Preparation and Performance of High Belite Sulfoaluminate Cement-based Recycled Wood Fiber Low-Carbon Material

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Using waste wood to prepare recycled wood fiber (RWF) and using it to enhance low-carbon cement-based materials can achieve the recycling utilization of waste resources, which meets the needs of green and sustainable development strategy. In this study, the performance of high-belite sulfoaluminate cement (HBSC) composites reinforced with recycled wood fibers (RWFs) derived from construction waste wood was investigated. The effects of RWF content and water-to-cement ratio on mechanical properties, hydration characteristics, thermal conductivity, and micro-structure were systematically evaluated. Increasing RWF content resulted in an initial increase followed by a decrease in the mechanical properties of HBSC-based materials. A 20% RWF incorporation simultaneously optimized flexural and compressive strength while mitigating crack propagation. The addition of RWF decreased the dry density of HBSC. Thermal conductivity exhibited a linear correlation with dry density and decreased with higher water-cement ratios. At 20% RWF content and a water-cement ratio of 0.45, the microstructure of the HBSC composite became denser (or more refined in pore structure), resulting in the optimal comprehensive performance.

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INTRODUCTION

With the acceleration of global urbanization, the amount of waste wood generated from building demolition and timber processing has been increasing annually. Traditional disposal methods such as landfilling or incineration not only occupy land resources but also release greenhouse gases like CO_2 and harmful substances, exacerbating environmental burdens (Kwon *et al.* 2025). Against this backdrop, the preparation of RWF (RWF) from waste wood through mechanical crushing, chemical treatment, and other methods, and its application as a reinforcing material in cement-based composites, has emerged as a critical research direction in the fields of waste wood recycling and green building materials (Tang *et al.* 2022). RWF exhibits advantages such as being lightweight, porous, high toughness, and biodegradable. Incorporating RWF into cement matrices not only reduces the consumption of natural sand and gravel resources but also leverages the bridging effect of fibers to mitigate the brittleness of cement-based materials, thereby enhancing crack resistance and toughness (Amiandamhen *et al.* 2021; Zhou *et al.* 2022).

This approach offers a new pathway for the development of green and low-carbon building materials.

Recent research on wood fiber-reinforced cement-based materials has made notable progress. Many studies have demonstrated that the appropriate incorporation of RWF can significantly enhance the flexural strength and toughness of cement-based materials. However, practical applications remain constrained by challenges such as the high water absorption of fibers and weak interfacial bonding (Xie *et al.* 2024). He *et al.* (2019) indicated that wood fibers decreased the brittleness and mitigated the low fracture toughness of autoclaved aerated concrete (AAC), particularly enhancing flexural strength. In addition, da Gloria and Toledo Filho (2021) revealed that wood and sisal fibers improved compressive strength, shear transfer capacity, and flexural failure resistance. Xu *et al.* (2019) observed that increasing fiber content reduced the bulk density and increased water absorption capacity of wood fiber-cement composites, while softwood fiber-based products exhibited significantly improved flexural toughness. Torkaman *et al.* (2014) studied the lightweight concrete blocks using wood fibers, rice husk ash, and limestone powder. A 25% extent of wood fiber replacement was identified as optimal, yielding substantial improvements in mechanical and physical properties of the blocks. Hamada *et al.* (2025) reported that densified woods hold promise for enhancing mechanical properties. The fibers from densified wood exhibited increased tensile strength and relaxation time compared to untreated fibers, with densified fiber composites outperforming raw fiber composites in both tensile and flexural strength. Lin *et al.* (2024) showed that the fibers effectively mitigated brittleness and enhanced toughness, significantly improving splitting tensile strength and fracture energy. The rough surface texture of bamboo fibers further facilitated the adhesion of cement hydration products. These findings collectively highlight the high application potential of RWFs in enhancing the performance of cement-based materials, offering a sustainable pathway for construction material innovation.

However, many other studies have revealed that the high content of hemicellulose and soluble sugars in wood fibers are the primary components responsible for retarding the hydration of cement-based materials (Chen *et al.* 2025; Liu *et al.* 2025). These substances readily hydrolyze or dissolve in the alkaline cement environment, thereby releasing monosaccharides or polyhydroxy compounds that delay cement hydration by adsorbing onto cement particles or chelating calcium ions (Olofin 2025). Current research mainly has focused on chemical modification of wood fibers, such as alkali treatment (*e.g.*, NaOH) or acid treatment (*e.g.*, H_2SO_4) to degrade hemicellulose and lignin, or high-temperature processing to pyrolyze organic components into inert carbonaceous materials (Fioroni *et al.* 2025). Fei *et al.* (2024) modified the interface of bamboo fiber-reinforced cement composites using sodium silicate. The modified material exhibited enhanced toughness, superior flexural and splitting tensile strengths, reduced shrinkage in the cement mortar, and improved fiber-matrix compatibility due to decreased hydrophilicity of the fibers, thereby enhancing durability. Bahja *et al.* (2023) found that at a fiber-to-mass ratio of 12%, the composites demonstrated optimal performance compared to ordinary Portland cement. Liu *et al.* (2022) prepared cement-based wood composites using NaOH, silane coupling agent, and acrylate copolymer emulsion to modify waste wood fibers. All three treatments improved interfacial bonding, mechanical strength, and adhesion by altering fiber surface morphology. Bamboo fibers have been modified with NaOH and used to fabricate metakaolin-based geopolymer composites. Alkali-treated fibers increased surface roughness, significantly enhancing mechanical properties, durability, and acid resistance (Sá Ribeiro *et al.* 2021; Riofrio *et al.* 2022; Shilar *et al.* 2025). Ajoku *et al.* (2023)

investigated wollastonite substitution in wood fiber-cement composites. Incorporating 9% wollastonite improved mechanical performance, while higher wollastonite content enhanced fire resistance. Ge *et al.* (2025) studied keratinization-modified bamboo fibers in sea sand-reactive powder concrete (SRPC). Moderate keratinization increased cellulose crystallinity and surface roughness, mitigating fiber-induced hydration inhibition and improving flexural strength, interfacial bonding, and bending toughness (Ge *et al.* 2025). Despite these advancements, the alkaline environment of traditional Portland cement remains prone to degrading wood fibers, compromising long-term durability. As evidenced by the above studies, current efforts largely have prioritized fiber modification and dosage optimization, with limited exploration of matrix material innovation. There is an urgent need to develop novel cement systems (*e.g.*, low-alkalinity or fast-setting cements) to synergistically enhance the performance of wood fiber-reinforced cement-based material.

Adopting High Belite Sulfoaluminate Cement (HBSC) as the matrix material offers a novel approach to developing RWF reinforced cement-based composites. HBSC, which is primarily composed of belite (dicalcium silicate, $2CaO \cdot SiO_2$) and calcium aluminum sulfate ($Ca_4Al_6O_{12}SO_4$) phases, exhibits rapid setting, high early strength, low hydration heat, and minimal shrinkage (Luo *et al.* 2025). These properties significantly shorten curing cycles, suppress the retarding effect of sugars in RWFs, and reduce fiber degradation risks caused by alkaline environments. Studies show that HBSC's mild alkalinity (pH 10 to 11) better inhibits plant fiber degradation compared to ordinary Portland cement (pH >13) (Su *et al.* 2025), while its slight expansion behavior during the hydration phase compensates for shrinkage stress induced by fiber water absorption, thereby optimizing the interfacial transition zone (ITZ) structure (Alzaza *et al.* 2022). The synergy between HBSC and RWFs holds promise for enhancing mechanical and durability, demonstrating strong technical feasibility and engineering potential.

In this study, high belite sulfoaluminate cement (HBSC) was employed as the cement matrix, combined with RWFs derived from waste wood. The replacement ratios of RWF in cement-based material were incrementally set at 0%, 10%, 20%, 30%, and 40% by volume, with systematic investigations conducted under varying water-to-cement ratios and RWF replacement ratios. The research evaluated the mechanical properties, hydration kinetics (*via* TG/DTG and XRD analysis), and microstructural evolution (observed through SEM method) of HBSC-RWF composites, which clarified the influence of RWF content and water-cement ratio on HBSC matrix performance. The findings provide theoretical insights and practical guidelines for advancing HBSC-RWF composites in eco-friendly low-carbon construction materials, while promoting sustainable, large-scale recycling of waste wood in the building field.

EXPERIMENTAL

Experimental Raw Materials

The high belite sulfoaluminate cement (HBSC) provided by Hebei Tangshan Polar Bear Co., LTD. (Tangshan, China) was used as the cementitious materials. The density of HBSC (strength grade 42.5) was 3150 kg/m³, the specific surface area was 420 m²/kg, the initial setting time was 50 min, the final setting time was 130 min, and the soundness of cement was qualified. The detailed chemical composition of HBSC is shown in Table 1.

Table 1. XRF Chemical Composition of HBSC (%)

Chemical composition	CaO	SiO_2	Al_2O_3	SO_3	MgO	Fe_2O_3	TiO_2	L.o.I.
HBSC	40.12	18.66	18.6	15.0	4.03	1.11	1.07	1.41

RWFs were obtained through multiple crushing and screening by wood crushers. The waste wooden panels used as raw materials were primarily sourced from urban construction and demolition waste. Coarse fragmentation was achieved using a wood cutter and a wood shredder (provided by Henan Zhuoyou Machinery Equipment Co., Ltd.), reducing the waste wood panels into large fragments. After the fragments were further pulverized into finer particles, a Fulaike fiber pulper (FLK-X40, motor power, 11 kW) was employed to process the refined wood particles. High-speed rotation and impact forces within the pulper separated the particles into elongated RWFs, which were subsequently sieved to ensure uniformity. Water absorption of prepared RWF was 96.3%, the particle size was mainly between 0.6 and 2.36 mm, and the bulk density was 1270 kg/m^3. This processing method ensures efficient conversion of waste wood into consistent RWFs, aligning with circular economy principles for sustainable construction material production. The soluble sugars in RWF can inhibit cement hydration, delaying setting and hardening. Thus, alkali solution modification is required to remove these sugars and hemicellulose. The RWFs were immersed in a 5% NaOH solution at room temperature for 6 h. After immersion, the RWFs were removed, neutralized with 0.1 mol/L dilute hydrochloric acid, and thoroughly rinsed with deionized water to eliminate residual alkali. Finally, the treated fibers were dried and stored for subsequent use. The fine aggregate adopted the ISO standard sand provided by Xiamen Aseo Cement Standard Sand Co., LTD., with a density of 1440 kg/m^3, which belongs to the category of medium sand. The water reducer adopted was the polycarboxylate high-efficiency water reducer (PCE) provided by Qingjian New Building Materials Co., LTD. The water reduction percentage of PCE was 25%, and the dosage was 2% of the cementitious material content.

Table 2. Mix Proportion of HBSC- Based RWF Materials

Group Series	RWF Content (%)	Raw material (g)				
		Sand	Wood fiber	HBSC cement	Water	PCE
HWF0-45	0	800	0	800	360	8
HWF10-45	10	700	70	700	315	7
HWF20-45	20	600	120	600	270	6
HWF30-45	30	500	150	500	225	5
HWF40-45	40	500	200	500	225	5
HWF0-50	0	800	0	800	400	8
HWF10-50	10	700	70	700	350	7
HWF20-50	20	600	120	600	300	6
HWF30-50	30	500	150	500	250	5
HWF40-50	40	500	200	500	250	5
HWF0-55	0	800	0	800	440	8
HWF10-55	10	700	70	700	385	7
HWF20-55	20	600	120	600	330	6
HWF30-55	30	500	150	500	275	5
HWF40-55	40	500	200	500	275	5

Mix Proportion Design

The content of RWF (RWFs) increased in gradients of 10% to 40%, The cement-sand ratio was designed as 1:1, and the water-cement ratios were 0.45, 0.50, and 0.55, respectively, for comparative analysis. The influences of different contents of RWFs on the properties of HBSC-based materials were systematically studied. The detailed mix proportion design of HBSC-RWF cement-based materials is shown in Table 2. Among them, in the numbering system of "HWF**-**", H represents HBSC, WF represents RWF, and **-** represents the content of RWF (%) - water-cement ratio. Taking HWF 20-45 as example, it represents HBSC- RWF reinforced cement-based materials when the content of RWF is 20% and the water-cement ratio is 0.45.

Experimental Method

The weighed high belite sulfoaluminate cement (HBSC) and RWFs were sequentially added to a cement mortar mixer, followed by the incorporation of standard sand during low-speed dry mixing. Ordinary tap water and polycarboxylate superplasticizer were then introduced into the mixture. After thorough mixing, the mortar was poured into 70.7×70.7×70.7 mm triple-cube molds, covered with film for 24 h, demolded, and subjected to standard curing. The compressive and flexural strengths of specimens at 3, 7, and 28 days were tested using a DYE-300S fully automatic cement flexural-compressive testing machine (Shanghai Rongjida Instrument Technology Co., Ltd.). At 28 days, specimens were dried to constant weight in an electrothermal convection drying oven to calculate the dry density of mortar with different mix ratios, and water absorption was characterized by measuring mass changes during immersion over time. Shrinkage ratios at 3, 14, 28, 45, and 90 days were recorded using a vertical mortar shrinkage-expansion instrument. Additionally, thermal insulation mortar blocks (300×300×35 mm) were cured at room temperature for 28 days, dried, and analyzed for thermal conductivity (Lyu *et al.* 2025).

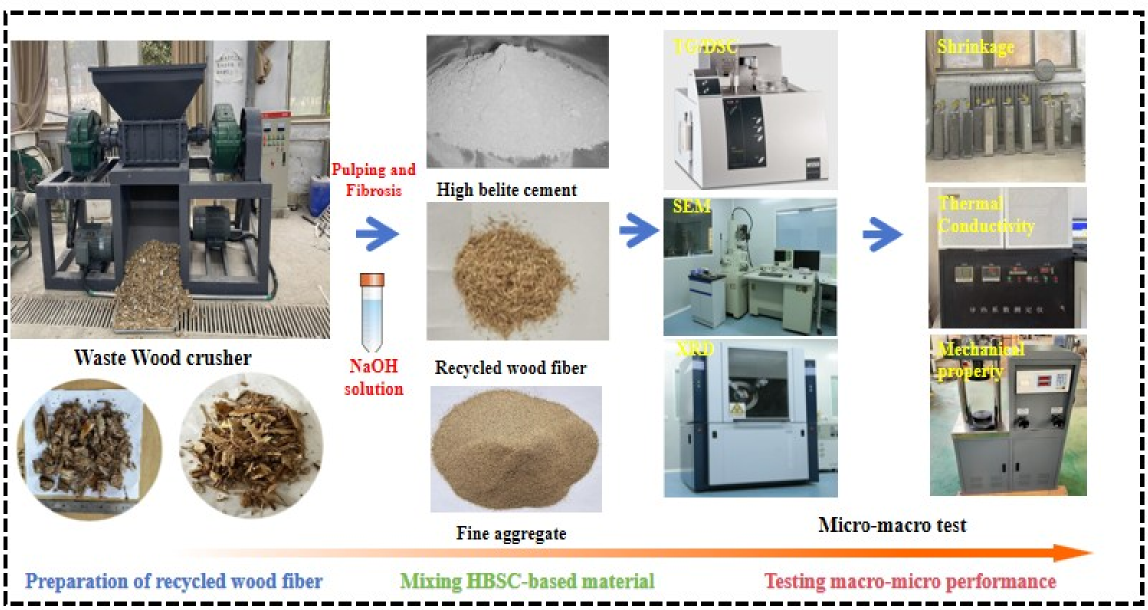

Fig. 1. Experimental process flowchart of HBSC-based materials with recycled wood fiber

Material characterization included X-ray diffraction (XRD) mineral composition analysis *via* a Bruker D8 ADVANCE, thermogravimetric/ differential scanning calorimetry (TG/DSC) using a METTLER TOLEDO equipment, and scanning electron microscopy (SEM) to observe hydration product distribution and micro-structure of paste (Lei *et al.* 2025), ensuring data reliability and comprehensive analysis. The detailed experimental process is shown in Fig. 1.

RESULTS AND DISCUSSION

Mechanical Properties of RWF HBSC-based Materials

Flexural strength of RWF HBSC-based materials

Figure 2 shows the effects of RWF content on the flexural strength development of HBSC-based materials at different water-cement ratios. Generally, the flexural strength was improved after incorporation of RWF. The flexural strengths of HBSC-based materials initially increased and then decreased with rising RWF content.

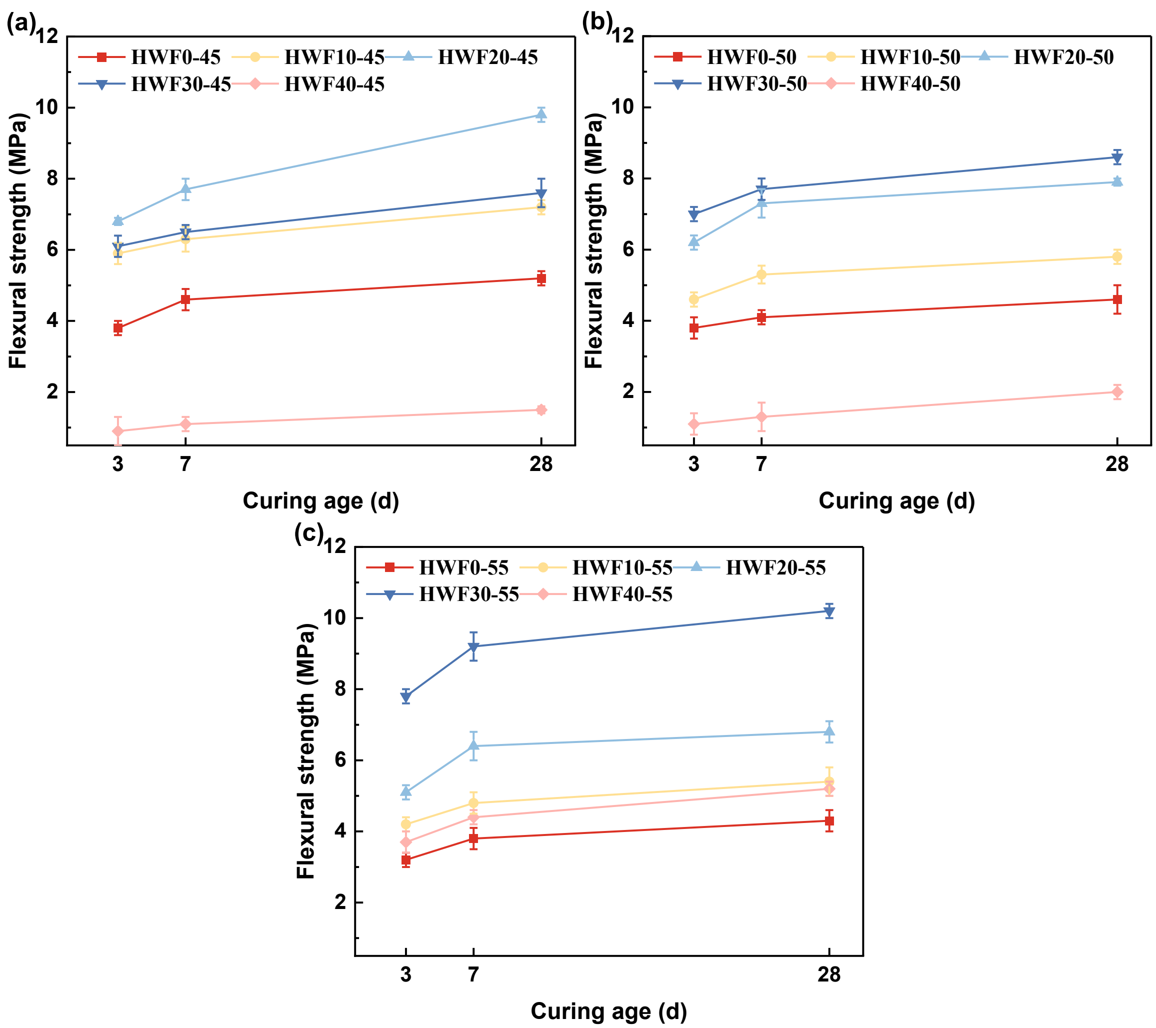

Fig. 2. Flexural strength of HBSC-based materials with different RWF contents: (a) W/C-0.45; (b) W/C-0.50; (c) W/C-0.55

The maximum flexural strengths under different water-to-cement (W/C) ratios reached up to 9.8, 8.6, and 10.2 MPa, representing an increment of 88.5%, 87%, and 137.3%, respectively, compared to the control group, demonstrating that RWF incorporation moderately enhanced flexural strength of HBSC-based materials. Higher W/C ratios led to looser cement internal structure and insufficient interfacial adhesion between RWFs and HBSC paste. Concurrently, excessive RWFs tended to entangle and agglomerate within the HBSC matrix, causing fiber inhomogeneity and weak zones that compromised reinforcement effects, resulting in significant strength reduction.

Notably, at the lower W/C ratio (0.45), 20% RWF content achieved nearly saturated water demand and peak flexural strength. As RWF content increased, higher water requirements elevated W/C ratios, providing more water for cement hydration demand. This enhanced hydration degree makes materials with 30% RWF content attain maximum strength. Therefore, moderate RWF contents (10 to 20%) improved cement matrix toughness by inhibiting crack propagation, thereby increasing flexural strength, while excessive RWFs (30 to 40%) introduced interfacial defects, resulting in strength degradation. In addition, when the water-cement ratio was 0.45 and 0.50, the water required for hydration and the cement paste used to wrap RWF of HBSC based materials with 40% RWF content was insufficient, resulting in a flexural strength lower than 2 MPa. This reduction was improved at a water cement ratio of 0.55.

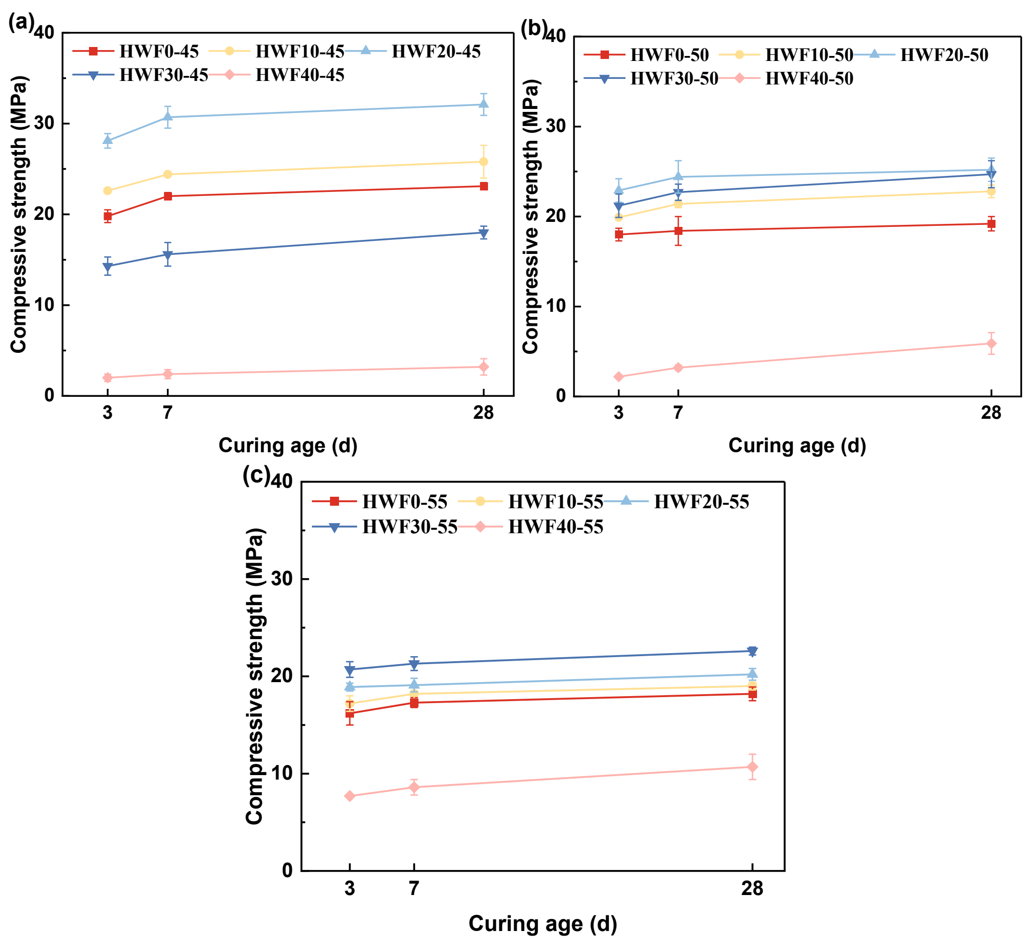

Fig. 3. Compressive strength of HBSC materials with different RWF contents: (a) W/C-0.45; (b) W/C-0.50; (c) W/C-0.55

Compressive strength of RWF HBSC-based materials

Figure 3 shows the influence of RWF content on the compressive strength development of HBSC-based materials under different water-cement ratios. The compressive strength of the HBSC-based materials demonstrated a consistent trend of initial increase followed by subsequent decrease with increasing RWF content. When the water-cement ratio was 0.45, the compressive strength of the material with 20% RWF content was the highest, reaching 32.1 MPa. Compared with the control group (HWF0-45), the strength was increased by 40%. When the RWF content exceeded 20%, the strength sharply decreased. As shown in Fig. 3(c), the strengths of the HBSC-based materials and the RWF content showed a clear cooperative relationship. Due to the high water absorption of RWF, when the RWF content reached 40%, the HBSC material failed to encapsulate the RWF under different water-to-cement ratios, resulting in incomplete cement hydration reactions. This led to RWF clumping and agglomeration, which impaired the workability of the paste. Concurrently, excessive RWF content deteriorated the interfacial properties between the cement paste and RWF, making the material prone to cracking and causing a sharp decline in compressive strength. As the W/C ratio increased, the compressive strength of HBSC decreased, which agrees with previous findings (Lin *et al.* 2025).

Dry Density of RWF HBSC-based Materials

Figure 4 presents the dry density characteristics of HBSC-based composites with varying RWF contents. All specimens exhibited dry densities below 1600 kg/m^3, classifying them as lightweight cementitious materials. At a water-cement ratio of 0.45, the dry density increased with increasing RWF content up to 20%, suggesting that the incorporated RWFs may establish an interconnected network within the cement matrix, thereby reducing porosity and enhancing compactness. Beyond this threshold value, higher water-cement ratios led to decreased dry densities, which was attributed to the release of bound water from RWF during drying, which increases material porosity. The optimal dry density occurred at approximately 20% RWF content. This was likely because the internal curing effect of RWFs promotes additional hydration reactions, generating more hydration products and consequently improve both density and mechanical strength. These findings correlate well with the mechanical performance of material, confirming the strong interdependence between material density and strength development.

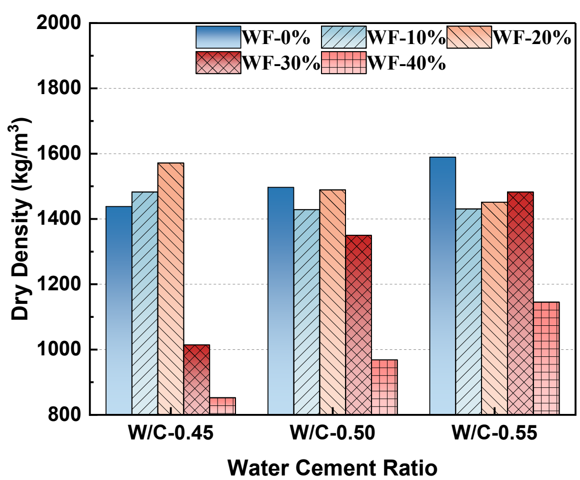

Fig. 4. Dry density of HBSC-based materials with different RWF content at different W/C ratio

Water Absorption of RWF HBSC-based Materials

Figure 5 shows the water absorption curve of HBSC-based materials with different RWF content. An appropriate content of RWF (20 to 30%) can reduce the water absorption of HBSC-based materials. The effect of the content of RWF on the water absorption percentage showed a trend of increasing first and then decreasing and increasing. The water absorption increased rapidly in the early stage, and the first 4 d (96 h) was the main period of water absorption growth. After 4 d, the water absorption of the test block was saturated, and the trend tended to be gentle. The measured water absorption represents the water absorption of both regenerated wood fiber and cement-based materials. Both pore structure water absorption and hydration product water absorption are included. When the content of wood fiber was 20% and 30%, the water absorption of cement paste was 13.7% and 14.9%, respectively, which was 0.6 to 1.8% lower than that of the control group. The incorporation of RWF affected the hydration process and pore structure of cement-based materials. The combination of fiber and matrix inhibited the generation of shrinkage cracks and reduced the connected porosity, which affected the water absorption. When the content was 40%, the excessive incorporation of RWF resulted in the failure of the cement incorporation with RWF, and the exposure of the RWF increased the water absorption.

Fiber agglomeration occurred when excessive fibers were added, and the hydration reaction of cement was not complete, resulting in an increase in the proportion of macropores and an increase in water absorption. Therefore, 20% RWF can reduce the formation of connected pores, optimize the pore structure of cement-based materials, and reduce the water absorption of cement-based materials.

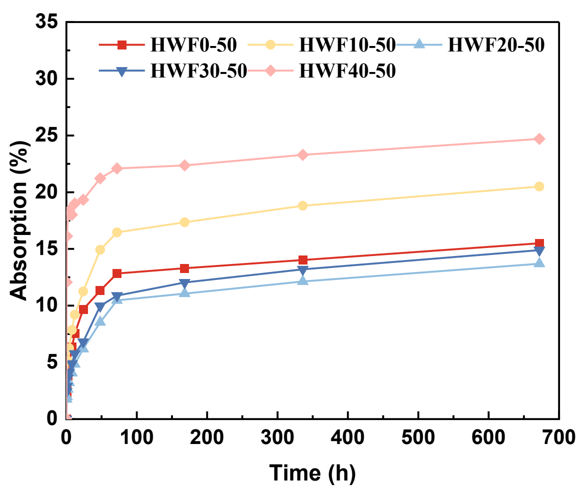

Fig. 5. Water absorption of HBSC-based materials with different RWF content

Thermal Conductivity of RWF HBSC-based Materials

Figure 6 presents the thermal conductivity characteristics of HBSC-based materials with varying RWF contents. As shown in Fig. 6(a), the thermal conductivity declined with increasing RWF incorporation. At a water-cement ratio of 0.45, the measured thermal conductivities for RWF contents of 0%, 10%, 20%, and 40% were 0.268, 0.244, 0.241, and 0.190 W/(m·K), representing reductions of 10%, 11.3%, and 40.4% compared to the control group, respectively. This improvement in thermal insulation performance stems from the intrinsic low thermal conductivity and low-density characteristics of RWFs. The observed enhancement becomes more pronounced at higher water-cement ratios, likely due to the formation of larger pore structures following the release of bound water during specimen drying.

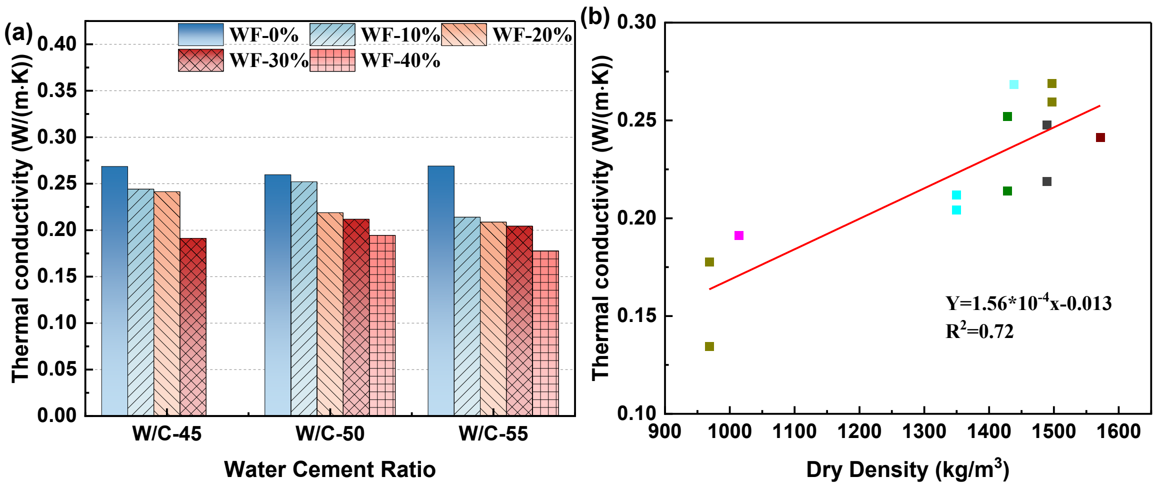

Fig. 6. (a) Thermal conductivity of HBSC-based materials; (b) linear fitting curve

Figure 6(b) demonstrates the linear relationship between dry density and thermal conductivity, with regression analysis yielding a determination coefficient (R^2) of 0.72, confirming a moderate correlation between these parameters. These findings indicate that RWF incorporation effectively reduces the thermal conductivity of HBSC-based materials (Xu *et al.* 2024), achieving simultaneous improvements in energy efficiency, lightweight performance, and multifunctionality. Such properties make these materials particularly suitable for modern construction applications that prioritize energy conservation and thermal comfort requirements.

Shrinkage Properties of RWF HBSC-based Materials

Figure 7 shows the shrinkage performance of HBSC cement-based materials with different RWF content. When the content of RWF was between 20% and 30%, the shrinkage value of HBSC cement-based materials was lower than that of the control group. Too little or too much content increased the amount of shrinkage of cement-based materials and reduced the anti-shrinkage characteristics of materials, which was consistent with the results of water absorption. At the same time, the autogenous shrinkage of all groups of materials increased rapidly in the first 28 d, slowed down after 28 d, and stabilized after 56 d, which was consistent with the typical hydration process of cement-based materials. The self-drying effect was significant due to the severe hydration reaction in the early stage and gradually stabilized in the later stage.

When the RWF content was 20%, the shrinkage value of HBSC-based materials was the lowest, and the shrinkage was reduced by 57.8% compared with that of control group. This addition of the current amount of RWF results in the formation of a three-dimensional network structure in HBSC paste, limiting the shrinkage deformation of the cement matrix. At the same time, the water absorption of the fiber may delay the decrease of the internal humidity of the matrix, reduce the self-drying effect, and thus reduce the self-shrinkage. The material with 30% RWF content was slightly higher than that with 20% content, which may be related to the uneven dispersion of fibers or the difference of local water absorption.

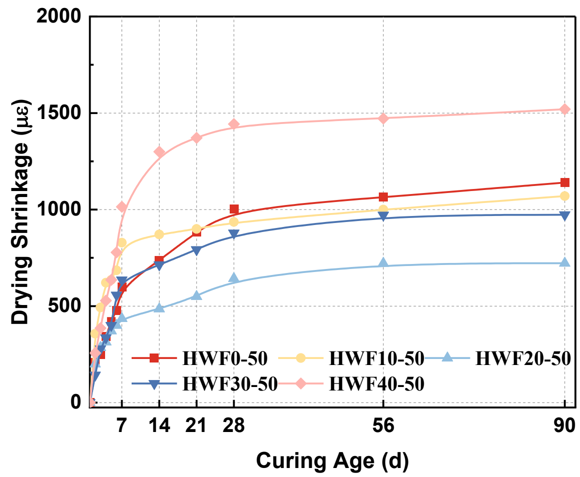

Fig. 7. Shrinkage curves of HBSC cement-based materials with different RWF content

Thermogravimetric Analysis(TG/DSC) of RWF HBSC-based Materials

Figure 8 shows the TG-DSC curves of HBSC cement-based materials with different RWF contents. In the TG diagram Figs. 8(a) and (b), the mass loss rate increased with the increase of RWF content. The mass loss was mainly from 300 °C after gradually widening the gap, indicating that the decomposition temperature of regenerated wood fiber was improved after being wrapped by cement. The DSC diagram shows three peaks during the heating process from 30 to 1000 °C. At 100 °C, the bound water in the calcium silicate hydrate (C-S-H) gel in the cement monitoring sample decreased with the increase of the RWF content, indicating that the content of C-S-H gel was less. From 180 to 300 °C, the characteristic peaks of ettringite are observed. These peaks were relatively small and concentrated, indicating that the content of ettringite in the hydration products of HBSC-material was low. When the RWF content reached 20%, the peak was the highest, which indicates that the amount of ettringite was the most at this time, which was also the reason for the highest strength of the material when the RWF content was 20%. From 300 to 400 °C, except for the group without RWF, the characteristic peaks appeared in other groups, and the characteristic peaks gradually increased with the increase of RWF content, indicating that the peak should be the characteristic peak generated by the decomposition of RWF. From 560 to 720 °C, the characteristic peak of calcium carbonate appeared in the slurry. The alkaline substance in high belite cement catalyzes to produce more $CaCO_3$, and the regenerated wood fiber generates elemental carbon at high temperature. This process produces larger pores, which promotes the circulation of CO_2 and generates more $CaCO_3$. In summary, the increase of RWF content leads to an increase in mass loss. The addition of 20% RWF makes the slurry structure denser.

Figures 8 (c)-(d) show the TG-DSC curve diagram under different water-cement ratios, and the influence of different water-cement ratios on cement-based materials is compared. When the water-cement ratio was 0.45 and 0.5, the thermogravimetric curve was the same, and the mass loss rate was 16% and 16.6%, respectively. When the water-cement ratio was 0.55, the mass loss rate of the slurry was 13.4%, which was 3.2% lower than that of 0.5 water-cement ratio. The results indicated that from 30 to 150 °C, a larger water-cement ratio resulted in a higher bound water content.

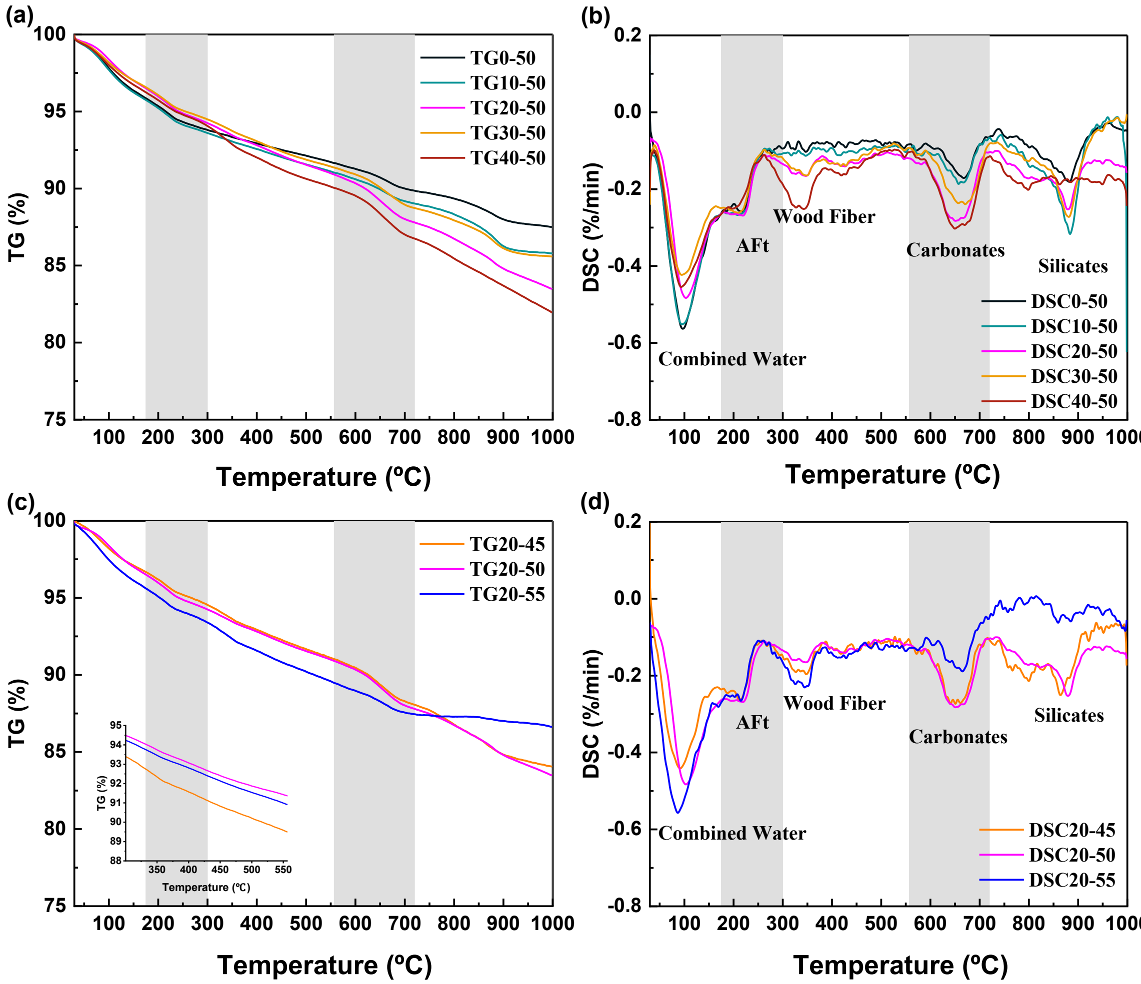

Fig. 8. TG-DSC curves of HBSC-based materials with different RWF contents: (a) TG with different contents of RWFs; (b) DSC with different contents of RWFs; (c) TG with different water-cement ratios; (d) DSC with different water-cement ratios

When the water-cement ratio was 0.5, the ettringite peak of the slurry was the highest, indicating that the ettringite content produced at this water-cement ratio was the highest. Because the content of RWF in this combination was the same, the inconsistency of the characteristic peaks of RWF at 300 °C may be caused by the inhomogeneity of sampling. For the characteristic peaks of $CaCO_3$ at 560 to 720 °C, the cement pastes with water-cement ratios of 0.45 and 0.5 were higher than the water-cement ratio of 0.55, indicating that there may be incompletely hydrated cement particles wrapped in carbonates (Xin *et al.* 2024). Similarly, the characteristic peak of silicate was attributed to the insufficient hydration of low water-cement ratio. The comparative analysis of different water-cement ratios shows that the hydration of HBSC in the HBSC system did not require a very high water-cement ratio. The ratios of 0.45 and 0.5 were similar in thermogravimetric performance. Taken together with the mechanical properties, the water-cement ratio of 0.45 was selected as the optimum water-cement ratio under different HBSC-based materials.

XRD Analysis of RWF HBSC-based Materials

Figure 9 shows the XRD analysis map of cement-based materials with different RWF content. Because the main mineral of HBSC paste is belite ($2CaO \cdot SiO_2$), the calcium silicate hydrate gel in its hydration products is the source of core strength. In the XRD pattern, the C-S-H gel usually exhibits an amorphous dispersion peak rather than a sharp diffraction peak. Figure 9(a) shows the XRD diffraction pattern of HBSC paste with different RWF content. The incorporation of RWF did not produce new hydration products. In the XRD diagram, the paste includes quartz, hydrated alumina, unhydrated calcium sulfate (gypsum), calcium silicate, and calcium sulfoaluminate, indicating that there were still many clinkers in HBSC at 3d that were not involved in hydration, and the early hydration was incomplete. The diffraction peak of hydrated alumina was the highest when the content of regenerated wood fiber was 10%, indicating that the cement hydration degree was higher at this content. When the content was 40%, the peak value of calcium sulfoaluminate was enhanced, indicating that the degree of hydration was lower than that of other groups and that the incorporation of RWF may affect the hydration process of cement. Comparing the XRD diffraction peaks of different water-cement ratios in Fig. 9(b) shows that with the increase of water-cement ratio, the content of gypsum became higher gradually, which may be due to the increase of water-cement ratio. This results in excessive dilution of gypsum or decrease of reaction efficiency, increase of residue, or secondary crystallization (Chang *et al.* 2024). As shown in the compressive strength test results, the water-cement ratio was optimal at 0.45 in the HBSC-based cementitious material system.

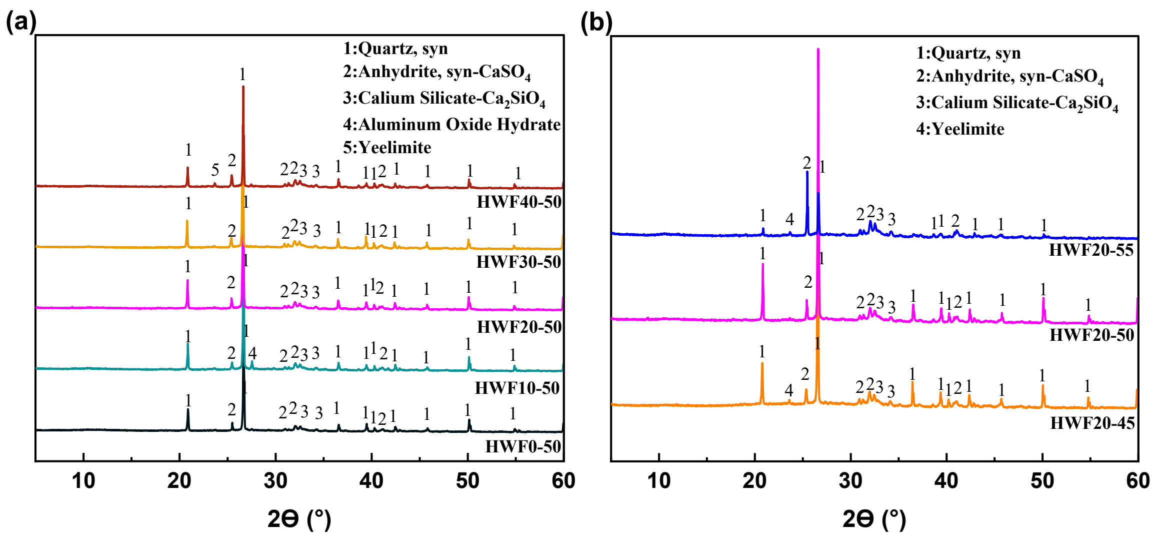

Fig. 9. XRD curve of HBSC-based materials: (a) different RWF content; (b) different water-cement ratios at 20% RWF content

SEM Micro-morphology Analysis of RWF HBSC-based Materials

Figure 10 shows the SEM micro-morphology images of HBSC-based materials under different RWF content and different water-cement ratio. As shown in Figs. 10(a) to (c), with the increase of RWF content, the ettringite (AFt) content of HBSC-based materials decreased. Compared with the RWF content of 20%, the porosity of the control group and the RWF content of 40% group at the same magnification was larger, there were more cracks, and the compactness was poor. The morphology of AFt in the group with 40% RWF content was coarser and shorter at 1 μm, indicating that sufficient water was not provided for hydration during cement hydration. The C-S-H gel was less, indicating that the hydration was not complete and the dense structure was not formed, resulting in a decrease in strength. Thus, 40% RWF content exceeded the optimal content. When the content of RWF was 20%, the microstructure of HBSC-based materials was more compact. This is consistent with the above strength and shrinkage research results. Figures 10(d) to (f) compare the microstructural evolution of HBSC-based materials under different water-cement (w/c) ratios. As the *w*/*c* ratio increased, the microstructure became increasingly porous and disordered, characterized by larger, more irregular voids and a less uniform distribution of hydration products. At a *w*/*c* ratio of 0.45, the structure remained dense, with closely interconnected cement particles. When the *w*/*c* ratio rose to 0.5, the overall compactness of the matrix declined. Further increasing the *w*/*c* ratio to 0.55 exacerbated these effects: at 1 μm magnification, hydration products exhibited pronounced agglomeration, accompanied by abundant irregular pores, indicating poor microstructural uniformity and density. This degradation likely stemmed from excessive water content disrupting the hydration process, hindering the formation of a robust, interlinked network of hydration products and ultimately impairing the mechanical performance of the HBSC-based material.

In summary, for different RWF content, the incorporation of 20% RWF caused the microstructure of cement-based materials to be denser, the morphology and distribution of hydration products to be more reasonable, and the pore structure to be optimized. Changes in these microstructures can have a positive impact on the macroscopic properties of cement-based materials. For the water-cement ratio, the structure was denser when the water-cement ratio was 0.45. The higher water-cement ratio adversely affected the microstructure and properties of cement-based materials.

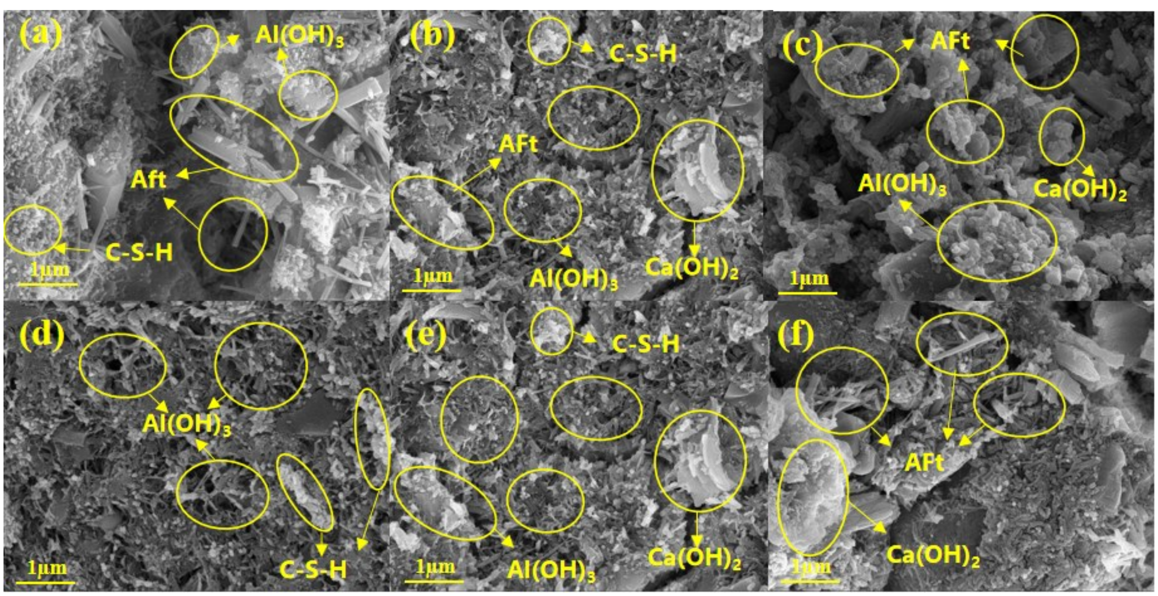

Fig. 10. SEM images of HBSC-based materials under different RWF content and water-cement ratio: (a) HWF0-50; (b) HWF20-50; (c) HWF40-50; (d) HWF20-45; (e) HWF20-50; (f) HWF20-55

DISCUSSION

Appropriate amounts of RWF significantly enhanced the compressive and flexural strength of HBSC matrix materials. This improvement is primarily attributed to the reinforcing network formed by RWF, which effectively inhibits crack propagation and optimizes the material's toughness and crack resistance. However, excessively high RWF content leads to fiber entanglement and agglomeration within the matrix, resulting in reduced interfacial bonding strength and consequently weakening the material's overall strength. Additionally, a higher water-cement ratio reduces the interfacial bonding strength between RWF and HBSC, resulting in a more porous internal structure that further diminishes mechanical properties.

Although composites with higher RWF content (*e.g.*, 30 to 40%) exhibited reduced mechanical strength such as flexural and compressive resistance, they demonstrated unique functional advantages in terms of density, water absorption, and shrinkage. These characteristics make them suitable for non-structural applications, such as lightweight thermal insulation boards, acoustic panels, or permeable ecological revetment materials. The performance emphasis shifts from load-bearing capacity to functional attributes including low thermal conductivity, efficient sound absorption, or good water permeability, indicating that high-RWF composites hold certain application potential in functional properties.

Despite achieving positive outcomes, this study had limitations. It considered only a single type of wood fiber, whereas fibers from different waste wood sources may exhibit varying physical and chemical properties, potentially affecting the composite's final performance. Long-term durability is a critical factor in the practical application of building materials. The current research was limited to short-term mechanical properties and did not consider long-term durability tests on concrete, such as freeze-thaw cycles.

Future research can be expanded and deepened in the following areas. First, long-term durability tests should be conducted to evaluate the performance changes of RWF-reinforced HBSC-based composites under different environmental conditions, ensuring their reliability and durability in actual engineering applications. Second, considering the diverse sources of waste wood, future studies should compare the effects of RWF from different origins on composite properties to develop more universally applicable, high-performance, low-carbon building materials. Through these investigations, it is anticipated that the comprehensive performance of RWF-reinforced HBSC-based composites will be further enhanced, promoting their widespread application in green and energy-efficient construction.

Based on its lightweight, enhanced thermal insulation, and optimized mechanical properties, the developed HBSC-based RWF composite demonstrates promising application prospects in modern green construction. Specifically, it is highly suitable for manufacturing non-load-bearing or semi-structural components, such as interior and exterior wall panels, partition boards, and acoustic/thermal insulation layers in prefabricated buildings. This material not only utilizes waste resources but also contributes to reducing building energy consumption and improving indoor environmental comfort, aligning with the goals of sustainable and low-carbon building practices.

CONCLUSIONS

1. Mechanical properties of recycled wood fiber – high belite sulfoaluminate concrete (RWF-HBSC) composites decreased with increasing water-cement ratio. At a water-cement ratio of 0.45 with 20% RWF content, the composite achieved its maximum mechanical strength of 32.1 MPa, representing a 40% improvement over the control group. However, significant deterioration in mechanical performance was observed when RWF content exceeded 30%.
2. The incorporation of RWF reduced the dry density of HBSC composites, with thermal conductivity showing a linear correlation with dry density. The thermal conductivity decreased to 0.22 W/(m·K), indicating enhanced thermal insulation performance and demonstrating high application potential for lightweight thermal wall materials. Both dry density and thermal conductivity decreased with increasing water-cement ratio.
3. Within the 20 to 30% RWF content range, the formation of interconnected pores in HBSC composites was effectively reduced, resulting in optimized pore structure and decreased water absorption. However, at 40% RWF content, increased water absorption and shrinkage values were observed, potentially leading to cracking and performance degradation during later stages.
4. X-ray diffraction (XRD) analysis revealed that RWF content did not generate new hydration products but did influence the hydration process of HBSC material, as evidenced by variations in diffraction peak intensities of hydration products. Microscopic analysis demonstrated that at 20% RWF content and 0.45 water-cement ratio, hydration products including aluminum gel, ettringite, and calcium silicate hydrate (C-S-H) gels were more pronounced, resulting in denser microstructure and optimal overall performance of the HBSC composites.

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