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Effect of Coconut Fiber Content on the Properties of Unfired Building Bricks Incorporating Thermal Power Plant Ashes

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Abstract

This study examined the effect of coconut fiber (CF) content on the properties of unfired building bricks (UBBs) using fly ash (FA) and bottom ash (BA) from the Nghi Son coal-fired thermal power plant (CTP). Cement and FA served as binders while BA replaced crushed stone as the fine aggregate. Raw brown CFs were treated with a 5% NaOH solution at 50 °C to increase their mechanical properties. The treated CFs were then cut to a short length of 15 mm and had an average aspect ratio of 103. Brick samples were cast with CF content at ratios of 0%, 3%, 6%, and 9% by binder weight (CF/*B*) and water-to-binder (*W*/*B*) ratios of 0.30 and 0.35. The UBBs were formed under a low pressure of 0.5 MPa and tested to evaluate the effects of CF/*B* and *W*/*B* ratios on brick properties. Results showed that compressive strength (CS) increased with higher CF content, with all samples exceeding 10 MPa after 28 days, classifying them as grade M10 per TCVN 6477:2016. The optimal CF content was 6%, which yielded the highest CS. Increasing CF content reduced unit weight (UW), ultrasonic pulse velocity (UPV), and thermal conductivity (TC), while water absorption (WA) increased. Conversely, a lower *W*/*B* ratio improved CS, UW, UPV, and TC, while reducing WA. Microstructural observations revealed that CF acts as a bridge connecting cracks, which helps restrain crack widening and enhance CS.

Keywords

coconut fiber, unfired building brick, fly ash, bottom ash, thermal power plant ashes

1 Introduction

Coconut is a significant perennial crop that is cultivated and distributed in tropical and subtropical regions around the globe, particularly in 97 countries across major continents. From 1994 to 2022, the average global production of coconuts was approximately 57.69 million tons, with contributions from various regions as follows: Asia accounted for 84.318%, the Americas for 8.250%, Africa for 4.045%, Oceania for 3.385%, and Europe for 0.002% [1]. Fig. 1 illustrates the average coconut production from 1994 to 2022 for several leading coconut-producing countries. The top producers included Indonesia, which contributed 28.93% of the total production, followed by the Philippines at 24.63% and India at 18.56%. Vietnam, accounting for 2.15% of global production, ranked 7th overall, with an average annual output exceeding 1.24 million tons during the same period. In 2022, global coconut production was estimated at 62.4 million tons, with Vietnam's production reaching 1.93 million tons, positioning the country 6th globally [1].

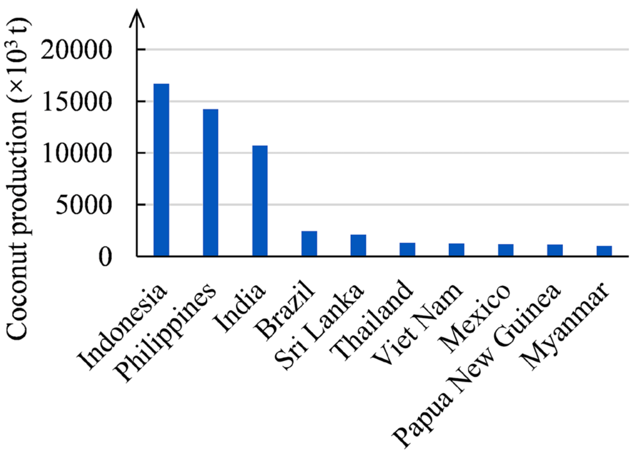

Fig. 1 Average coconut production of some of the world's leading countries from 1994 to 2022 [1]

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As estimated by the government, Vietnam has approximately 188,000 hectares of coconut plantations, representing 1.67% of the world's and 2.07% of Asia's coconut areas. In 2022, 85.26% of Vietnam's coconut production was concentrated in the Mekong Delta, with a production growth rate of 4.4% per year from 2011 to 2022.

CF is derived from the dried shells of coconuts and is extensively utilized in various applications, including in carpets, mattresses, pillows, handicrafts, and wastewater treatment [2]. CF can be classified into two types based on coconut maturity: white or light brown fiber, sourced from immature coconuts, and dark brown fiber, extracted from mature coconuts. The white fiber is distinguished by its smooth and fine texture, whereas the brown fiber demonstrates superior strength, thickness, and abrasion resistance, despite requiring a longer growth period, which renders it more suitable as a reinforcement material [2–5]. Research [3–5] has demonstrated that CF exhibits a deformation capability four to six times greater than that of other natural fibers such as jute, bamboo, banana, bagasse, hemp, etc. and possesses the highest toughness among all-natural fibers. Additionally, CF is a renewable and recyclable resource that is cost-effective and abundantly available in tropical and subtropical regions. Its production requires minimal energy and does not lead to an increased carbon footprint in concrete applications, unlike synthetic fibers and steel reinforcements. Similar to other natural fibers, CFs have several disadvantages, including considerable variation in their physical and mechanical properties, relatively low durability, decreased resistance to microbial degradation, and a tendency to clump during processing, which can impair adhesion to the matrix [5]. These characteristics are largely affected by factors such as plant species, growing conditions, climate, weather, methods of fiber extraction, cell structure, and the types and degrees of polymerization of cellulose present. However, these problems can be resolved by modifying the surfaces of CFs through chemical, physical, and mechanical treatment methods [5].

The potential of CF for reinforcing construction materials has garnered increasing interest from researchers, with applications now extending to concrete, mortar, boards, roofing materials, UBBs, and other building materials [6–27].

Many studies in the literature have investigated the effects of CF in concrete on flexural strength (FS), post-cracking load-bearing capacity, splitting tensile strength (STT), and compressive strength (CS) [6–12]. Nadgouda [6] found that the optimal replacement level of CF for cement is approximately 3%, resulting in a 12% increase in FS. However, it was noted that the CS of the concrete decreased with higher CF content. Khan and Ali [7] demonstrated that incorporating 10% fly ash, 15% silica fume, and 2% CF (with 50 mm length) improved the workability and mechanical properties of concrete. The elastic modulus, CS, STT, and FS increased by 93%, 92%, 39%, and 36%, respectively. Ali et al. [8] showed that incorporating 25 mm and 50 mm long CFs at 1% to 5% by mass of cement resulted in CS increases of up to 24% compared to CF-free specimen. However, when 75 mm long CFs were used at 2% or 3%, CS was lower than that of the control specimen. Additionally, a significant decrease in CS was observed as the CF content increased. Ali et al. [8] concluded that 50 mm long CFs at a 5% content provided the optimal performance. Srinidhi et al. [9] revealed that as the content of 10 mm long CF increased from 0.5% to 1.5% by total mass of concrete, the 28-day CS increased by 20.15% to 27.26% compared to plain concrete. Additionally, the 28-day STT and FS increased by 6.5% to 26.8% and 2.27% to 28.33%, respectively. Krishna et al. [10] also noted that adding 1% to 2% CF by mass of cement with a length of 32 mm improved CS by 11.3% to 36%. The optimal CF content was of 1.5%. However, at 2% CF, CS decreased due to increased voids and uneven bonding in the matrix, which resulted from the excess fiber. Ahmad et al. [11] found that high-strength concrete reinforced with 50 mm CFs at 1.5% content by cement mass performed the best, showing improved CS, STT, FS, energy absorption, and toughness compared to high-strength concrete without CF. Varghese and Unnikrishnan [12] observed that coconut fiber-reinforced concrete exhibited enhanced mechanical properties, particularly in shear strength, with improvements of 25% to 30% for both 50 mm and 75 mm long fibers. For optimal performance, 75 mm long fibers with 0.5% content are recommended.

Previous researchs [13–23] have incorporated CF into cementitious composite to investigate mechanical properties, density, thermal conductivity (TC), and other effects. Li et al. [13] found that untreated and alkaline CFs, with lengths of 20 mm and 40 mm, enhanced the FS of cementitious mortar by up to 12%, increased energy absorption by up to 1680%, and improved ductility by up to 1740%, while making the mortar lighter than conventional types. Sathiparan et al. [14] used 24 mm long CF at various contents of 0.125%, 0.25%, 0.5%, and 0.75% by total mass in cement-lime mortar. Adding CF decreased the UW but increased WA and porosity. Mortar with 0.5% CF showed a 5.7% increase in CS and a 6% increase in FS compared to the control. However, at 0.75% CF, both CS and FS declined. Hwang et al. [15] found that replacing 4% of mortar volume with 17 mm long CF reduced its CS by about 50%, but increased FS, modulus of rupture (MOA), and impact resistance, with WA and FS rising by 33% and 50%, respectively. Lertwattanaruk and Suntijitto [16] tested CF-to-cement mass ratios of 5%, 10%, and 15% in cement mortar, utilizing 5–10 mm long CFs. Their results showed that both CS and FS decreased with higher CF content, contrary to Hwang et al. [15]. Increased CF content led to greater porosity and WA, while UW decreased. TC also decreased, with coefficients of 0.41, 0.38, and 0.37 W/m·K for 5%, 10%, and 15% CF, respectively. Zulkarnen and Ismail [17] observed that CS decreased with higher CF content, with an optimal CF content of 2% by mass of sand for CFs ranging from 37 to 250 mm in length. Dhandhania and Sawant [18] found that concrete with 0.25% CF had a higher crushing load compared to 1% CF and conventional concrete. Additionally, CF-reinforced concrete panels offer natural cooling due to their low TC. Quiñones-Bolaños et al. [19] found that adding 15% CF to mortars can double the specific heat value compared to conventional mortar and increase CS by 2.47%. Additionally, TC decreased from 1.4 to 0.27 W/m·K with 15% CF. Khedari et al. [20] identified 20% CF by mass of cement as optimal for young CF, resulting in a TC and UW reduction of about 85% and 52%, respectively. However, CS was lower than that of non-CF mortar. Wongsa et al. [21] studied high-calcium fly ash mortar with CF content of 0%, 0.5%, 0.75%, and 1% by volume, using 35–40 mm long CFs. They observed that FS and STT increased with CF content, while flow, dry density, UPV, and CS decreased. CF volume fraction had minimal impact on TC and WA. Danso and Manu [22] examined coconut fiber-reinforced soil-cement mortar with 50 mm-length CF contents of 0.2–0.8%, lime of 0–15%, and 5% cement by soil weight. Optimal strength was achieved with 0.2% CF and 5% lime. The study concluded that CFs and lime improve soil-cement mortar properties for construction. Andiç-Çakir et al. [23] reported that increasing CF content from 0.4% to 0.75% enhances FS and CS while reducing UW and WA.

Several studies have examined the use of CF in UBBs [24–27]. Gampathi [24] found that adding 1%, 2%, and 3% 50 mm long CF by cement mass reduced the CS of cement hollow blocks by 0%, 5.6%, and 12%, respectively, but improved shear strength by 31%, 38%, and 41%. It was concluded that 2% CF by cement weight optimally increases the shear strength of these blocks. Purnomo et al. [25] demonstrated that uneven CF addition can enhance the CS of bricks more effectively than uneven fiber content. Although CF generally increased WA, uniformly treated CF positively affected both FS and CS. Over 90 days, CS decreased slightly, while FS dropped significantly. Thanushan et al. [26] revealed that adding 24 mm-length CF at 0.2%, 0.4%, and 0.6% by mass of cement and soil mix improved the post-peak resistance of coconut fiber-reinforced earth cement blocks, though CF did not enhance initial CS or FS. Instead, it improved residual strength, ductility, toughness, and energy absorption, while increasing WA and decreasing dry density. Mudiyono and Sudarno [27] reported that adding 0.1% CF by mass of cement in paving blocks improved both CS and FS.

In recent years, Vietnam has seen a high and growing demand for bricks due to strong economic development, rapid population growth, and high urbanization [28]. Concurrently, the annual production of CTP ash, including FA and BA, continues to rise. However, the utilization of these ashes remains low—approximately 47% for FA and only 5.28% for BA [28], putting pressure on the problem of environmental pollution that needs to be solved.

As presented previously, CFs have both advantages and disadvantages. The disadvantages of CFs could be significantly mitigated through alkaline treatment, which is widely recognized as the simplest and most cost-effective approach for enhancing some characteristics, and resin-fiber interfacial bonding [5]. As an overview study, treated CF has the potential to replace synthetic and steel fibers to enhance the strength, and durability of UBBs, and reduce carbon emissions.

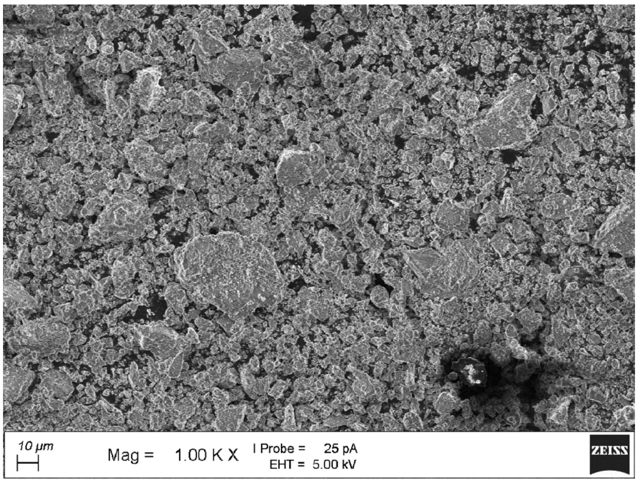
In Vietnam, UBBs are typically made from cement and crushed stone, resulting in a heavy unit weight (2.0 to 2.2 t/m^3). The lightweight nature of CF can significantly reduce the UW of UBBs, thereby decreasing the structural self-weight and potentially lowering construction costs. While the incorporation of FA into UBBs has received considerable attention from researchers [29–32], however, the utilization of BA remains limited [28, 33, 34]. Furthermore, the incorporation of CF in UBBs, particularly those primarily composed both of FA and BA from CTPs, has not been extensively studied. The use of ashes from CTPs in conjunction with CF can lead to reduced production costs, a replacement for traditional natural materials, and contributions to environmental protection, resource conservation, and sustainable development. Additionally, the properties of FA and BA can vary significantly depending on the combustion technology and type of coal utilized at different CTPs, which subsequently affects the technical characteristics of UBBs. In this study, pretreated brown CFs were used in producing UBBs incorporating FA and BA. The effect of CF contents and *W*/*B* ratios on CS, UW, WA, UPV, TC, and microstructure of UBBs were investigated.

2 Materials and experimental program

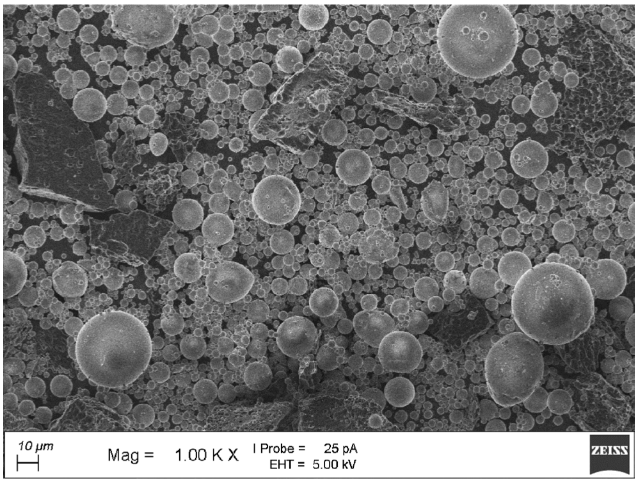
2.1 Material

FA and BA were collected from a CTP in Thanh Hoa province of Vietnam, with specific gravities of 2.16 and 1.99 t/m^3, respectively. The cement type PCB40 has a specific gravity of 3.12 t/m^3 and an average particle diameter of about 14 µm. Fig. 2 (a), (b), and (c) illustrates the scanning electron microscopy (SEM) micrographs of cement, FA, and BA, respectively. Table 1 shows the physical properties and chemical compositions of cement, FA, and BA. The cement is primarily composed of SiO_2 and CaO, making up more than 80% by mass. The FA, which has a low CaO content and a total content of (SiO_2 + Al_2O_3 + Fe_2O_3) greater than 70%, is classified as Group F according to the ASTM C618-19 standard [35]. The average particle diameter of FA is about 16.5 µm. In this study, BA has a similar chemical composition to FA, with a low CaO content and main components being SiO_2, Al_2O_3, and Fe_2O_3 with contents of 52.24%, 19.99%, and 7.16%, respectively. It is noted that the FA and BA in this study were untreated materials with a relatively high loss on ignition (LOI) of 15.85% and 15.04%, respectively. Table 2 shows the percentage of material passing through the sieve of BA, which has a modulus of fineness of 1.97 and a maximum particle size of 5 mm. The particles of BA are relatively small and consistent in size, similar to natural sand. For this reason, BA is used as a fine aggregate substituted for crushed stone in the production of UBBs, while cement and FA are used as binders.

Fig. 3 shows the natural appearance of CFs used in this study, which was produced using a hand-operated CF extraction machine. CF consists of cellulose, hemicellulose, lignin, pectin, and minerals. The average content of the primary components in dried CF (% by mass) includes cellulose, which accounts for 32–43.8%, lignin at 40–45%, and hemicellulose at 0.15–20% [5]. Cellulose is the main contributor to the fiber's stability and strength, while lignin provides water resistance, fungal protection, and flexibility [5]. The enhanced flexibility of these fibers improves fracture resistance in components reinforced with CFs, reducing the risk of concrete debonding during cracking and ultimately increasing the overall durability of the structure [5]. CF has a tensile strength of 95 to 230 MPa, a tensile modulus of elasticity of 2.8 to 6 GPa, and an elongation of 15 to 51.4% [5]. In this research, raw brown CFs underwent alkaline treatment, following the procedure



(a)



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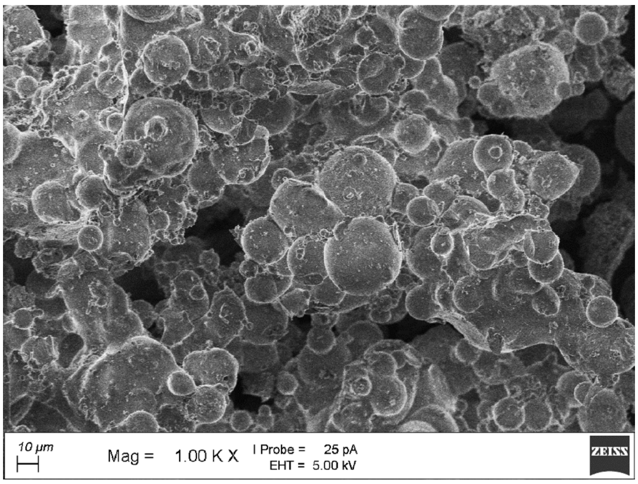

(c)

Fig. 2 SEM micrographs of (a) cement, (b) fly ash, and (c) bottom ash

Table 1 Chemical compositions of cement, fly ash, and bottom ash

Composition (%)	Cement	Fly ash	Bottom ash
SiO_2	21.23	51.50	52.24
Al_2O_3	5.50	20.20	19.99
Fe_2O_3	4.90	7.07	7.16
CaO	61.02	1.99	2.37
MgO	2.97	1.23	1.22
SO_3	1.47	-	-
K_2O	0.49	-	-
Others	2.01	2.16	1.98
LOI*	0.41	15.85	15.04

* LOI = Loss on ignition

Table 2 Sieve analysis and fineness modulus of bottom ash

Sieve size (mm)	5.0	2.5	1.25	0.63	0.315	0.14	FM*
Percentage of passing (%)	80.6	75.8	71.6	65.8	59.7	50	1.97

* FM = Fineness modulus

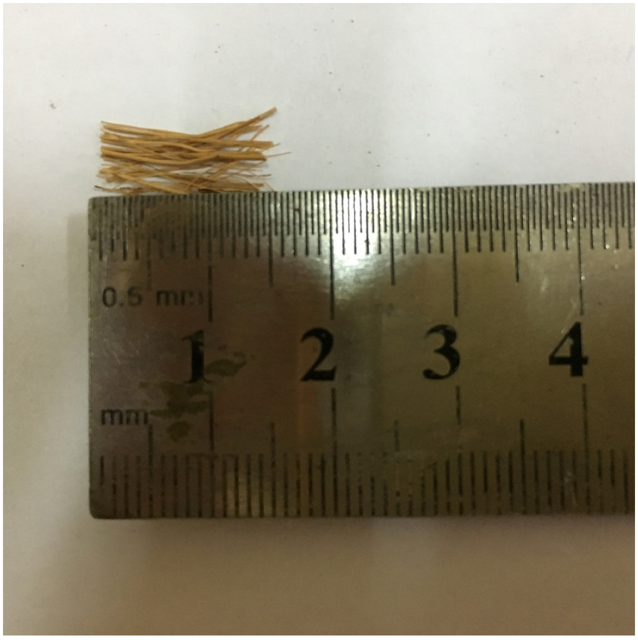

Fig. 3 Natural appearance of coconut fiber

recommended by Nguyen et al. [36]. This treatment effectively removed hemicellulose, pectin, and other impurities, resulting in a roughened surface texture and enhancing the tensile strength of CFs by up to 40% [36]. Initially, the CFs were separated from the remaining husk and shell and soaked in water for 24 hours. After soaking, the fibers were naturally dried for 5 days. The dried CFs were then immersed in a 5% NaOH solution at 50 °C for 6 hours. Following the NaOH treatment, the CFs were filtered and washed until the pH of the wash water reached around 7. Finally, the CFs were dried at 50 °C for 6 hours, until they reached a dryness of 90%. Untreated CFs exhibited an uneven diameter distribution, ranging from 50 µm to 600 µm, with 79% of the fibers within the 100 µm to 300 µm range, as reported by Nguyen et al. [36]. In this study, the average diameter of the untreated CFs was 183 µm, consistent with typical sizes found in previous research [36]. After treatment, CFs appeared clean and homogeneous, with an approximate 20% reduction in diameter, resulting in an average diameter of about 146 µm. This reduction enhanced the adhesion of the treated CF with matrix by increasing the effective surface area and the aspect ratio (length-to-diameter). Before use, the treated CFs were cut to a short length of 15 mm, had an average aspect ratio of 103, and exhibited a specific gravity of 0.96 t/m^3.

2.2 Mix design and proportions

In this study, UBBs were designed using the absolute volume method with water-to-binder (*W*/*B*) ratios of 0.3 and 0.35 [28, 30]. Table 3 presents the mix proportions. There were 08 mixtures divided into two groups which are B30 and B35 corresponding to *W*/*B* ratios of 0.3 and 0.35, respectively. Previous studies [6–27] have used CF contents ranging from 0.1% to 15% by mass of binder. In this study, the sample fabrication was difficult due to poor workability if the CF content used was over 9%. Therefore, within each group, three mixtures were designed with coconut fiber-to-binder (CF/*B*) contents of 3%, 6%, and 9% by mass, while the remaining mixture served as a control without CF for comparison. The purpose of preparing three mixtures with varying CF content was to assess the effect of CF content on the properties of UBBs made with FA and BA. To facilitate the recycling of industrial solid waste, FA was used with high volume as 70% of total binder, and BA instead of

Table 3 Mix proportions

Mixture	*W*/*B**	Ingredient proportions (kg/m^3)				
		Cement	Fly ash	Bottom ash	Coconut fiber	Water
B30CF0	0.30	180	420	1128	0	180
B30CF3		177	412	1108	18	177
B30CF6		173	405	1088	35	173
B30CF9		170	398	1068	51	170
B35CF0	0.35	154	360	1200	0	180
B35CF3		152	354	1181	15	177
B35CF6		149	349	1163	30	174
B35CF9		147	343	1145	44	172

* *W*/*B* = Water-to-binder ratio

crushed stone played a role as fine aggregate in UBB mixtures. It means that just a small amount of cement was used to save production costs and contribute to protecting the environment. The mixtures were labeled as B*x*CF*y*, where B stands for Brick, *x* represents the *W*/*B* ratio in %, CF denotes coconut fiber, and *y* indicates the CF/*B* ratio in percentage. The addition of CF could significantly decrease the workability of the mixtures. To counteract this, a superplasticizer was incorporated at approximately 1% of the binder mass to ensure optimal performance, following the recommendations of Khan and Ali [37]. The quantity of superplasticizer was adjusted to maintain consistent levels across all mixes. As a result, the average amount of superplasticizer used was around 6.0 kg/m^3 for the *W*/*B* ratio of 0.3 and 5.1 kg/m^3 for the *W*/*B* ratio of 0.35.

2.3 Sample preparation

The production of UBBs with the proportions specified in Table 3 was carried out in the laboratory. Before mixing, the superplasticizer was stirred in water to create a water-additive solution. The mixing and sample preparation process is as follows: First, the materials including cement, FA, BA, and CFs were mixed homogeneously in a pan to avoid local dispersion, with a mixing time of one minute according to ASTM C305-14 [38]. Next, the water-additive solution was gradually added, and the mixture was blended at a moderate speed for approximately 3 to 5 minutes until a homogeneous consistency was achieved. The UBBs were then cast into rectangular steel molds with dimensions of 160 mm × 85 mm × 40 mm under a low compression pressure of about 0.5 MPa [28]. After casting, the bricks were de-molded and allowed to cure naturally.

2.4 Test methods

The physical and mechanical properties of the UBB, including UW, CS, and WA were determined following TCVN 6477:2016 [39]. The UPV of the UBB was measured according to ASTM C597-16 [40]. Both CS and UPV were assessed at 3, 7, 14, and 28 days. Density characteristics, including UPV and TC, were directly measured using MATEST C369 and ISOMET-2114, respectively. The microstructure of the UBBs was examined using an SEM technique provided by the manufacturer SEISS. WA, UW, TC, and microstructural features of the brick samples were evaluated at 28 days, while CS and UPV were tested at 3, 7, 14, and 28 days. The reported results for the UBBs are average values from at least three measurements.

3 Results and discussion

3.1 Compressive strength

The developments of CS with curing time for UBBs with *W*/*B* ratios of 0.3 and 0.35 and varying CF contents are shown in Fig. 4 and Fig. 5, respectively. It is observed that as the curing time increased from 3 days to 7, 14, and 28 days, the CS of the brick samples increased. The increase in CS with curing time is attributed to the continuous hydration and pozzolanic reaction of cement and FA over time. This finding is consistent with previous studies on the use of CF in mortar and concrete [6, 9, 17] as well as the use of both FA and BA in UBBs [34]. The test results also indicated that the lower the *W*/*B* ratio the higher CS. This observation is consensus with the research results on CF cementitious composites by Hwang et al. [15].

Fig. 4 and Fig. 5 also show that the CS of all brick samples containing CF is higher than that of the control sample. This improvement can be attributed to the high durability and strong resin-fiber interfacial bonding of treated

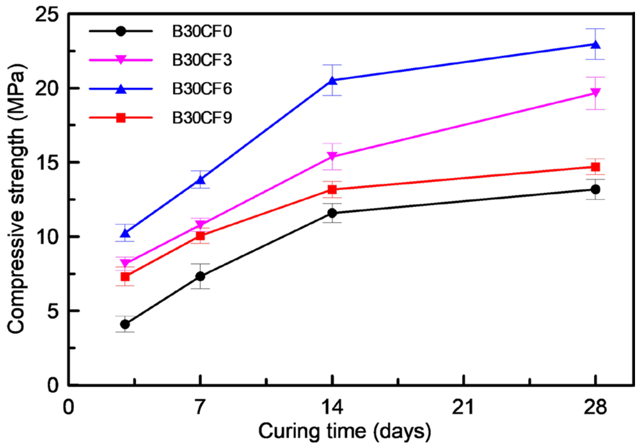

Fig. 4 Compressive strength of B30 samples

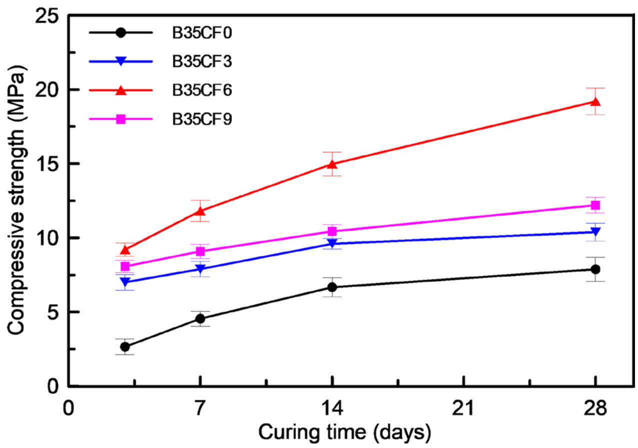

Fig. 5 Compressive strength of B35 samples

CFs, along with their high lignin content, which enhances stiffness and functions similarly to steel fiber reinforcement in concrete. Treated CFs help delay crack formation when the brick expands under compression, thereby enhancing the strength of the brick sample [11, 14]. It is worth noting that the BA used in this study has high porosity (Fig. 2 (c)), hence the ability of delay crack propagation may be particularly important in this case. For brick samples with a *W*/*B* ratio of 0.3, increasing the CF content from 0% to 3, 6, and 9% resulted in 28-day CS increases of 49.2%, 74.2%, and 11.5%, respectively. Meanwhile, for brick samples with a *W*/*B* ratio of 0.35, the CS increased by 31.9%, 143.7%, and 54.8% with the CF content rising from 0% to 3%, 6%, and 9%, respectively. The test results reveal that as CF content increased from 0% to 6%, the CS of the brick sample increased, reaching its highest strength at 6% of CF content. However, as the CF content increases from 6% to 9%, the CS tends to decrease. In other words, the optimum CF content is 6% in this study. The decrease in CS at CF contents above 6% may be due to increased voids, reduced bonding efficiency between the cement mortar and CFs, and the tendency of the CFs to clump when mixed in large quantities [6, 10, 41].

The CS results from this study were compared with those reported by other researchers. Ali et al. [8], Srinidhi et al. [9], Krishna et al. [10], and Ahmad et al. [11] also observed improvements in CS due to the addition of CFs. Ali et al. [8] found that incorporating 25 mm and 50 mm CFs at 1% to 5% by mass of cement increased CS by up to 24% compared to control concrete. However, a significant decrease in CS was noted at higher CF content, attributed to the formation of air voids caused by excess fibers. Similar findings were reported by Srinidhi et al. [9], who observed that increasing 10 mm CF content from 0.5% to 1.5% by the total mass of concrete resulted in a 20.15% to 27.26% increase in 28-day CS compared to plain concrete. Krishna et al. [10] reported that adding 1% to 2% CF by mass of cement (32 mm long) improved CS by 11.3% to 36%, with an optimal CF content of 1.5%. However, at 2% CF, CS decreased due to increased voids and uneven bonding in the matrix. Ahmad et al. [11] found similar trends, noting that for 25 mm CFs, CS increased up to 1.5% CF content but decreased when the fiber content reached 2%. For 50 mm and 75 mm CFs, CS consistently decreased with increasing fiber content. This means that the length of CF may affect the CS. In the present study, the CF with a length of 15 mm was used, so the finding is a similar trend to the study conducted by Ahmad et al. [11] with a CF length of 25 mm.

All brick samples demonstrated comparable or even superior CS compared to some bricks produced in previous studies. For instance, the 28-day CS values of B30 brick samples are 13.2, 19.7, 23.0, and 14.7 MPa for CF contents of 0%, 3%, 6%, and 9%, respectively. In comparison, the 28-day CS values for B35 brick samples were 7.9, 10.4, 19.2, and 12.2 MPa for the same CF contents. All brick samples have 28-day CS greater than 10 MPa and are classified as grade M10 conforming to TCVN 6477:2016 [39]. In a previous study [34], the CS for cement bricks and traditional clay bricks were reported as 12 MPa and 15 MPa, respectively. Additionally, the bricks produced from CTP ashes had a CS from 1.88 to 7.70 MPa [28]. This finding suggested that it is possible to produce UBBs by using BA completely replacing crushed stone with a high volume of FA as a binder material, while the use of CF as a role of steel or polymer fibers helps to enhance the strength of UBBs.

3.2 Unit weight

Besides compressive strength, the UW of bricks is an important parameter affecting building structures. Lighter bricks reduce the load on the building, which can lead to smaller structural dimensions and lower construction costs. Fig. 6 illustrates the effect of CF content and *W*/*B* ratio on the UW of the brick samples. The UW of the brick samples in this study ranged from 1.27 t/m^3 to 1.57 t/m^3. Brick samples with a *W*/*B* ratio of 0.35 (B35 samples) had a lower UW compared to those with a *W*/*B* ratio of 0.3 (B30 samples). The UW of B30 brick samples was 1.1% to 7.0% higher than that of the corresponding B35 brick samples.

It can be seen that the UW of the brick samples decreased with increasing CF content. The UW of the brick samples without CF ranged from 1.49 t/m^3 to 1.57 t/m^3. As the CF

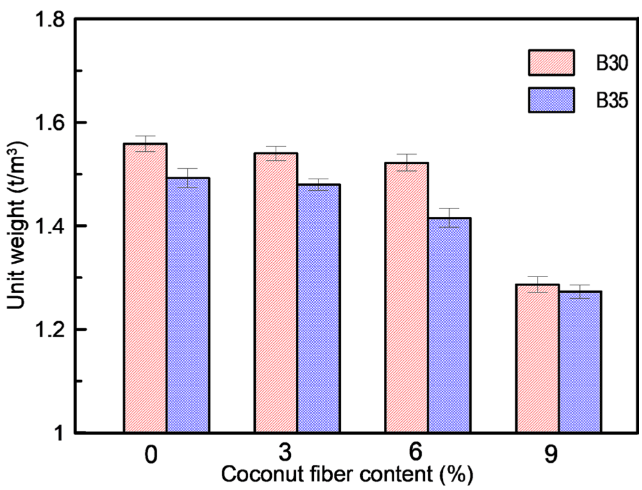

Fig. 6 Effect of coconut fiber content on unit weight of brick samples

content increased to 9%, the UW of the brick samples dropped to between 1.27 t/m^3 and 1.29 t/m^3. This decrease is attributed to a lower density of CF (0.96 t/m^3) compared to the densities of cement (3.12 t/m^3), fly ash (2.16 t/m^3), and bottom ash (1.99 t/m^3). It means that the reduction in UW is associated with the increase in CF content and the corresponding decrease in the amounts of cement, FA, and BA, as shown in Table 3. It is worth noting that the UW of the brick samples in this study is significantly lower than that of cement brick made by crushed stone and cement (about 2.0–2.2 t/m^3) and traditional clay brick (about 1.8 t/m^3) produced in Vietnam [28]. The UW of these samples is comparable to and somewhat lower than, that of self-compacting bricks made from FA, BA, and cement [34].

3.3 Water absorption

Water absorption is a crucial property of UBBs, influencing the adhesion between bricks and mortar during construction. It affects the permeability and resistance to chemical corrosion of the bricks. The relationship between WA and CF for *W*/*B* ratios of 0.3 and 0.35 are shown in Fig. 7. The WA of the bricks varied from 12.4% to 26.0% and increased with higher CF content. These results are consistent with findings from previous studies [14–16, 22]. Specifically, the results align with CF mortars tested after boiling but differ from those of CF mortars tested before boiling as reported by Andiç-Çakir et al. [23]. As aforementioned, even the CF is durable enough to enhance the mechanical properties of UBB; however, the voids between CF and cement mortar also increase [6, 10], leading to a rise in the WA value.

For the same amount of added coconut fiber, the brick sample with a *W*/*B* ratio of 0.35 exhibited a higher WA than compared to the corresponding samples with a lower

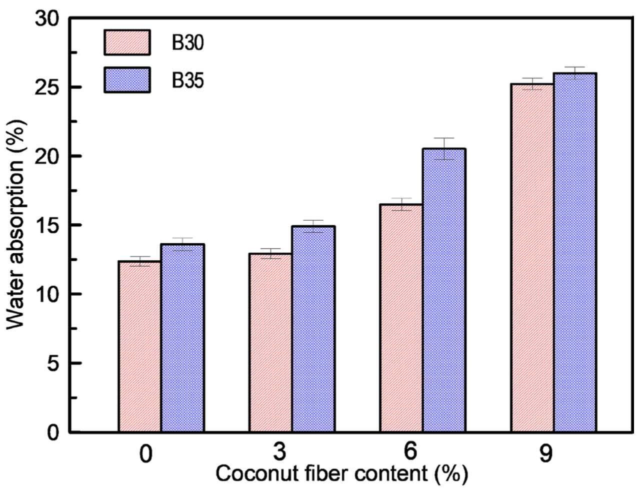

Fig. 7 Effect of coconut fiber content on water absorption of brick samples

W/*B* ratio of 0.3. The WA of the brick samples containing coconut fiber in this study is comparable to that of bricks produced from CTP ashes conducted by Ngo et al. [28] and Naganathan et al. [33] but it is higher than that of bricks in several previous studies [14, 15, 23, 24]. This increase in WA is attributed to the porous structure of the FA and BA mentioned above, as well as the low pressure when making the bricks of this study.

3.4 Ultrasonic pulse velocity

Ultrasonic pulse velocity is utilized to assess the homogeneity of bricks by detecting voids and cracks within the brick structure. The relative quality of UBBs is indicated by the UPV values. These values have been employed to classify the quality of concrete, with higher UPV values typically corresponding to bricks of high quality [42]. Fig. 8 and Fig. 9 show the relationship between UPV values and curing time for brick samples with different CF contents at *W*/*B* ratios of 0.3 and 0.35, respectively. Bricks with a *W*/*B* ratio of 0.3 have a higher UPV value compared to those with a *W*/*B* ratio of 0.35 at the same age.

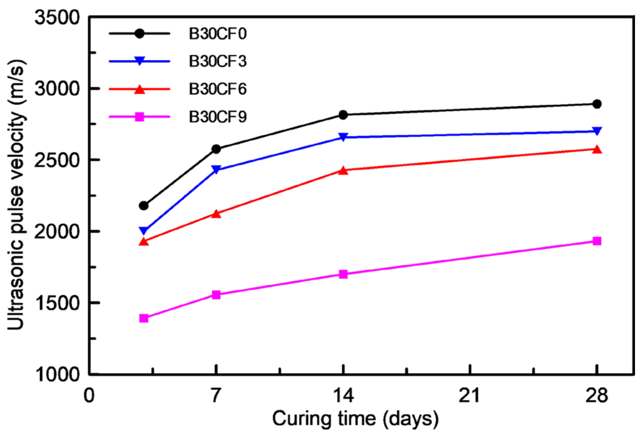

Fig. 8 Ultrasonic pulse velocity of B30 samples

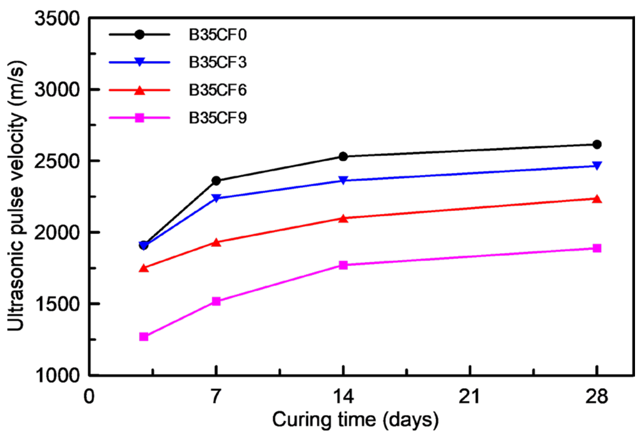

Fig. 9 Ultrasonic pulse velocity of B35 samples

A lower *W*/*B* ratio means a higher amount of binder is used, which accelerates hydration and pozzolanic reactions, thereby enhancing the brick's solid strength and resulting in a higher UPV. Bogas et al. [43] pointed out that the UPV value is higher in dense and high-CS concrete than in loose and low-CS concrete. As demonstrated by the experimental results, the UW and CS of the UBBs with a *W*/*B* ratio of 0.3 are higher than those of the UBBs with a *W*/*B* ratio of 0.35. Therefore, the lower the *W*/*B* ratio the higher the UPV value of bricks was achieved. The test results also showed that the UPV values decrease with increasing CF content. This implied that higher CF content reduces the internal homogeneity of the bricks, which lowers their UW and results in a reduced UPV value.

As presented above, the UPV and UW have a close relationship. Fig. 10 demonstrates the relationship between UPV and UW of bricks. The correlation between UPV value and UW of bricks at 28 days of age is described by the linear equation $y = 3188x - 2197$ ($R^2 = 0.96$). In this study, the UPV values for all the bricks ranged from 1.889 to 2.891 m/s. Based on previous studies [33, 34], the acceptable UPV range of bricks is 1435–2758 m/s]. Shakir et al. [31] reported UPV values of 793 m/s for clay bricks and 1501 m/s for cement bricks. This indicates that the quality of all the bricks in this study surpasses that of both clay and cement bricks [31], and is comparable to, or even slightly better than, the bricks studied in previous research [33, 34].

3.5 Thermal conductivity

The TC test is used to assess the heat isolation properties of bricks. Materials with lower TC values are typically preferred for thermal insulation purposes. However, research on the thermal conductivity of construction bricks is still limited [21, 29, 32]. Fig. 11 shows the 28-day TC values of all bricks produced in this study. As seen in Fig. 11,

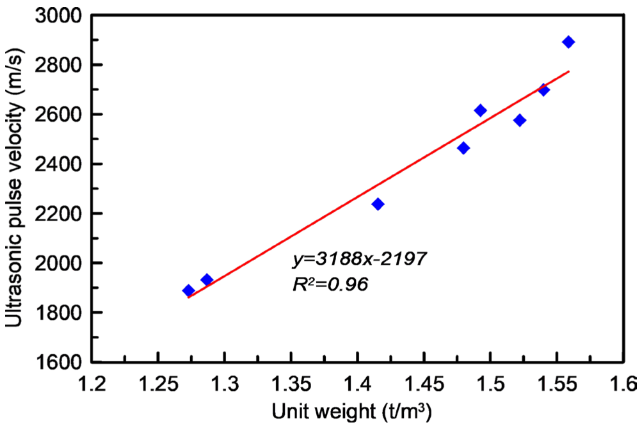

Fig. 10 The relationship between UPV and unit weight

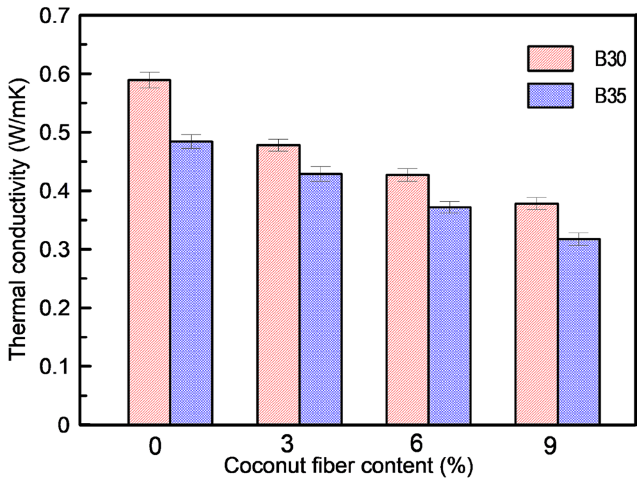

Fig. 11 Effect of coconut fiber content on TC of brick samples

the TC value of brick samples decreased with both higher *W*/*B* ratios and increased CF content. Previous studies have identified moisture content [44] and UW [20, 45] as the primary factors influencing TC. Consequently, brick samples with a higher *W*/*B* ratio resulted in lower UW and higher WA, resulting in lower TC values. This result is in line with earlier studies [20, 21]. On the other hand, increasing the CF content leads to a decrease in the UW and an increase in WA, thus reducing the TC value.

The TC values of brick produced in this study ranged from 0.317 W/m·K to 0.589 W/m·K. These values are higher than those of the lightweight bricks investigated by Cicek and Tanrıverdi [32], which ranged from 0.34 to 0.36 W/m·K. However, they are lower than the TC values of the fly ash-limestone powder bricks studied by Turgut [29] (0.91–1.02 W/m·K), red clay brick (0.93 W/m·K), and hollow concrete block (0.683 W/m·K) investigated by Alavez-Ramirez et al. [46]. As mentioned above, UW and WA are the main influences on the TC of bricks. In Turgut's [29] study, the UW of bricks was approximately 1.8 t/m^3, which was higher than that of the bricks produced in this study, leading to a higher TC. On the other hand, the UW of bricks produced by Cicek and Tanrıverdi [32] was significantly lower than those of bricks in this study, thus the TC of the former was lower than that of the latter.

As discussed above, the main factors that affected the TC values of bricks are UW and WA. Fig. 12 and Fig. 13 show the correlation between TC value and UW and WA of bricks, respectively. It can be seen that increasing UW or decreasing WA increases the TC value of bricks. The relationship between TC and UW can be represented by the linear equation $y = 0.624x - 0.468$ ($R^2 = 0.69$), while the correlation between TC and WA follows the linear equation $y = -0.013x + 0.669$ ($R^2 = 0.75$).

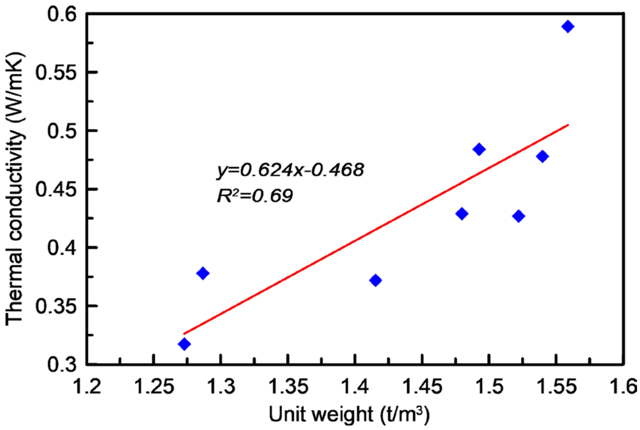

Fig. 12 The relationship between TC and unit weight

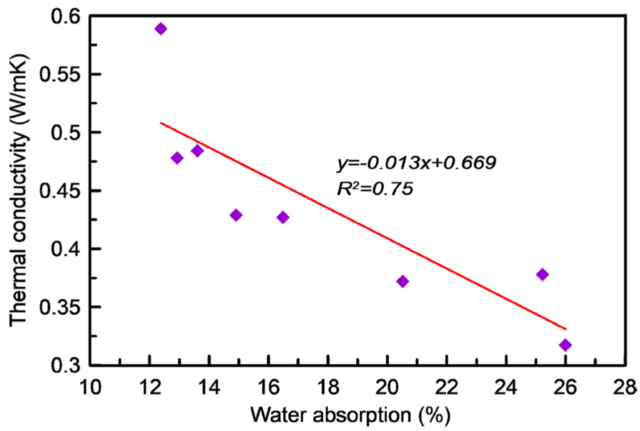

Fig. 13 The relationship between TC and water absorption

3.6 Microstructure analysis

The microstructural micrograph of the brick sample is shown in Fig. 14. As shown in Fig. 14, CF resembles a steel fiber that acts as a bridge connecting cracks that form when the brick expands under compression. The CF plays a role as transverse reinforcement to limit horizontal expansion by developing hoop tensile forces. This reinforcement can produce inelastic deformations that increase the brick's ductility. This phenomenon is demonstrated by the gradual decline in the post-peak stress-strain curve of concrete as observed by Ali et al. [8]. In conclusion, the effect of CF is to reduce the widening of cracks and plays a role as transverse reinforcement, enhancing both the strength and the ductility of bricks. This finding supports again the above experimental results.

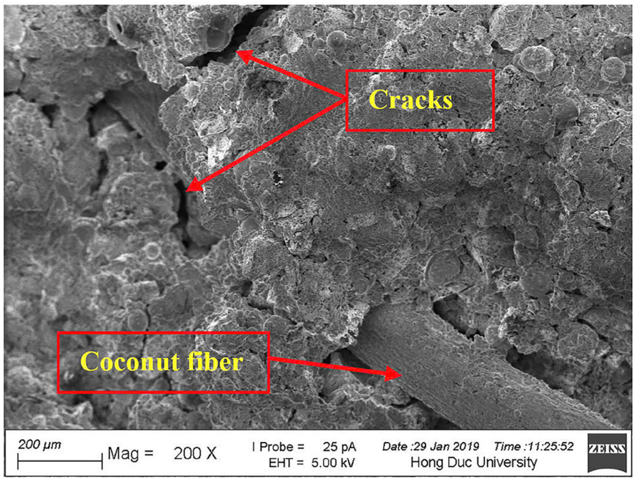

Fig. 14 SEM observation

4 Conclusions

This research investigates the use of CF in producing UBBs incorporating FA and BA sourced from Nghi Sơn CTP in Thanh Hoa province. Cement and FA served as binders, while BA was used as a fine aggregate instead of crushed stone. Brown CFs were treated with a 5% NaOH solution at 50 °C to upgrade their mechanical properties. The treated CFs were then cut to a short length of 15 mm and had an average aspect ratio of 103. The effects of CF content and *W*/*B* ratios on some properties of UBBs were examined. The main conclusions from the experiments are as follows:

1. The CS of UBBs improved with the used CF contents. All brick samples had 28-day compressive strengths greater than 10 MPa, classifying them as grade M10 according to TCVN 6477:2016 [39]. The optimal CF content was 6%, which yielded the highest CS compared to other CF contents.
2. Increasing CF content led to a decrease in UW, UPV, and TC of UBBs, while the WA increased.
3. A lower *W*/*B* ratio improved CS, UW, UPV, and TC while decreasing WA.
4. The SEM image shows that coconut fiber acts as transverse reinforcement in concrete, which helps to prevent crack widening and increase the CS of UBBs. However, if the CF content used was over the optimal level, the CS of UBBs was reduced due to increasing voids.

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