Proc 22:781–787
72. Reddy AN, Meena T (2018) A study on compressive behavior of ternary blended concrete incorporating alccofine. Mater Today Proc 5:11356–11363
73. Reddy PN, Kavyateja BV, Kunamaneni V (2020) Effect of alccofine on the mechanical and durability performance of concrete. Authorea Preprints
74. Qureshi M, Tandel Y, Patel B (2013) An experimental study on high strength concrete using fly ash and alccofine. i-manager's J Struct Eng 2:1
75. Chithra S, Kumar SRRS, Chinnaraju K (2016) The effect of colloidal nano-silica on workability, mechanical and durability properties of high performance concrete with copper slag as partial fine aggregate. Constr Build Mater 113:794–804
76. Sagar B, Sivakumar MVN (2020) An experimental and analytical study on alccofine based high strength concrete. Int J Eng 33:530–538
77. Bınıci H, Durgun MY, Rızaoğlu T, Koluçolak M (2012) Investigation of durability properties of concrete pipes incorporating blast furnace slag and ground basaltic pumice as fine aggregates. Sci Iran 19:366–372
78. Georget F, Wilson W, Scrivener KL (2021) edxia: microstructure characterisation from quantified SEM-EDS hypermaps. Cem Concr Res 141:106327
79. Tiecher F, Langoski M, Hasparyk N (2021) Behavior of mortars with different types of cement when induced to Delayed Ettringite Formation (DEF). Rev ALCONPAT 11:1–16
80. Srinath BLNS, Patnaikuni CK, Raghava Rao EV et al (2021) Microstructure analysis of M30 grade alccofine concrete. Int J Mech Eng 6(3):2030–2038
81. Senff L, Labrincha JA, Ferreira VM et al (2009) Effect of nanosilica on rheology and fresh properties of cement pastes and mortars. Constr Build Mater 23:2487–2491