Synergistic impacts of fly ash and sugarcane bagasse ash on performance of polyvinyl alcohol fiber-reinforced engineered cementitious composites

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ABSTRACT

Disposal of waste materials in fertile land is one of the pressing environmental issues, disrupting human, animal, and plant life. This has led researchers to process and use such waste materials in eco-friendly construction products like mortar and concrete. Their usage as supplementary cementitious materials (SCMs) would reduce the quantity of cement utilized in the manufacturing of cement-based materials, lowering carbon dioxide emissions related to cement production. In this regard, this study examines the feasibility of replacing high-volume of ordinary Portland cement in engineered cementitious composites (ECCs) with two widely employed waste materials, sugarcane bagasse ash (SCBA) and fly ash (FA) as SCMs. Five different mixes were produced, each containing a fixed amount of polyvinyl alcohol (PVA) fibers at a dosage of 1.5% by volume of the mix and a constant cement content of 50% by weight of the binder (Cement + FA + SCBA). However, FA was replaced with SCBA in these mixes up to 100% by the combined weight of the waste materials (FA + SCBA) in increments of 25% (i.e., FA100-SCBA0, FA75-SCBA25, FA50-SCBA50, FA25-SCBA75, and FA0-SCBA100). The results showed that the compressive and flexural strengths of ECCs with increasing the levels of SCBA were reduced. Interestingly, the 28-day compressive strength of ECC incorporating 50% FA and 50% SCBA was still as high as 25.58 MPa, which satisfied the minimum compressive strength requirement of ASTM C270, making the newly produced ECC suitable for use in normal construction works and repairs. The same optimum mix (FA50-SCBA50) produced an average density of 1867.96 kg/m³ as a result of substituting a significant amount of the binder with SCBA, demonstrating that it has evolved into a lightweight ECC. Furthermore, the ultrasonic pulse velocity of the mixes decreased, whereas the water absorption increased as the proportion of SCBA to FA increased. According to the microstructural analysis, unreacted SCBA particles were mostly responsible for the detrimental effects of rising the SCBA levels on properties of ECCs. Based on the aforementioned results, this research concluded that SCBA, when combined with FA, could be a viable alternative for replacing regular cement up to 50% by weight in the production of cost-effective and environmentally friendly ECCs.

Author contributions


1. Introduction

With the advent of technology, the use of concrete and other cement-based materials as a construction product has significantly increased, however, challenges remain. One of the major challenges faced by...
Concrete is its low tensile strength, which is almost ten times lower as compared to its compressive strength [1]. Conventional cement-based materials are problematic owing to their brittleness and low tensile strength. In addition, the formation of cracks in conventional cement-based materials poses a major threat to its stability and durability. The idea of engineered cementitious composites (ECCs), fiber-reinforced cement-based materials that can bend and self-heal under tension, has been developed [2]. The flexural performance of cement-based materials can be improved by using different fibers during mixing, which reduce the number and size of cracks and improve the strength and durability [3,4]. Different types of fibers have been in use in ECCs such as polyvinyl alcohol (PVA), polypropylene (PP), and some natural fibers [5]. Due to the high tensile performance of ECCs, they can be utilized in structural composites where high crack control is required. ECCs have the potential to be used in a variety of structural applications because of their superior characteristics than conventional cement-based materials. ECCs can be employed in seismic- and blast-resistant structures, as well as in the retrofitting and repair of existing structures like bridges and dams [6-9].

The presence of the PVA fibers enhances the properties of ECCs by improving their modes of failure, as such fibers act as a bridge across the matrix cracks [10]. These micro cracks absorb energy and utilize it to propagate alternatively instead of widening minor cracks. This phenomenon causes an increase in the tensile strength and enhances the ductility of cementitious composites [11]. Steady-state crack analysis reveals that in case of PVA-ECC, a minor crack can transfer its energy to the matrix, which causes the production of another minor crack, resulting in a phenomenon of multiple cracking with the formation of micro crack widths, which ultimately reduces the possibility of spalling or corrosion, making it more durable than normal cement-based materials [12]. Moreover, the minor cracks formed by the presence of the PVA fibers can impart self-healing properties to the cementitious matrix, thus improving the durability of the composite [11].

Although ECCs are expensive per cubic yard compared to conventional concrete, they are more durable, extending the life of construction [13]. Unlike conventional concrete, in which coarse aggregates act as fillers, the mix of ECCs is exclusive of such aggregates, thus demanding more cement to fill the matrix of ECCs [14,15]. Owing to an increase in the cement content, the cost of the design mix increases, making it uneconomical. In addition, regular cement in conventional cement-based materials has a greater possibility of shrinking. Also, the manufacture of cement gives rise to more carbon dioxide (CO₂) emissions, endangering the environment worldwide [16]. In fact, the cement and concrete industry is a major contributor to climate change, emitting 5% of the world’s CO₂[17]. One of the eco-friendly solutions for reducing the cement consumption is to partially replace it with supplementary

![Fig. 1. Methodology of current study.](Image)
cementitious materials (SCMs), which can be industrial by-products or agricultural wastes. The use of such waste products as partial replacements of cement makes the construction eco-friendly and cost-effective. The increasing disposal of waste and CO₂ emissions from the cement and concrete industry have led researchers to investigate alternatives that can combat these environmental challenges. In this regard, there are many industrial wastes which possess pozzolanic properties and therefore can be used as partial replacements of cement in the production of concrete and other concrete-associated materials. Among other SCMs, fly ash (FA) has been widely utilized as a partial substitute for cement in cement-based materials [15,18–23] and as a precursor in alkali-activated materials [24–29]. However, the availability of FA may not be guaranteed in future because the energy sector has been shutting down coal-burning power plants, necessitating the search for novel, practical, and eco-friendly FA substitutes [30]. Like other countries such as Brazil, USA, and China, Pakistan produces a lot of sugarcane each year, as its economy is primarily based on agriculture. Sugarcane bagasse ash (SCBA) is generally regarded as a by-product of the sugarcane industry, and thankfully, it comes at no cost because it is freely available from sugar mills in Pakistan. SCBA has been used by many researchers, either alone or in combination with other waste materials in the manufacture of building materials [31]. Because SCBA contains mainly amorphous silica (SiO₂), it possesses considerable potential to be utilized as a pozzolanic material [32–34]. Extensive research studies have demonstrated that SCBA plays active role in the pozzolanic reaction with calcium hydroxide (CH) produced during cement hydration [35]. The incorporation of SCBA up to an optimum dosage has indicated positive impact on the mechanical and durability properties of cement mortar and concrete [34,36–39]. The influence of 5–30% SCBA on the mechanical characteristics of concrete was documented by Ganesan et al. [34]. Their findings revealed that 20% SCBA improved the compressive strength and splitting tensile strength of concrete by 18% and 7%, respectively, at 28 days. However, SCBA can also reduce the strength of composite owing to the untreated large sized ash particles [40]. In these situations, where the treatment of SCBA (such as grinding or burning at higher temperatures) is unfavorable for increased sustainability, it can be combined with other conventional pozzolans, such as FA, to partially replace cement while preserving the composite material’s properties.

Although, FA and SCBA have both been extensively explored in terms of their respective uses in construction materials, there is little information available on their combined application [27,28]. Moreover, there is less attention paid to the use of SCBA in the production of ECCs [41]. This was the driving force for the current research, which inspired us to examine the combined use of FA and SCBA in PVA-ECCs. This will make the construction more affordable and environmentally friendly, supporting the objectives of sustainable development.

In order to simultaneously contribute to (1) enhancement in performance of cementitious composite, (2) waste management, and (3) reduction in cost and CO₂ emission on account of reduced cement consumption, this study was attempted to investigate the synergistic effects of FA with SCBA in the development of PVA-ECCs. In all the experiments, the PVA and cement contents were kept constant at 1.5% by volume and 50% by weight of the binder, respectively. The concentrations of FA and SCBA were varied to determine their optimum mix ratio by performing physico-mechanical tests, including the compressive strength, flexural strength, water absorption, ultrasonic pulse velocity (UPV), and density tests. The microstructure of ECCs was evaluated using scanning electron microscopy (SEM) combined with energy dispersive spectroscopy (EDS).

2. Materials and methods

2.1. Materials

The methodology opted for this study is presented in Fig. 1. Ordinary Portland cement was used as the main binder for the preparation of ECCs. Other used materials were PVA fibers, SCBA, FA, sand, superplasticizer or high-range water reducer (HRWR), and water. The cementitious materials’ chemical composition and their physical properties, as determined through X-ray fluorescence (XRF) and as per ASTM standards, are given in Tables 1 and 2, respectively. The specific gravity and fineness of the cementitious materials were determined in accordance with ASTM C188 [42] and ASTM C184 [43], respectively. For the fineness test, a 50 g of specimen was sieved through a 75 μm (No. 200) sieve. FA was provided from Sahiwal power plant. Based on the chemical composition of FA, it was classified as Class-F according to ASTM C618 [44]. Raw SCBA was collected from Pattoki Sugar Mills. SCBA was deemed to have been adequately burnt under controlled conditions in the sugar mill’s cogeneration combustion boilers for power production. After passing SCBA through a 300-μm (No. 50) sieve to exclude large particles, the specimen was placed under a fan to eliminate the moisture content that could evaporate quickly. No further processing (i.e., grinding or burning) was performed on SCBA to make its use more feasible and sustainable. From Table 1, it can be seen that the loss on ignition (LOI) for SCBA was higher than the allowable limit as per ASTM C618 [44]. The higher LOI of SCBA was the direct indication of the presence of unburnt carbon fibers [32]. SCBA had the specific gravity value of 1.9 as compared to cement and FA (Table 2), which is consistent with other studies [32,45]. SCBA had a lower fineness rating (63.4%) than cement and FA, indicating that a considerable amount of the SCBA particles could not pass through the 75-μm (No. 200) sieve utilized.

Natural sand from a local source, Lawrencepur, was used as fine aggregates in the mixes. Sand particles of two different sizes were employed to achieve properties comparable to those of silica sand. The required amount of sand was passed through 1-mm (No. 18) sieve. The sand was then passed through a 0.6-mm (No. 30) sieve and 0.15-mm (No. 100) sieve. 90% of the total required sand was obtained from the fraction retained on 0.15-mm (No. 100) sieve. Finally, both fractions were mixed to achieve the required amount of sand. The PVA fibers used in this research work were procured from Kuraray company in Japan. The physical properties of the PVA fibers are listed in Table 3. Regular potable water was utilized in all the mixes. Chemrite-
NN was employed as a superplasticizer or HRWR, and its characteristics are summarized in Table 4.

### 2.2. Mix design

The mix design in this study included three types of binders: cement, FA, and SCBA. The total amount of the binder was divided into 50% of the binder for cement and the remaining 50% for the combined use of FA and SCBA. Five ECC mix proportions were prepared in which FA was the binder for cement and the remaining 50% for the combined use of FA and SCBA. The total amount of the binder was divided into 50% of the combined proportion of FA and SCBA from 0 to 100% of the combined proportion of FA and SCBA at intervals of 25%, as 0%, 25%, 50%, 75%, and 100%. The used constant parameters are given in Table 5, and the mix proportions and durability performances of ECCs are achieved \([47, 48]\). According to the literature, with a PVA volume fraction of 2%, optimum mechanical and durability performances of PVA-ECCs are achieved \([47, 48]\). Keeping the aspect of the economy in mind without compromising the mechanical and durability performances of ECCs, a fixed content of 1.5% PVA fibers (volume-based) was used in this study. Other studies have also assessed 1.5% PVA by volume instead of the typically used 2% volume fraction \([49]\). A fixed water-to-binder (w/b) ratio of 0.25 was utilized in all the experiments. In addition, the amount of superplasticizer or HRWR was kept constant for all the mixes at 1% by weight of the binder.

Hobart A-200 mortar mixer was employed for the mixing purpose. The raw materials (cement, FA, SCBA, and sand) were poured into the mixing bowl and then dry mixed for 2 minutes at low mixing speed of 107 revolutions per minute (rpm). Water was added to the mix, and the mixing continued for further 1 minute at the same low speed. HRWR was added to the mix, and the mixer was operated at an intermediate speed (198 rpm) for 2 minutes. Thereafter, the PVA fibers were put into the mix for 3 minutes while the mixing proceeded at the same intermediate speed. To obtain a more uniform mixture, the mixer was stopped and restarted at a high speed (361 rpm). It is worth noting that upon the addition of water, HRWR, and PVA fibers, the mixer was paused to remove any attached material from the sides and bottom of the mixing bowl. After mixing, the mortar cubes and prism were cast and demolded after 24 hours. To prevent leaching from one type of mix into another, the demolded specimens were placed in separate curing chambers and were water cured until testing.

#### 2.3. Methods

Table 7 demonstrates the details of the tests conducted to evaluate the properties of hardened ECC mixes, ASTM standards, sizes and number of the specimens, and the number of days after which the tests were performed.

#### 2.3.1. Compressive strength

The compressive strength test was carried out on 50 mm × 50 mm × 50 mm cubes after a curing period of 7 and 28 days based on ASTM C109 \([50]\). The test is shown in Fig. 2. For each mix, eight specimens were tested to report the average value for the compressive strength at the respective test ages. The compressive strength was determined using Eq. (1).

$$f'_c = \frac{P}{A} \tag{1}$$

where \(f'_c\) is the compressive strength in MPa, \(P\) is the maximum load in N at which the specimen was failed under the compression, and \(A\) is the cross-sectional area of the cubic specimen in mm\(^2\).
2.3.2. Flexural strength

A three-point flexural strength test was done on 40 mm × 40 mm × 160 mm prisms at 28 days of curing according to ASTM C348-20 [51], which was utilized to determine the flexural strength of hydraulic cement mortars (Fig. 3). Eight specimens were tested for each mix to obtain the maximum accuracy of the results. The flexural strength was calculated according to Eq. (2).

$$f_t = 0.0028P_f$$  \tag{2}$$

where $f_t$ is the flexural strength in MPa and $P_f$ is the total maximum load.
performed after 28 days of water curing. Specimens were removed from the curing chamber, their surfaces were dried with an absorbent cloth to obtain the average water absorption value. This test was performed according to Eq. (3).

For these weights, the specimens were kept in an oven and their oven-dried weights were recorded until the oven-dry weights on successive days became constant. The water absorption of the specimens was determined using Eq. (3).

\[ w.a = \frac{(M_S - M_o)}{M_o} \times 100 \]  

where \( w.a \) is the water absorption in %, \( M_S \) is the surface-dry mass of the specimen in g, and \( M_o \) is the over-dry mass of the specimen in g.

### 2.3.4. UPV

The UPV test was conducted on ECC cubes of 50 mm × 50 mm × 50 mm as per ASTM C597-16 [53]. The UPV test was performed on the specimens before they were crushed under compression. For the UPV test, transmitting and receiving transducers were firmly attached to the sides of the specimens. While selecting the sides in contact with the transducers, special care was taken to avoid honeycombing and irregularities. The test specimen and equipment are depicted in Fig. 4. The display unit indicated the time in microseconds taken by the waves to travel across the specimen. UPV was then determined utilizing Eq. (4).

\[ UPV = \frac{L}{t} \]  

where \( UPV \) is in m/s, \( L \) is the length of the specimen between center of transducers in m, and \( t \) is the transit time in s.

### 2.3.5. Density

The density test was done on 50 mm × 50 mm × 50 mm cubes after curing for 7 and 28 days, in accordance with ASTM C39 [54]. The dimensions of each specimen were measured, and the volume was calculated. Each specimen was weighed using a balance, and the density was calculated according to Eq. (5).

\[ D = \frac{M}{V} \]  

where \( D \) is the density of the specimen in kg/m², \( M \) is the mass of the specimen in kg, and \( V \) is the volume of the specimen in m³.

### 3. Results and discussion

#### 3.1. Compressive strength

The compressive strength results at 7 and 28 days of curing are illustrated in Fig. 5. The inclusion of the PVA fibers provided the cubes with lateral and radial reinforcements against the applied loading, and the PVA fibers developed a strong bond with the matrix due to their hydrophilic behavior, which is a major factor in the development of the compressive strength of ECCs [55,56]. Regarding the pozzolanic action, SiO₂ from FA was combined with CH and formed additional calcium silicate hydrates (C-S-H), which contributed significantly to the compressive strength of ECCs [57-59]. Owing to the increased fineness of the FA particles as a result of their maximum content in the FA100-SCBA0 mix, the volume of voids decreased, leading to a dense matrix and a higher compressive strength [60,61]. The addition of SCBA to cement-based products creates nucleation sites for more cement hydration because of its amorphous nature. Many researchers have reported considerable values of compressive strength using higher contents of SCBA as a partial replacement of cement. For example, up to 25% replacement of cement with SCBA was made in a study [62], and the resulting compressive strength achieved with 25% SCBA was 40 MPa. However, in another study, up to 30% SCBA in the binary mixes and up to 50% substitution of cement in the ternary mixes were considered, and it was found that the specimens with 33% SCBA and 7% silica fume demonstrated improvements in the compressive strength compared to all other mixes, including the control (i.e., with 100% cement) [63]. The dense microstructure of the produced C-S-H, high specific area, and low intruded pore volume were credited in these research works as the causes of the high strength even with 33% SCBA.

It can be seen that the compressive strength at 28 days has decreased with the increase in the replacement ratio of SCBA. At 7 days, the compressive strength of FA100-SCBA0 was 34.27 MPa, which was reduced to 2.05 MPa for FA0-SCBA100. The reduced compressive strength of specimens with high content of SCBA was strongly related to the SCBA’s lower specific gravity, as can be seen in Table 2. Because the pores become wider when SCBA is used in large quantities, they continue to grow in size and lose their ability to withstand the compressive load per unit area, which is the cause of the downward trend in the compressive strength [40,64]. Similar results were obtained by Zareei et al. [62]. The decrease in the strength is also attributable to the fact that excessive SiO₂ is leached out of the matrix when the amount of utilized SCBA is greater than that required to react with the freed lime during the hydration process [65]. Other factors that contributed to the reduced strength of the specimens with high quantities of SCBA are its...
higher LOI and lower fineness value (Tables 1 and 2), as well as the dilution effect that occurs when high volume of SCBA replaces other cementitious materials. LOI of material refers to loss of volatile substances such as water, CO₂, and organic matter. The greater the LOI of SCBA (16.56% in this case, as shown in Table 1), the more unburnt or partially burned organic matter in the ash, and hence the lower the strength. This is well supported by Chusilp et al. [66], where they reported that the increased LOI and percentage contents of SCBA reduced the compressive strength of mortar. The lower fineness (63.4%, as can be seen in Table 2) also contributed to the reduced strength when SCBA was used in high proportion. Cordeiro et al. [35] concluded that the reactivity of SCBA was mainly dependent on the fineness, affecting the strength of mortar. When comparing different types of cementitious mortars, it is common practice to assess their performance based on their compressive strength as specified by ASTM C270 [67]. This standard provides guidelines for the minimum compressive strength requirements of a few mortar types such as M (17.2 MPa), S (12.4 MPa), N (5.2 MPa), and O (2.4 MPa) types, allowing for their appropriate use in various construction applications. By specifying the minimum compressive strength of different mortar types, ASTM C270 ensures that users can select the appropriate mortar for their specific project needs, considering factors such as load-bearing capacity and durability requirements. From the results found in this study, it can be seen that the cementitious mortar with equal proportions of FA and SCBA (50% FA and 50% SCBA) has exceeded the minimum 28-day compressive strength requirement of 17.2 MPa for all types of mortars specified by ASTM C270, i.e., M, S, N, and O types. Even, the compressive strength of FA25-SCBA75 was also higher than the minimum threshold of 5.2 MPa for type N mortar. Thus the mortar with equal proportion of FA and SCBA (FA50-SCBA50) can be recommended for use in normal construction works and repairs and other applications including masonry units such as foundation walls, sewers, and load-bearing walls. This synergistic utilization of up to 50% SCBA by the combined weight of FA and SCBA (or 25% by weight of the whole binder) is in line with its abundance across the world. The optimum content of 25% SCBA by weight of the binder in ECCs investigated in this study is also consistent with the recommendations of Katare and Madurwar [68].

Overall, the PVA-ECC cubes in this research work did not display crushing failure under the compression as opposed to an ordinary mortar cube where such failure is more common. The PVA-ECC cubes with high amount of FA (FA100-SCBA0) exhibited a ductile failure under the compression as can be observed from Fig. 6 (a). However, with the increase in the SCBA content, the failure mode changed to a less ductile one. The failure modes resulted for the FA100-SCBA0 and FA50-SCBA50 specimens (Fig. 6 (a and b)) were quite consistent with other studies [69,70]. On the other hand, the specimen with high volume of SCBA (FA0-SCBA100 in Fig. 6 (c)) indicated bulging failure. Because the increased content of lightweight and porous SCBA could not intrinsically tolerate the applied loading, the cube’s bulging could have been induced by the lateral and radial stiffening of the PVA fibers in response to resisting the imposed loading.

### 3.2. Flexural strength

Fig. 7 depicts the flexural strengths of the PVA-ECC prisms after 28 days of curing. FA100-SCBA0 had the highest flexural strength, while FA0-SCBA100 had the lowest. The trend for the flexural strength was similar to that observed for the compressive strength. Similar results for the flexural strength were obtained in previous research as well [71]. As presented in Fig. 8 (a), a flexural failure mode was witnessed in the PVA-ECC prisms initiated by multiple micro cracks in the mid-length of the prisms, which is at the point of the maximum moment. After a certain deflection and development of additional micro cracks, a single macro crack appeared (either on the left or right of the black vertical middle lines), ultimately leading to the loss of the flexural capacity. This ductile behavior of the prisms is attributed to the development of a strong bond between the internal matrix of the composite and the PVA fibers, resulting in a phenomenon called slip hardening or multiple cracking. After the appearance of the initial micro cracks, the PVA fibers continued to resist the applied loading until the peak flexural load was achieved, after which ‘fiber pullout’ or ‘fiber fracture’ (Fig. 8 (b)) resulted in the ultimate failure of the specimens. Similar results were reported in multiple studies performed on the evaluation of the ECCs performance [72-74]. Even while the PVA fibers played a substantial part in the high flexural strength of FA100-SCBA0, the FA’s contribution cannot be discounted. FA contributes to the pozzolanic activity of OPC, whereby SiO₂ from FA combines with CH to form a C–S–H gel, which is the primary strength-giving agent in cementitious composites [75]. Furthermore, the unhydrated particles of FA bridge the cracks, thereby enhancing the flexural strength of PVA-ECCs [39].

Results showed that the flexural strength of the PVA-ECC prisms decreased with an increase in the SCBA content. The irregular and porous structure of the SCBA particles, as well as the difficulty of coarser particles to fill internal voids, led to a fall in packing density, which in
turn resulted in a decrease in the flexural strength. Moreover, it is widely accepted that when SCBA or other SCMs are employed in greater quantities than required for effective pozzolanic reaction, the strength is greatly reduced due to the cementitious materials dilution effect. Earlier research on the impact of SCBA on the mechanical characteristics of cementitious composites has demonstrated similar behavior [62, 76].

3.3. Water absorption

Water absorption tests were conducted on the PVA-ECC cubes after 28 days of curing, and the results are illustrated in Fig. 9. FA100-SCBA0 exhibited 11.3% water absorption compared to FA0-SCBA100, which

![Fig. 8. (a) Flexural failure mode of representative prisms; (b) High resolution camera image of a prism specimen with PVA.](image1)

![Fig. 9. Effect of replacing FA with SCBA on 28-day water absorption of PVA-ECCs.](image2)

![Fig. 10. Effect of replacing FA with SCBA on 28-day UPV of PVA-ECCs.](image3)

![Fig. 11. Effect of replacing FA with SCBA on 7-day and 28-day densities of PVA-ECCs.](image4)
had the highest water absorption of 31.43%. The literature states that the PVA fibers result in an increase in the porosity of the matrix, consequently degrading the resistance to the water permeability [72, 77]. Since the PVA content was kept constant at 1.5% by volume of the mix, it did not contribute to the later change in the water absorption of the mixes. Contrary to this, while there has been some contradiction in the results of studies performed on the permeability of concrete blended with FA, research studies mention that the high fineness of FA slightly reduces the porosity of concrete [60, 78]. Moreover, calcium alumina silicate hydrate (C-A-S-H) gel, resulting from the reaction of alumina (Al₂O₃) and SiO₂ from FA with CH, decreases the void ratio of the composites, which is the reason for the low water absorption of FA100-SCBA0 [75]. The water absorption of the ECC cubes increased with the SCBA content. This result is supported by the fact that the replacement of cementitious materials with SCBA creates pores and voids in the internal matrix owing to the porous and amorphous nature of the SCBA particles; hence, the water demand for the ECC specimens increased with the increase in the SCBA content [62, 79].

### 3.4. UPV

UPV tests were done to determine the porous nature of the internal...
cement sand matrix after 28 days of curing, and the results are displayed in Fig. 10. The reason for higher UPV of FA100-SCBA0 was the quality of FA as a micro filler [27, 60]. The fine particles of FA filled the voids, resulting in a dense structure that provided sound waves with a solid medium to travel through. However, with the increase in the SCBA content, UPV decreased due to higher porosity of the specimens [62].

Upon an increase in the SCBA content, voids were created in the specimens, leading to a honeycombed structure; hence, the sound waves took more time to travel through those voids, which ultimately decreased UPV [80, 81]. ECCs with SCBA up to 50% by the combined weight of FA and SCBA possessed the UPV values greater than the threshold value of 3600 m/s for good-quality concrete [82]. This indicates that when FA and SCBA are proportioned equally, their synergistic action is sufficient to create good-quality cementitious composites.

3.5. Density

The density of the PVA-ECC cubes was calculated after 7 and 28 days of curing. The density of ECC cubes decreased with increasing the SCBA concentration, as can be seen in Fig. 11, due to the larger sizes of the SCBA particles and their porous structure [83, 84]. For instance, at 7 days of testing, the density of FA100-SCBA0 was 2099.18 kg/m³ which was reduced by 32% to 1417.77 kg/m³ for FA0-SCBA100. Similarly, at 28 days, the density of FA100-SCBA0 was 2087.22 kg/m³ which was reduced to 1529.97 kg/m³ for FA0-SCBA100, i.e., a decrease of 26%. The lower densities for the high volume-based SCBA specimens were attributed to the lower specific gravity and fineness of SCBA compared to cement and FA [Table 2], as also elaborated by Ahmat et al. [85] and Salini et al. [86] that the specific gravity and fineness of materials are the two factors which largely affect the density. The current findings are consistent with those of Mehmood et al. [28] who reported that for composites containing a high proportion of SCBA (relative to FA and metakaolin), the 28-day density was as low as 1440 kg/m³. Although in light of previous studies, the inclusion of the PVA fibers increased the porosity of the ECC matrix [72, 77, 87], the fineness of the FA particles allowed them to fill the gaps in the structure of ECC and resulted in a higher density of FA100-SCBA0 [66, 61]. In contrast, the reason for the decrease in the density with high SCBA contents is that, as the number of pores increased with the increase in the porous SCBA particles, the weight of the specimens decreased in the same volume of the specimen, resulting in a reduction in the overall mass per unit volume of the specimen [62, 79]. This, in turn, has resulted in the development of lightweight construction products. The specimen with 50% FA and 50% SCBA with a density of 1867.96 kg/m³ is close to 1880 kg/m³ for lightweight concrete, according to ACI Committee 213 [88]. Much more effective utilization of the maximum amount of SCBA in ECCs can be achieved through the optimization of the strength and density requirements. Based on the findings of the current study, one can opt for ECCs incorporating an equal amount of FA and SCBA with a compressive strength of 25.58 MPa and density of 1867.96 kg/m³, at a 28-day curing period, leading to lightweight and economical construction.

3.6. Microstructural analysis

SEM with EDS of the fractured specimens was carried out to assess the microstructure of the produced cementitious composites. The SEM images with different magnifications are shown in Fig. 12(a–e). The SEM analysis provided the necessary information to assess the variation in the
physico-mechanical properties of the specimens. The morphologies of the specimens demonstrated the presence of hydration products, mainly in the form of CH. However, the formation of C–S–H was not clearly observed in the SEM images while it is generated as a result of the pozzolanic reaction in addition to the hydration reaction. This needs further research to validate formation of C–S–H in addition to CH produced during the cement hydration. The hydration products were accompanied by a number of additional products, which may have resulted due to natural carbonation [89]. The presence of CH leads to the formation of weak areas in the internal matrix [37, 57, 90]. In FA50-SCBA50, the presence of CH cloaked the strength-imparting cement hydration products, resulting in a decrease in the compressive and flexural strengths. As the amount of SCBA increased in the mixes, the microstructure revealed the existence of the SCBA porous and fibrous particles and other unreacted phases, which increased the water absorption and decreased the density of ECCs. The negatively impacted properties of the composites as a result of rising the SCBA levels could be attributed to the existence of the porous structure and seemingly unknown unreacted phases, as identified in the matrix microstructure.

The EDS results for five ECC mixes are depicted in Fig. 13. The elements of interest for the present study are calcium (Ca), oxygen (O), silicon (Si), and aluminum (Al). Although carbon (C) is a major element in terms of the PVA portions, it was not reflected in the EDS results because no fiber was selected at the time of generating map data [55]. The elements Ca and O signify the presence of CaO, which is mainly found in cement, indicating that CH was formed during the hydration of cement [12], whereas Si and O imply the existence of SiO, a major component of FA and SCBA, which may have led to formation of additional C–S–H during the hydration.

4. Conclusions

This research work focused on investigating the effect of the partial replacement of cement with FA and SCBA on the performance of ECCs. The major conclusions drawn from this study are as follows:

- The compressive strength of ECCs decreased with increasing the replacement of FA with SCBA. However, it is worth mentioning that a
compressive strength (25.58 MPa) greater than 17.2 MPa at 28 days of curing was achieved for the specimens with 50% FA and 50% SCBA, which can be used in normal construction and repair applications. Therefore, this optimized replacement ratio makes PVA-ECCs sustainable and more economical without compromising the compressive strength.

- All five ECC mixes exhibited multiple-cracking behavior under three-point flexural loading. The flexural strength decreased with the replacement of FA with SCBA; however, at optimized replacement ratios, ECC mixes yielded an ultimate flexural strength greater than the flexural strength of normal concrete, which generally ranges from 3 to 5 MPa. The specimens with 50% FA and 50% SCBA, 75% FA and 25% SCBA, and 100% FA exhibited the flexural strengths of higher than 4 MPa. Therefore, it can be established that the ECCs produced in this study enhanced the flexural behavior of concrete even at a lower percentage of the PVA fibers (~1.5%).
- By increasing the SCBA content, the water absorption increased due to the increased porosity resulting from the porous SCBA particles.
- UPV decreased with an increase in the SCBA content in the PVA-ECC mixes. However, we were still able to obtain ECCs with 50% FA and 50% SCBA contents, lying in the good-quality range according to the UPV classification, i.e., UPV above 3000 m/s in general.
- By increasing the SCBA content, the density of the ECC specimens decreased, which in turn resulted in a higher strength-to-weight ratio.
Fig. 13. (continued).
of the ECC specimens compared to conventional concrete. The specimen with 50% FA and 50% SCBA had a density of 1867.96 kg/m³, which was within the range of lightweight concrete, thus ensuring the lightweight property of ECCs.

- From the SEM and EDS results, it was concluded that by replacing FA with SCBA, the C-S-H gel declined, which reduced the strength of the tested specimens. The SEM images also demonstrated the presence of CH and pores alongside the unreacted phases as the SCBA concentration was increased in comparison to FA, which further validated that, by replacing FA with SCBA, the water absorption of the specimens increased, whereas the density decreased.

Overall, the outcomes of this study can be useful thanks to their potential for utilizing a large amount of industrial waste (50% by weight of the binder) in the development of ECCs with the improved environmental impact along with the enhanced mechanical performance and durability of ECCs. Although this study provides deeper insight into the synergetic effect of FA with SCBA on the strength gain and microstructure development of PVA-ECCs, future studies regarding the optimization of the PVA fibers with a special focus on strain hardening mechanism of PVA-ECCs incorporating SCBA in combination with FA are worthwhile.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Data availability

Data will be made available on request.

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