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ORIGINAL ARTICLE

Mechanical properties and durability of mortar with full fine aggregate replacement using combined fly ash and bottom ash

Muhammad Akbar Caronge[a,*], M. W. Tjaronge[a], Rita Irmawaty[a], Dahlia Patah[b], Nur Hafizah A. Khalid[c], Suharman Hamzah[a]

[a]Department of Civil Engineering, Faculty of Engineering, Universitas Hasanuddin, Gowa 92171, South Sulawesi, Indonesia
[b]Department of Civil Engineering, Universitas Sulawesi Barat, West Sulawesi Province, Majene 91214, Indonesia
[c]Faculty of Civil Engineering, Centre for Advanced Composite Materials, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia
[*]Corresponding Author: Muhammad Akbar Caronge. Email: ma-caronge@unhas.ac.id

Abstract: This study aimed to investigate mechanical properties and durability of mortar containing fly ash (FA) and bottom ash (BA) as a full replacement of fine aggregate. Different combinations of BA and FA were tested for mechanical properties and durability over 180 days. The results showed that mortar containing FA and BA required extra water to achieve similar workability as the control mortar. Furthermore, 90BA:10FA and 80BA:20FA mortars had higher compressive and split tensile strengths compared to the control at all curing ages due to the contribution of the pozzolanic reaction of FA. The presence of FA reduced porosity due to the pozzolanic reaction and micro-aggregate effect. This was particularly observed at the end of the curing, showing the production of high-quality mortar. Based on the results, combining of 80%BA and 20%FA offered a sustainable alternative to naturally sourced fine aggregate that produced mortar of comparable performance.

Keywords: recycling, fly ash, bottom ash, fine aggregate, mortar, sustainable

1 Introduction

Natural sand is widely used as fine aggregate in the construction sector. In 2020, approximately 10 billion tons of sand was used for construction, which is expected to increase twofold by 2060 [1,2]. A previous study has shown that more than 60% of natural sand is used as fine aggregate in mortar and concrete to develop infrastructure globally [3]. However, the excessive exploitation to meet the demand for fine aggregate has led to significant environmental destruction. This shows the need for suitable alternative materials to reduce the usage of natural sand in mortar and concrete in sustainable construction.

An alternative material is coal ash, a combustion residue from coal thermal power plant, which shares characteristics like sand. Large quantities of coal ash are produced globally in the form of 70%–80% fly ash (FA) and 10%–20% bottom ash (BA) [4]. Most of this product is disposed of around the plant, which negatively affects the surrounding environment. In 2019, 560 million tons of FA and 190 million tons of BA were produced [5,6], with Asian countries producing 66%, followed by Europe, the USA, and Africa [7]. Indonesia produced 12 million tons of coal ash in 2021, with projection of an annual production of 16.2 million tons in 2027 [8]. As coal continues to be a primary fuel in thermal power plants, the production of coal ash is expected to grow. This increase contributes to the

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accumulation of coal ash in landfills, which poses negative impacts on human health and the environment [9,10].

FA and BA are widely used as substitutes for cement or fine aggregate in mortar and concrete. Moreover, FA is mostly used to replace cement in mortar and concrete due to the pozzolanic characteristics that refine the pore structure of the matrix, which enhances performance over time [9–12]. Despite these numerous benefits, the major drawback of slow strength development in the early stages of hydration has limited the replacement of cement by FA to 30%, which is only 6%–8% of the total volume of the concrete mix [13]. BA has a particle size range like fine to coarse sand and is often used as fine aggregate in mortar and concrete [14–16]. However, it has a porous nature, high absorption capacity, and low crushing value, which limited the replacement with sand to 40% to obtain concrete with acceptable strength and durability [17, 18]. Fine aggregate comprises 50%–80% of the total volume of mortar and concrete. Using the combination of FA and BA to fully replace sand as fine aggregate can increase the amount of each alternative in concrete mix. The exploitation of coal ash will reduce environmental risk and lead to a cleaner environment, producing sustainable building materials.

Several studies have used FA as a replacement for sand in mortar and concrete. Siddique [19] replaced FA as fine aggregate at dosages of 0%–50% by weight for concrete cured in tap water for approximately 365 days. The results showed that increasing FA content required improving the water–cement ratio to achieve similar workability as the control concrete. Replacing sand with 50% FA increased the compressive, flexural, and split tensile strength, as well as the modulus of elasticity at all ages compared to the control concrete. Siddique [20] found that using 40% FA in concrete improved the abrasion resistance by 39.29%, 38.10%, and 42.61% at 28, 90, and 365 days, respectively.

Bilir et al. [21] investigated using FA at 100% of fine aggregate in mortar by weight and reported decreased workability and unit weight of mortar. The 30% FA mortar achieved a compressive strength 3.87% higher than the control at 28 days. However, increasing FA content further decreased the compressive strength by 37.43%–73.1%. Similar trends were observed for the flexural strength and modulus of elasticity. Based on the results, replacing approximately 70% of sand with FA would produce mortar suitable for structural application with a compressive strength of 20 MPa. Titiksh et al. [22] used FA as 100% of fine aggregate in paving blocks and found that the workability could be improved by adding hyper-plasticizers and extra water to the mix without bleeding. Compared to the control, 100% FA specimen improved the compressive, flexural, and split tensile strengths by 48.32%, 5.88%, and 13.89%, respectively, at 28 days. Additionally, there was significant improvement in the chloride resistance and abrasion by 2.59% and 25.44%, respectively. Zhang et al. [23] reported a significant improvement in carbonation resistance of concrete specimens that replaced 10%–40% of fine aggregate with FA. According to Zhang et al. [24], using FA as fine aggregate rather than as a cement replacement reduced porosity and carbonation depth of the concrete due to the hydration process and micro-aggregate effect of the material.

The effect of BA has been examined as fine aggregate in mortar and concrete [14, 16, 25]. Singh et al. [26] found that increasing BA content decreased workability and bleeding of the concrete. The result concluded that using approximately 30% BA without a superplasticizer and 50% BA with a superplasticizer could produce concrete suitable for structural applications. Although the use of this material reduced the early compressive and split tensile strengths of the concrete, comparable strengths to the control concrete were achieved after 90 days with approximately 50% BA. The same trend was observed for the pulse velocity and abrasion. According to another study [27], BA increased the connectivity between capillary pores in the matrix, which enhanced porosity and water absorption of the concrete at 28 days. However, the effect decreased with high curing age because the pozzolanic contribution of BA to C–S–H gel structure caused dense, compact, and crumpled sheets.

Kim et al. [28] evaluated the properties of normal and high-strength mortar with 100% BA at different water–cement ratios. The results showed that increasing BA content decreased the density of mortar while improving the workability due to the lower specific gravity, porous structure, and high water absorption of BA particles. The compressive strength specimen tested was 5%–15% lower than the control for all water–cement ratios. Additionally, there was a greater capillary water absorption due to the porous structure of BA. Siddique [29] investigated the performance of self-compacting concrete (SCC) containing BA as fine aggregate. The results confirmed that SCC could be produced with approximately 30% BA as fine aggregate. High BA content was observed to reduce the compressive and split tensile strengths, although the chloride penetration resistance, water absorption, and sorptivity increased linearly.

Torkittikul et al. [30] found that increasing BA content decreased the workability as well as density of mortar and concrete due to the lower specific gravity and increased pore volume compared to sand. Moreover, 100% BA increased the volume of permeable voids and water absorption of mortar and concrete compared with the control specimen. The higher porosity of mortar and concrete also improved the thermal conductivity. Srivastava et al. [31] reported that the compressive strength and pulse velocity of 20% BA mortar were comparable to the control at 28 days, but a significant decrease was observed when BA content increased. These previous studies showed that using large volumes of BA to replace fine aggregate reduced the strength as well as durability of mortar and concrete, particularly in the early stages of hydration.

Previous studies have shown that FA, when used as fine aggregate, enhances the strength and durability of mortar and concrete through early-age pozzolanic activity and micro-filler effects, whereas high-volume BA replacement is often limited by its porous structure and high water demand, leading to reduced performance. Although FA–BA combinations have been explored, existing research remains largely restricted to partial replacement levels, with limited emphasis on long-term durability under full fine-aggregate substitution. This study addresses this gap by systematically investigating mortar in which natural sand is fully replaced by high-volume BA combined with FA. The novelty lies in demonstrating that optimized FA incorporation can effectively mitigate BA-induced porosity, resulting in a dense microstructure and balanced mechanical–durability performance suitable for sustainable construction.

2 Significance of the study

The limited use of coal ash is the main obstacle to preventing environmental pollution. This is particularly attributed to the large coal ash production, which is not accompanied by a large amount of use. In this study, efforts were made to use coal ash products, namely, FA and BA, as a full replacement for fine aggregate in mortar mix. Previous studies by [13] showed that the combination of FA and BA as a replacement for sand in concrete can increase mechanical properties. Further investigation regarding the full replacement of sand with these materials in mortar or concrete mix is still required to assess durability. The porous nature of BA may introduce large amounts of pores in the mix when used in large quantities, thereby affecting the life of building structure. Despite previous analyses, there is a lack of information durability performance of cement-based material containing FA and BA as full replacement for fine aggregate. Therefore, this study aimed to investigate mechanical properties and durability of mortar containing FA and BA as a full replacement for fine aggregate. This study examines the effects of different proportions of FA and BA on the workability, density, compressive strength, splitting strength, water absorption, chloride resistance, and ultrasonic pulse velocity (UPV) of the resulting mix. The contribution of FA to the strength was quantitatively analyzed using strength indices. Scanning electron microscopy (SEM) was used to analyze the microstructure. The novelty of this study is threefold: (i) it evaluates the feasibility of 100% fine aggregate replacement using combined BA–FA systems, (ii) it quantitatively assesses the ability of FA to mitigate BA-induced porosity and durability degradation, and (iii) it integrates long-term durability indicators with microstructural evidence and correlation analysis. These aspects distinguish this work from previous studies that primarily focus on partial replacement or short-term mechanical performance.

3 Experimental programs

3.1 Materials

The binding material used was Portland cement composite, locally available in Indonesia with a specific gravity of 3.1. Both FA and BA were sourced from a coal thermal power plant in Punagaya, South Sulawesi, Indonesia. BA was sieved through a No. 4 mesh to remove coarse particles before use, while natural river sand (NS) was applied as fine aggregate. **Tables 1** and **2** present the physical and chemical properties of all materials, with FA and BA showing lower specific gravities compared to NS. BA had a higher water absorption than NS due to the porous nature and a higher fineness modulus.

According to ASTM C618 [32], both FA and BA can be categorized as Class F with total oxide contents of $SiO_2 + Fe_2O_3 + Al_2O_3 > 70\%$, $CaO < 10\%$, and $SO_3 < 5\%$.

Table 1. Physical properties of FA, BA, and NS

Item	FA	BA	NS
Specific gravity	2.55	2.48	2.61
Water absorption (%)	-	2.91	1.34
Fineness modulus	31.84% retained on No. 325 sieve	2.24	2.08

Table 2. Chemical properties of FA, BA, and NS

Oxide (%)	SiO_2	Fe_2O_3	Al_2O_3	CaO	MnO	SO_3	K_2O	TiO_2	Others
FA	50.9	12.3	16.1	7.2	0.55	2.12	1.1	1.17	5.87
BA	42.7	16.82	14.22	9.35	1.74	4.84	0.57	1.88	6.31
NS	64.32	3.32	8.83	5.98	-	-	0.48	0.58	16.49

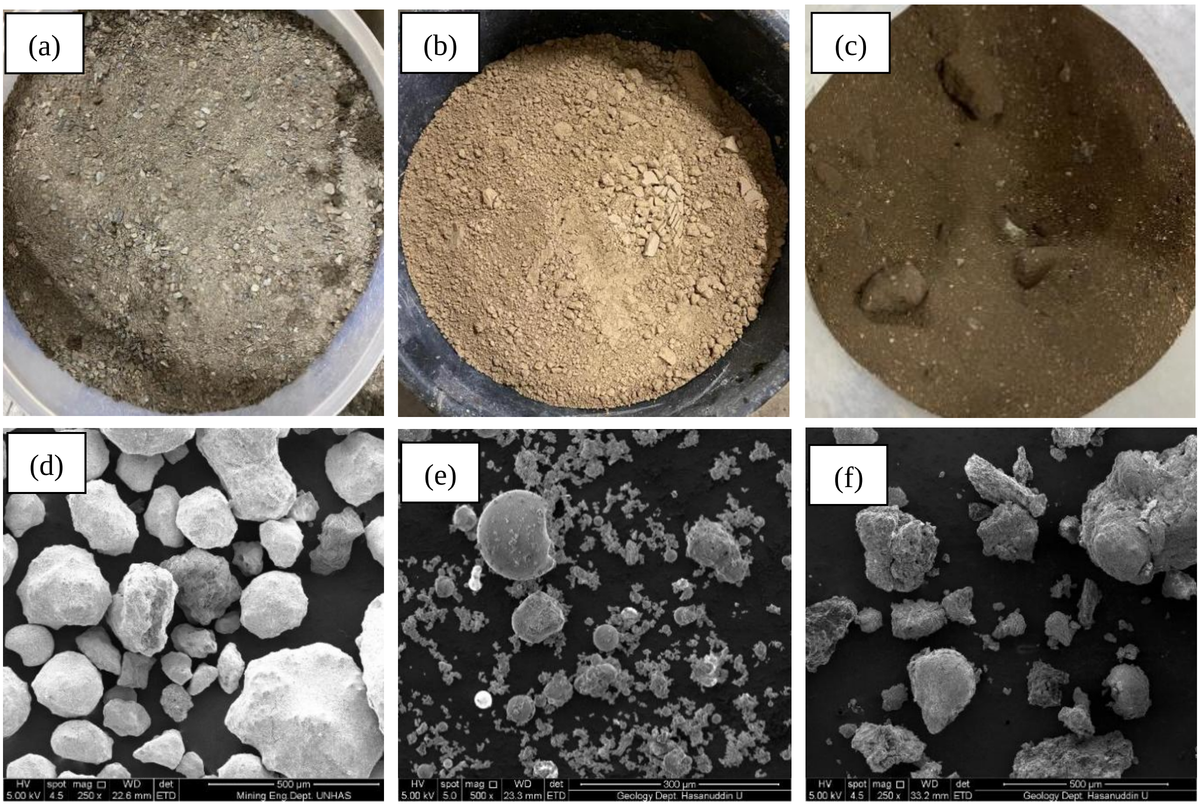

Fig. 1. Physical appearance and SEM images of (a, d) NS, (b, e) FA, and (c, f) BA.

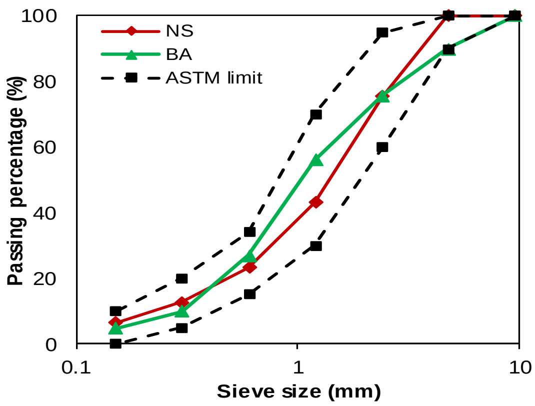

Fig. 2. Particle size distributions of NS and BA.

Fig. 1 shows the physical appearance and SEM images of FA, BA, and NS, while **Fig. 2** shows the grading curves of BA and NS. Moreover, NS particles are rounded and angular in shape, and FA particles are spherical. BA particles are irregularly shaped with a porous texture, which degrades the concrete performance and satisfies the gradation requirements according to ASTM C33 [33] for fine aggregate in concrete and mortar mix.

3.2 Specimen preparation and test methods

Mortar was mixed according to SNI-03-6825-2002 [34], using constant water–cement ratio of 0.48 and fine aggregate–cement ratio of 2.75 to produce specimens. The control mortar was prepared by using river sand as fine aggregate. Other specimens were prepared by fully replacing fine aggregate with BA or a combination of FA and BA, with mix ratio presented in **Table 3**. The porous structure of BA and finer particles of FA showed potential to decrease the workability of mortar. Therefore, additional water was added to mortar containing FA and BA during the mixing process to obtain similar workability as the control mortar. No chemical admixtures were used in this study in order to evaluate the intrinsic behavior of FA–BA mortar systems under full fine-aggregate replacement and to maintain simplicity and cost efficiency relevant to practical applications in resource-limited construction. The fresh mortar specimens were cast in steel molds, demolded after 24 h, and cured in tap water until testing.

Table 3. Mix design of 1 m^3 mortar specimens.

Mix ID	Water (kg/m^3)	Cement (kg/m^3)	NS (kg/m^3)	FA (kg/m^3)	BA (kg/m^3)	Extra water (kg/m^3)
C	259	535	1470	0	0	0
100BA	259	535	0	0	1470	13.85
90BA:10FA	259	535	0	147	1323	24.55
80BA:20FA	259	535	0	294	1176	45.95
70BA:30FA	259	535	0	441	1029	72.71

Note: C: Control; 100BA: 100% BA; 90BA:10FA: 90% BA and 10% FA; 80BA:20FA: 80% BA and 20% FA; 70BA:30FA: 70% BA and 30% FA.

The workability of the fresh mortar specimens was evaluated by the slump flow test according to ASTM C1437 [35]. The compressive strength was measured according to SNI-03-6825-2002 [34] using cubic specimens with dimensions of 50 mm × 50 mm × 50 mm at curing ages of 7, 28, and 180 days. The measurement of split tensile strength was based on ASTM C496 [36] using cylindrical specimens with a diameter of 50 mm and height of 100 mm at curing ages of 28 and 180 days. The average of three measurement values for each mortar was recorded as the compressive and split tensile strengths.

Porosity and water absorption were measured according to ASTM C 642 [37] by using cylindrical specimens with a diameter of 100 mm and thickness of 50 mm at 28 and 180 days. These specimens were obtained by cutting cylinders with a diameter of 100 mm and a height of 200 mm in the middle. The chloride resistance was measured according to ASTM C 1202 [38] by using mortar disks with a diameter of 100 mm and thickness of 50 mm at 28 and 180 days. The UPV was measured according to ASTM C 597 [39] by using cubic specimens with dimensions of 50 mm × 50 mm × 50 mm at curing ages of 28 and 180 days under the saturated surface dry condition. All tests were performed in triplicate for each mix ratio, and the average value was recorded. SEM image analysis was performed on selected mortar specimens at 180 days. Subsequently, a small piece of mortar obtained after the compressive strength test was dried in a vacuum for 24 h and coated with platinum for further testing.

4 Results and discussion

4.1 Water content

The replacement of fine aggregate with FA and BA required extra water to achieve a similar workability as the control mortar. **Fig. 3** shows the water content for each mortar, with the control having 259 kg/m^3. A significant increase was observed for 100BA, 90BA:10FA, 80BA:20FA, and 70BA:30FA mortar by 5.35%, 9.48%, 17.74%, and 28.07%, respectively. Bleeding was observed in 70BA:30FA mortar, showing that high water content was required to wet FA particles. The linear increase in water demand observed in **Fig. 3** is governed by the combined effects of BA porosity and FA surface characteristics. BA particles exhibit a highly porous internal structure and irregular morphology, which promotes rapid absorption of mixing water and reduces the amount of free water available for particle lubrication [40]. Simultaneously, the incorporation of FA as fine aggregate increases the overall specific surface area of the solid phase, thereby elevating the surface water demand required to form a continuous water film and maintain flowability. As the FA content increases, this surface-controlled mechanism becomes increasingly dominant. Although additional water was introduced to achieve comparable workability, the resulting increase in effective water-to-cement ratio represents a limiting factor at high FA contents. In particular, the 70BA:30FA mixture required excessive water, which led to increased capillary porosity after hydration and consequently diminished strength and durability performance, despite the inherent pozzolanic reactivity of FA [21].

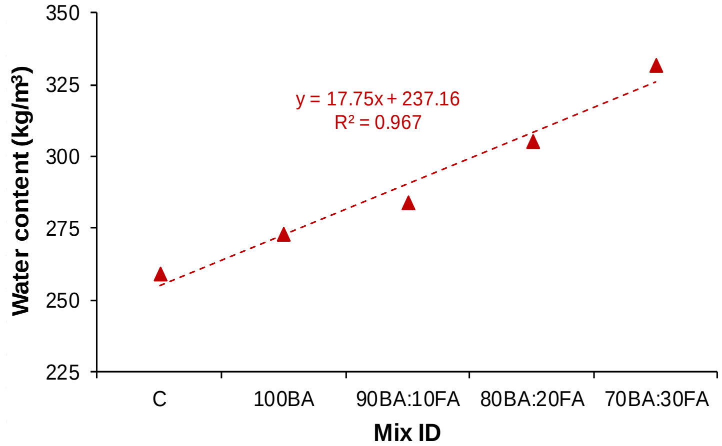

Fig. 3. Water content for each mortar.

4.2 Compressive and split tensile strengths

Fig. 4 shows the compressive strength development of mortar, which increases generally with curing at 7, 28, and 180 days of curing. Based on the results, the compressive strength of 100BA mortar at 7, 28, and 180 days was 74.78%, 72.13%, and 85.39%, respectively. This poor performance could be attributed to the porous structure of BA and the increased water content of mortar to improve the workability, as reported in previous studies [6, 26–28, 40]. Moreover, the addition of FA compensated for the poor performance of using BA in mortar. The compressive strengths of 90BA:10FA and 80BA:20FA mortars at 7, 28, and 180 days were 117.76%–124.64%, 107.94%–112.16%, and 110.79%–119.48%, respectively. The results showed that using FA as a replacement for fine aggregate did not significantly reduce the compressive strength compared to cement [24]. FA particles improved mortar strength by the pozzolanic reaction and filler effect, which filled the pores generated by BA, densifying the microstructure of mortar at all curing ages [19, 21]. However, 70BA:30FA mortar had a lower compressive strength than the control at all curing ages due to the higher water content increasing porosity. Abdulmatin et al. [18] and Kumar et al. [17] reported similar results for mortar that extra water was added to improve the workability.

Based on the results, the compressive strength of the 100BA mortar increased at 180 days compared to 7 and 28 days. This delayed strength gain is primarily attributed to continued cement hydration and secondary densification effects associated with fine BA particles, rather than strong intrinsic pozzolanic activity. While BA exhibits limited pozzolanic reactivity, its finer fractions can contribute to micro-filler effects and slow secondary reactions over extended curing periods, leading to gradual strength improvement, as also reported in previous studies [25, 41]. The compressive strength of 90BA:10FA and 80BA:20FA mortar improved significantly from 28 to 180 days by 28.51% and 23.83%, respectively, while the control was enhanced by 19.76%. Due to increased curing age, a sufficient amount of $Ca(OH)_2$ was produced from the cement hydration process to support the pozzolanic reaction of FA and BA. This reaction produced additional calcium silicate hydrate (C–S–H), which increased the compressive strength of FA:BA mortar [13]. Rafieizonooz et al. [41] reported that concrete replacing 20% of cement with FA and 100% of fine aggregate with BA increased in strength from 28 to 180 days by 22.35%. The results showed that replacing 20% of fine aggregate with FA increased the strength compared to replacement with 20% of cement.

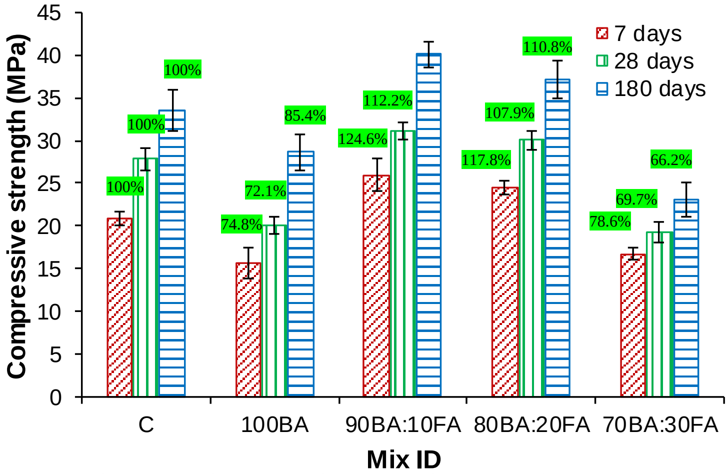

Fig. 4. Compressive strength development of mortar at 7, 28, and 180 days.

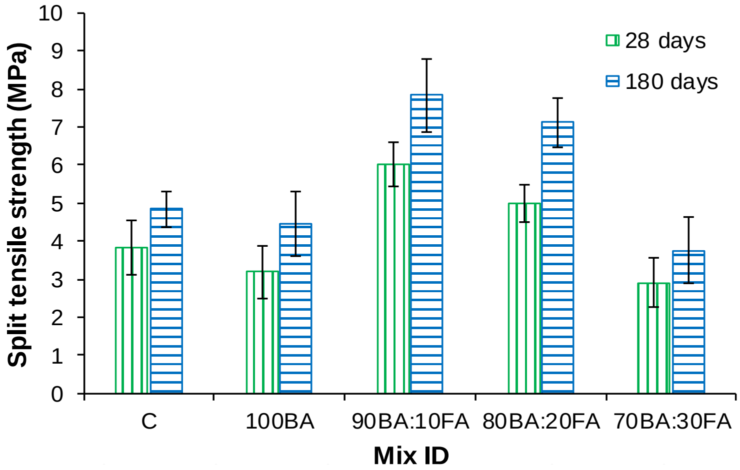

Fig. 5. Split tensile strength development of mortars at 28 and 180 days.

Fig. 5 shows that the split tensile strength of 90BA:10FA and 80BA:20FA mortar increased with curing age. Compared to the control, these specimens increased in tensile strength at 28 and 180 days by 31.03%–57.26% and 47.11%–61.98%, respectively. The split tensile strength increased with the compressive strength, as also reported in previous studies [23,31], with 90BA:10FA mortar producing the optimal performance.

4.3 Contribution of FA to mortar strength

The contribution of FA to mortar strength with BA was analyzed by using the strength index proposed by Yu et al. [42]. This index has been widely adopted to quantify the contribution of the pozzolanic material and recycled aggregate to the strength of cement-based materials [43–45].

The specific strength index (R) is expressed by Eq. (1).

$$R = f / q \tag{1}$$

where f is the compressive strength of mortar and q is the amount of replacement of the natural fine aggregate. R_r is the contribution of FA as fine aggregate to mortar strength and is defined in Eq. (2).

$$R_r = R_{FA} - R_{BA} \tag{2}$$

where R_{BA} is the contribution of the unit BA to mortar strength, and R_{FA} is the contribution of the unit FA. Finally, the percentage contribution (P) of FA to mortar strength is expressed by Eq. (3).

$$P = (R_r / R_{FA}) \times 100\% \quad (3)$$

when P is greater than the amount of FA replacing BA, it shows that FA makes a positive contribution to mortar strength and vice versa.

Table 4 shows the strength indices (q, RFA, Rr, and P) of BA:FA mortar. Based on the results, 90BA:10FA and 80BA:20FA mortar had P values of 46%–49.2%, 42.1%–46.6%, and 35.7%–38.3% at curing ages of 7, 28, and 180 days, respectively. These values were higher than the percentage replacement of FA for BA, showing that using 10%–20% FA in fine aggregate had a positive contribution to mortar strength at all curing ages due to the pozzolanic reaction. However, using 30% FA had a negative effect on mortar strength according to P value, particularly at curing ages of 28 and 180 days. This correlated with the results of the compressive and splitting tensile strength tests.

Table 4. Strength indices of mortar

Mix ID	q	R_{FA}			R_r			P		
		7d	28d	180d	7d	28d	180d	7d	28d	180d
100BA	100	0.17	0.2	0.29	-	-	-	-	-	-
90BA:10FA	90	0.29	0.35	0.45	0.13	0.15	0.16	46	42.1	35.7
80BA:20FA	80	0.31	0.38	0.47	0.15	0.17	0.18	49.2	46.5	38.3
70BA:30FA	70	0.238	0.27	0.33	0.08	0.07	0.04	34.6	26.8	12.9

4.4 Porosity and water absorption

Porosity plays an essential role in durability, affecting how effectively mortar can resist the penetration of aggressive chloride and sulfate ions. **Fig. 6** shows porosity of mortar at 28 and 180 days, indicating a decrease with increased curing age. This showed that the presence of FA and BA did not change the overall trend of the hydration process. Adding up to 20% FA decreased porosity of mortar at 180 days. Additionally, 90BA:10FA and 80BA:20FA mortar showed reductions of approximately 18% and 5%, respectively, at 180 days compared to the control. This was attributed to the pozzolanic and filler effects of FA, which improved the microstructure and filled in the pores. Similar results were reported by Zhang et al. [23], where replacing 10% and 20% of fine aggregate with FA reduced porosity of concrete by 2.29% and 7.54%, respectively. This reduction could be attributed to the denser microstructure produced from the pozzolanic reaction of FA and BA at all curing ages. However, 70BA:30FA mortar showed a different trend, where porosity increased due to the high water demand. During the vibration process, water bubbles developed in mortar. After the hydration process, these bubbles left the internal structure, creating permanent pores in mortar [43, 46].

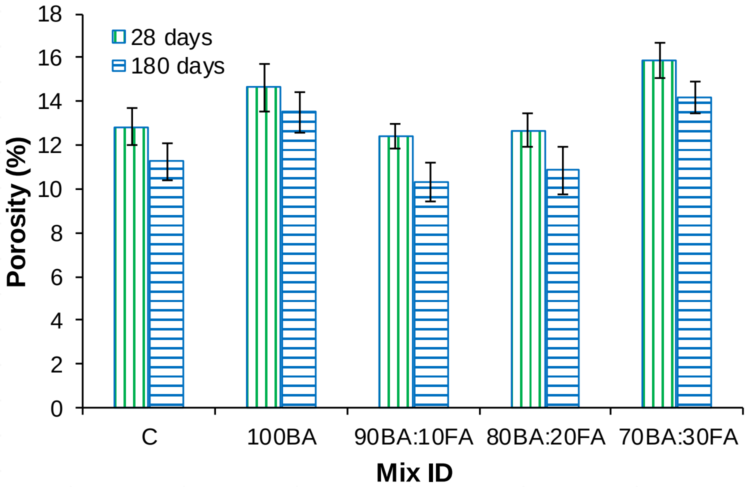

Fig. 6. Porosity of mortar at 28 and 180 days.

Fig. 7 shows the water absorption of mortar at 28 and 180 days, which decreases with increasing curing age. At 28 days, 100BA mortar had the highest water absorption at 9.12%. However, 90BA:10FA and 80BA:20FA had lower water absorption than the control by 5.59% and 2.38%, respectively. At 180 days, these specimens showed a significant decrease of 13.79% and 7.37%, respectively. This could be attributed to the pozzolanic reaction of FA and BA reducing porosity, which led to a decrease in water absorption. Similar results were reported for mortar replacing fine aggregate with FA [21].

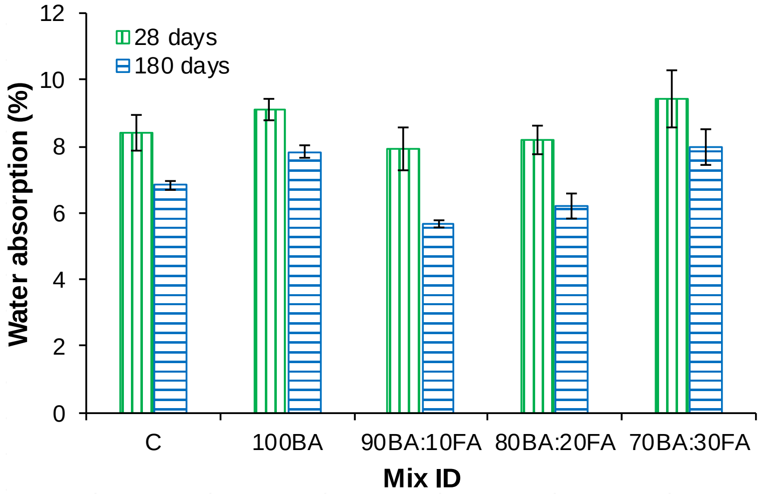

Fig. 7. Water absorption of mortars at 28 and 180 days.

4.5 Rapid chloride permeability test (RCPT)

Chloride resistance is a key factor that determines concrete quality, often assessed using RCPT. **Fig. 8** presents RCPT results of mortar at curing ages of 28 and 180 days, the general trend observed across all mixtures was a reduction in RCPT values with increasing curing time. This reduction is attributed to the continuous hydration of cement and the delayed but beneficial pozzolanic reaction of FA, which progressively densifies the matrix and refines the pore structure. Among the mixtures, the control mortar demonstrated a moderate decline in RCPT values from 2573 C at 28 days to 1520 C at 180 days a 1.69-fold reduction. Although this indicates ongoing hydration and microstructural refinement, the addition of pozzolanic materials was found to further enhance this effect.

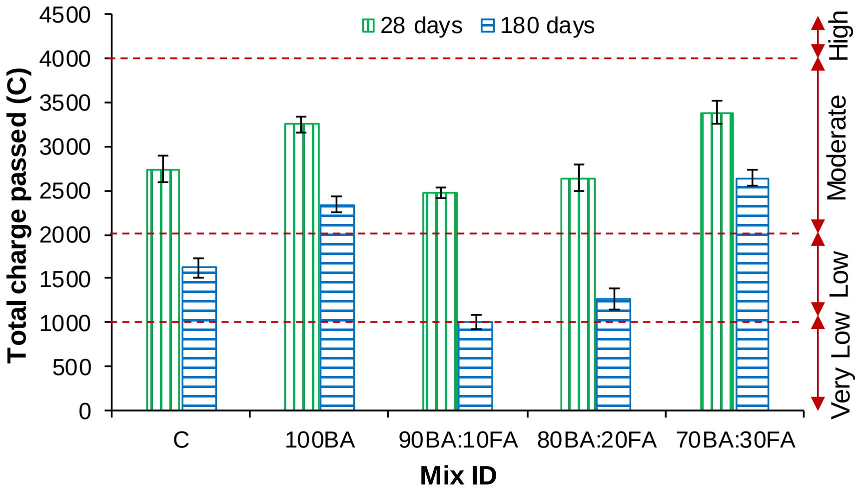

Fig. 8. Total charge passed of mortar at 28 and 180 days.

The mortar incorporating 100% bottom ash (100BA) presented RCPT values of 3253 C at 28 days and 2340 C at 180 days. These values were 16.61% and 30.64% higher than those recorded for the control mixture at the corresponding curing ages. This performance can be linked to the relatively high porosity and lower reactivity of bottom ash, which lacks sufficient pozzolanic behavior to significantly reduce the permeability of the mortar. Similar observations were reported by [25], who found that high levels of bottom ash substitution increased the transport properties of concrete due to its coarser texture and irregular shape. In contrast, binary mixes of BA and FA showed markedly improved performance. The 90BA:10FA mortar exhibited a reduction in RCPT values of 10.21% at 28 days and a significant 38.26% at 180 days compared to the control. This mixture also showed the largest reduction over time, with values dropping from 2312 C to 1422 C—a 2.46-fold decrease. Similarly, the 80BA:20FA mortar recorded a 3.83% reduction in RCPT at 28 days and a 22.06% reduction at 180 days, with a corresponding 2.09-fold decrease between the two curing stages. These improvements indicate a denser and less permeable mortar matrix due to a synergistic effect between the fly ash's pozzolanic reaction and the filler role played by both ashes.

The improved chloride resistance in the 90BA:10FA and 80BA:20FA mortars is primarily due to the development of additional C-S-H from the pozzolanic reaction between FA and the calcium hydroxide liberated during cement hydration. The formation of C-S-H not only consumes the relatively porous and less durable calcium hydroxide but also reduces pore connectivity, thereby limiting the mobility of chloride ions. Additionally, FA's fine and spherical particles enhance packing density, filling voids between larger particles and reducing the capillary porosity. These findings are consistent with the results of earlier research by [21,24], who emphasized the significant contribution of FA in enhancing durability-related properties of cementitious systems, including reduced charge passed in RCPT tests. Interestingly, the 70BA:30FA mortar did not follow the same trend. This mixture showed minimal or no improvement in RCPT values at both curing ages. The absence of significant change suggests that the higher volume of FA may have disrupted the optimal particle packing or led to an insufficient amount of calcium hydroxide to sustain the pozzolanic reaction at an effective rate. High volumes of FA can also delay early hydration, leading to a more porous structure in the short to medium term, which undermines its chloride resistance potential.

4.6 UPV

Fig. 9 illustrates the ultrasonic pulse velocity (UPV) values of various mortar mixtures measured up to a curing age of 180 days. The results reveal a progressive increase in UPV with curing age across all mortar types. This trend aligns with expectations based on the ongoing hydration of cement and the gradual pozzolanic reaction of fly ash (FA), both of which contribute to the development of a denser and more cohesive microstructure over time. As hydration progresses, the continuous formation of calcium silicate hydrate (C-S-H) gel fills the capillary pores, enhancing the compactness and reducing the permeability of the matrix [47, 48]. These developments result in an improvement in UPV, as also reported by [41], who observed a similar correlation between curing duration and UPV in pozzolanic mortars.

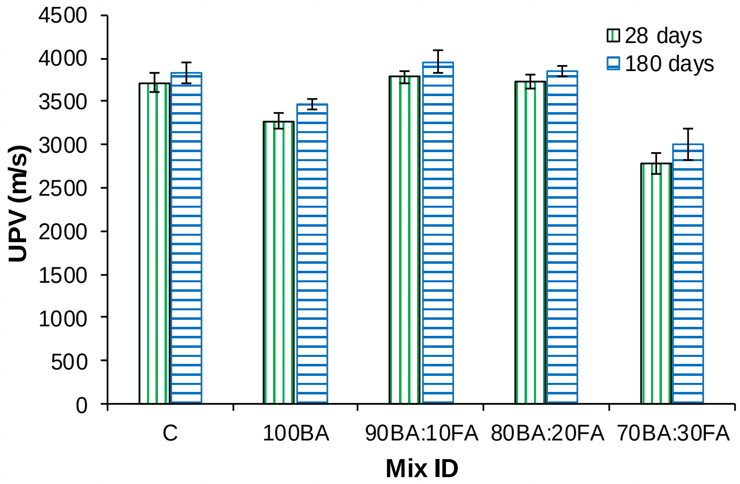

Fig. 9. Ultrasonic pulse velocities of mortars at 28 and 180 days.

Among the tested mixtures, the mortar incorporating 100% bottom ash (100BA) exhibited relatively lower UPV values, registering 3275 m/s and 3471 m/s at 28 and 180 days, respectively. These values were approximately 14.6% and 11.3% lower than those of the control mortar. The reduced UPV in 100BA mortar is likely due to the inherently porous nature of bottom ash, which leads to a more open and disconnected pore structure, thereby impeding wave propagation. A study by [20] supports this observation, indicating that bottom ash, when used in higher proportions, often results in reduced density and mechanical integrity due to its irregular particle shape and low pozzolanic activity. In contrast, the binary mixtures comprising bottom ash and fly ash in proportions of 90:10 and 80:20 demonstrated superior performance in terms of UPV. At 28 days, the 90BA:10FA and 80BA:20FA mortars showed UPV values that were 8% to 14% higher than the control, while at 180 days, the improvements ranged from 11% to 18%. These mixtures consistently recorded UPV values exceeding 3500 m/s, which, based on the classification by [49], signifies "good quality" concrete. Such UPV readings indicate the absence of internal microcracks or structural deficiencies, suggesting that the integration of fly ash enhances the microstructural development of the mortar matrix.

The observed improvement can be attributed to several synergistic effects of using both bottom ash and fly ash. The fine, spherical particles of fly ash improve packing density and help fill voids left by the coarser bottom ash particles, effectively reducing porosity. Additionally, the pozzolanic reaction between fly ash and calcium hydroxide further contributes to secondary C–S–H formation, which strengthens the interfacial transition zone (ITZ) and densifies the matrix. These outcomes are consistent with the findings of [19], who reported enhanced UPV and reduced porosity in fly ash-modified mortars. The UPV results reinforce the beneficial role of combining BA and FA in mortar applications. While bottom ash alone tends to reduce the quality of the mortar due to its porous nature and limited reactivity, the inclusion of fly ash significantly mitigates these drawbacks. The 90BA:10FA and 80BA:20FA mixtures not only achieved higher UPV values but also demonstrated consistent improvement with age, highlighting their potential for durable and high-quality mortar production. These findings suggest that partial substitution of BA with FA in appropriate ratios can optimize the performance characteristics of mortar, making it a viable and sustainable alternative in construction applications.

4.7 Microstructural analysis

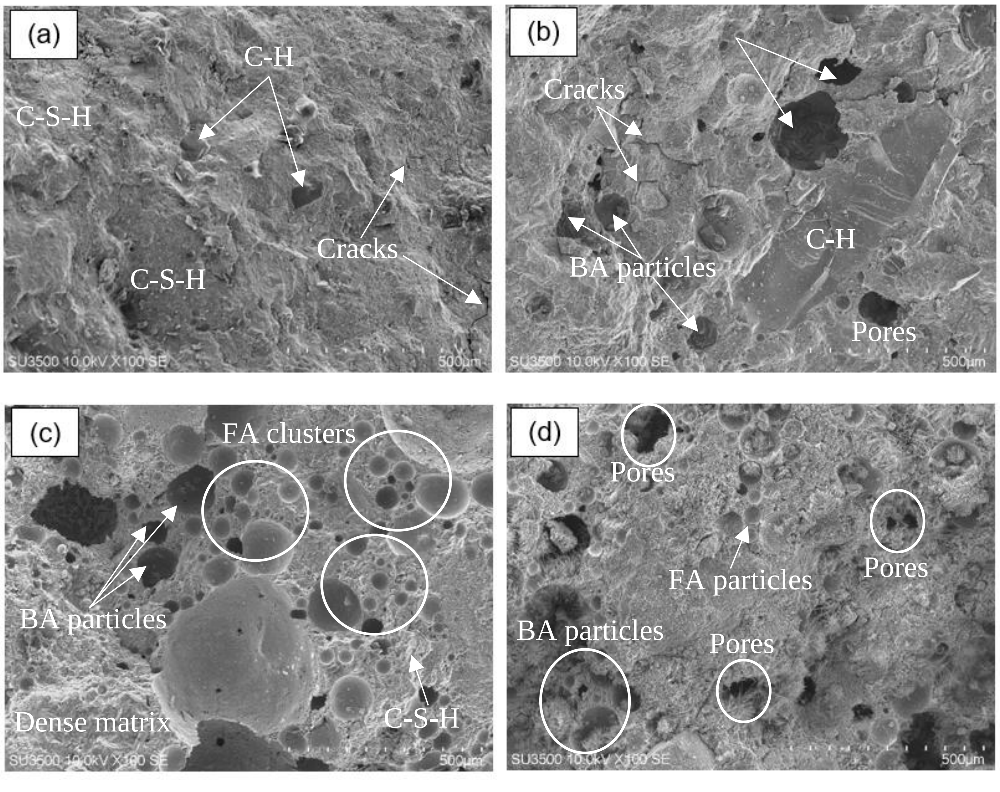

Fig. 10. SEM images of mortars at 180 days: (a) control, (b) 100BA, (c) 90BA:10FA, and (d) 70BA:30FA.

SEM images were used to analyze the microstructure of selected mortar. **Fig. 10** shows small pieces of the control, 100BA, 90BA:10FA, and 70BA:30FA mortar specimens after the compressive strength test at 180 days. These micrographs provide visual confirmation of the internal structure and corroborate the mechanical and durability results discussed earlier. The control specimen (**Fig. 10a**) exhibited typical microstructural features of hydrated Portland cement mortar, with distinguishable hydration products such as C–S–H gel and crystalline calcium hydroxide (C–H). While these hydration products are essential for strength development, several microcracks and voids were visible throughout the matrix. These imperfections are likely the result of thermal stress induced during early hydration, where the exothermic reaction between cement and water releases significant heat, causing expansion and eventual microcracking as the material cools and hardens. Similar features have been described by previous studies, such as those by [43, 50], which also noted the formation of internal cracks in ordinary Portland cement systems due to self-desiccation and shrinkage.

The mortar incorporating 100% BA (**Fig. 10b**) showed a less cohesive and porous structure compared to the control. The presence of irregular voids and unreacted ash particles indicated limited cementitious activity and weak bonding within the matrix. The inherent porosity of BA, combined with its angular shape and low pozzolanic reactivity, hindered the development of a dense microstructure. This poor microstructural integrity likely contributed to the lower compressive strength and higher chloride permeability observed in this mix. The lack of secondary gel formation and minimal particle interlocking further explain its suboptimal performance. In contrast, the 90BA:10FA specimen (**Fig. 10c**) demonstrated a significantly more refined and compact microstructure. The FA particles appeared to be well-integrated into the matrix, acting as both micro-fillers and reactive agents. Their spherical morphology allowed them to fill micro voids efficiently, while their pozzolanic activity resulted in additional C–S–H formation over time. This dual function contributed to the densification of the paste and the reduction of pore connectivity. Fewer cracks and voids were observed, indicating improved mechanical integrity. This visual evidence supports the previously discussed enhancements in strength, UPV, and chloride resistance for this mix. The improved bonding and homogeneity can be attributed to the optimal FA content, which complemented the physical and chemical shortcomings of bottom ash.

On the other hand, the 70BA:30FA mortar (**Fig. 10d**) exhibited a more porous and disconnected structure compared to the 90BA:10FA mix. Numerous voids and poorly bonded areas were identified throughout the matrix. This behavior may be linked to the high FA content, which increases water demand during mixing due to its high surface area and fine particle size. The excess water, when evaporated during hydration, leaves behind capillary voids that weaken the structure. Moreover, the high replacement level may reduce the availability of calcium hydroxide needed for effective pozzolanic reaction, thus limiting the formation of binding gel products.

Overall, the SEM images provided critical insights into how varying combinations of BA and FA influence the internal structure of mortar. These visual findings were in strong agreement with the mechanical strength and durability results, confirming that 90BA:10FA mortar achieved the most favorable microstructure due to a balanced synergy between filler effects and pozzolanic reactions.

4.8 Correlations among engineering properties

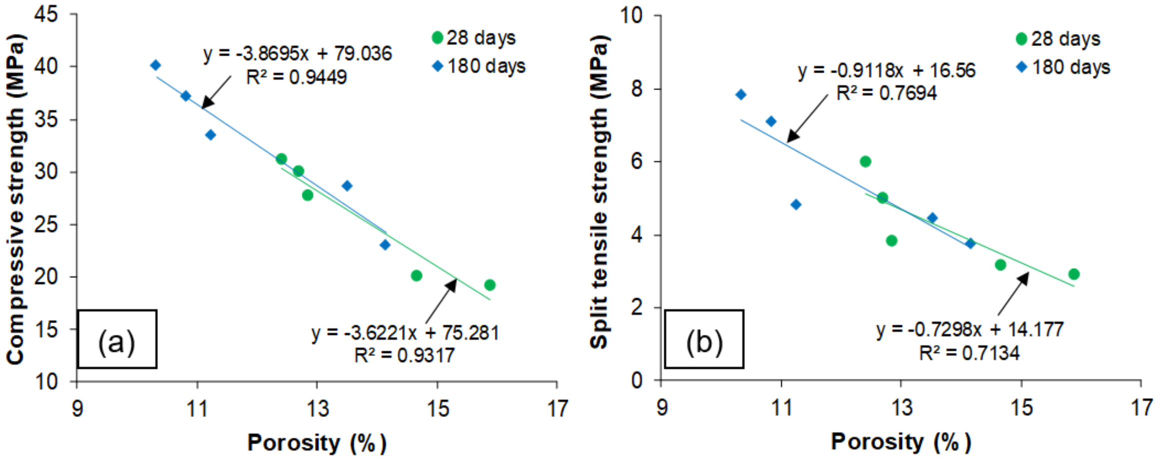

Fig. 11. Correlation between porosity and mechanical properties: (a) compressive strength and (b) split tensile strength.

Porosity plays a crucial role in determining both the mechanical behavior and durability performance of mortar. **Fig. 11** presents the relationship between total porosity and key mechanical properties, specifically compressive and split tensile strengths, for all mortar mixes evaluated in this study. A clear inverse trend was observed: as porosity decreased, both strength parameters increased. This relationship is underpinned by the fact that higher porosity generally results in more voids and weak points within the hardened matrix, which act as stress concentrators under loading. These flaws compromise the material's ability to resist both axial and tensile forces. Mortars with lower porosity, on the other hand, exhibit more homogeneous and denser structures, which enhance the load-bearing capacity of the matrix.

Quantitative analysis of the data revealed a strong correlation between porosity and strength, with coefficient of determination (R^2) values ranging from 76% to 94%. These values indicate that a significant proportion of the variation in mechanical performance can be attributed to differences in porosity among the various mixes. This finding aligns with observations made by [51], who demonstrated that porosity is a key predictor of strength properties in cement-based materials. Their work emphasized that the control of internal pore structure is essential in optimizing mortar and concrete performance.

Further supporting the importance of porosity, **Fig. 12** illustrates its correlation with durability-related indicators, namely water absorption, rapid chloride permeability test (RCPT) values, and ultrasonic pulse velocity (UPV). As with the mechanical properties, water absorption and RCPT values decreased with reduced porosity, while UPV increased. This is logical, as higher porosity generally allows for more interconnected capillary channels, facilitating the ingress of water and aggressive ions such as chlorides. A denser microstructure, characterized by reduced pore connectivity and size, impedes fluid transport and ion migration, thereby improving durability.

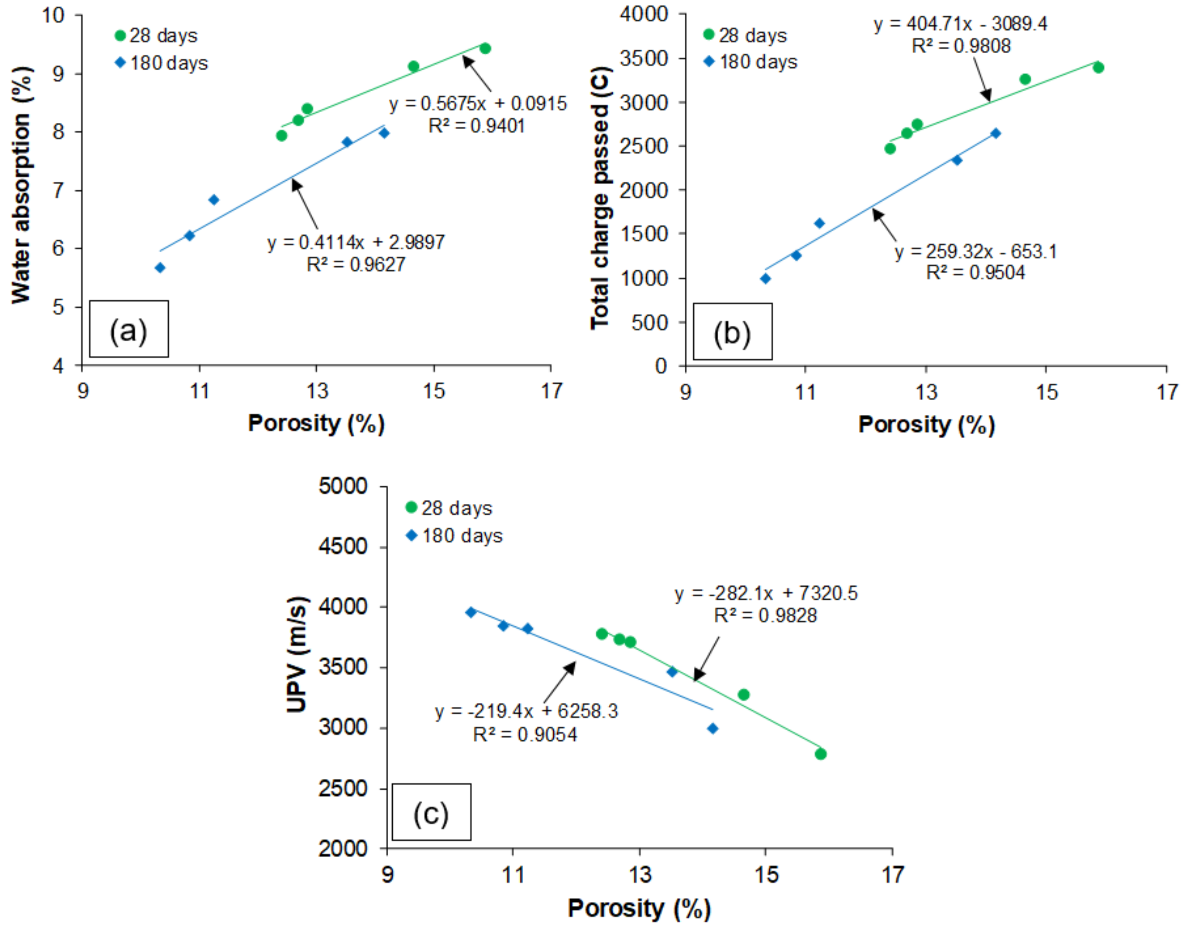

Fig. 12. Correlation between porosity and durability: (a) water absorption, (b) RCPT, and (c) UPV.

The strength of these correlations was confirmed through linear regression analysis, with all three durability parameters showing R^2 values exceeding 90%. This high level of statistical fit highlights the predictive power of porosity when assessing mortar quality. The inverse relationship between porosity and UPV, in particular, demonstrates how non-destructive testing methods can be used to estimate internal compactness and durability. Higher UPV values indicate better material integrity and reduced internal flaws, which typically correspond to lower porosity levels. Similar observations have been reported by earlier researchers [52–54], who found consistent relationships between porosity, transport properties, and ultrasonic measurements in various cementitious systems.

The results strongly suggest that porosity serves as a unifying parameter that influences both mechanical strength and long-term durability. A reduction in porosity, whether achieved through material selection or mix design optimization, contributes to improved structural integrity and resistance to environmental degradation. Consequently, porosity can be considered a reliable and practical indicator in the assessment and prediction of mortar performance. This finding reinforces the importance of microstructural refinement strategies, such as the use of pozzolanic additives like fly ash, for enhancing both strength and durability characteristics in sustainable construction materials.

5 Conclusions and recommendations

This study successfully investigated mechanical properties and durability of mortar by fully replacing fine aggregate with FA and BA. Correlations were established among the various mortar properties, which obtained the following results:

(1) FA and BA could be used to fully replace fine aggregate in mortar. Moreover, 90BA:10FA and 80BA:20FA mortar required extra water to obtain a similar workability as the control.

(2) The optimal mechanical properties were obtained by 90BA:10FA mortar. Over curing ages of 28–180 days, the compressive and split tensile strengths improved by 15%–28% and 32%–48%, respectively, compared to the control. The pozzolanic reaction and micro-aggregate effect of FA contributed to the improved mechanical properties.

(3) The water absorption, RCPT, and UPV results confirmed that using FA and BA as a full replacement of fine aggregate reduced porosity by the pozzolanic reaction, with 90BA:10FA mortar showing good quality.

(4) SEM images showed that 90BA:10FA mortar had less porosity, as well as a more compact and denser microstructure than the control mortar, which improved mechanical properties and durability.

(5) Linear regression analysis obtained high R^2 values confirming the close correlations among porosity, compressive strength, split tensile strength, water absorption, RCPT, and UPV of mortar specimens.

Although this study demonstrates the feasibility of fully replacing natural fine aggregate with combined BA–FA systems, several aspects warrant further investigation. Future research should focus on improving workability control through the use of water-reducing admixtures to minimize excess water demand, particularly at high FA contents. Extended durability assessments under aggressive environments (chloride, sulfate, and carbonation exposure) are also recommended. In addition, long-term field validation and life-cycle performance evaluation would further support the practical application of full fine-aggregate replacement using BA–FA systems.

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CRediT authorship contribution statement

Muhammad Akbar Caronge: Investigation, Formal analysis, Visualization, Writing – original draft. **M. W. Tjaronge**: Conceptualization, Supervision, Formal analysis, Writing – review & editing. **Rita Irmawaty**: Formal analysis, Visualization, Writing – review & editing. **Dahlia Patah**:

Investigation, Visualization, Writing – review & editing. **Nur Hafizah A. Khalid**: Formal analysis, Visualization, Writing – review & editing. **Suharman Hamzah**: Formal analysis, Funding acquisition, Writing – review & editing.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

Data Availability Statement

All data are available from the corresponding author upon reasonable request.

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