

Article

Investigation on Macroscopic and Microscopic Properties and Application of Straw Fiber-Reinforced Red Mud Unfired Bricks

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Abstract

To address the environmental hazards caused by massive bauxite red mud stockpiles, phase-change unburned bricks have been developed. The slump flow and initial setting time of fresh mortar were tested, while the flexural strength, compressive strength, splitting tensile strength and rebound hardness of hardened mortar specimens were measured. The synergistic influence of stearic acid on mechanical strengths, rebound hardness and thermal conductivity was revealed, and the corresponding indoor simulation tests were performed. X-ray diffraction (XRD), scanning electron microscopy (SEM) and Ultra-depth-of-field microscope cross-section scanning were adopted to interpret the intrinsic microstructure and inner mechanism. Results indicate that slump flow, initial setting time and all mechanical indices follow cubic functional relationships with red mud mass ratio. Specimens incorporating 20 wt.% red mud achieve the optimal mechanical strength, rebound hardness and thermal conductivity, with the maximum growth rates of up to 32.7%, 18.7% and 27.0%, respectively. Appropriately, straw fibers improve the mechanical properties and rebound hardness yet reduce thermal conductivity. In simulated thermal cabin tests, wall temperature continuously rises under heating and declines after heat termination; red mud and straw fibers jointly slow the heating-up rate and post-heating cooling rate. Samples with 5 wt.% red mud possess the densest hydration matrix. Red mud promotes the generation of ettringite (AFt), calcium carbonate and dolomite crystals, and elevates the content of dicalcium silicate (C₂S) within the binder system. This study provides a reference for fabricating functional wall materials using industrial solid waste (red mud) and agricultural solid waste (straw fibers).

Keywords: solid waste; temperature test; resource utilization; mechanical properties; stearic acid



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1. Introduction

Red mud, a solid waste product generated during aluminum smelting, has conventionally been managed through inert stockpiling techniques, including both wet and dry storage methods [1]. These conventional disposal practices, however, do not facilitate the recovery of valuable resources and thus do not mitigate the increasing depletion of raw materials. In response, numerous valorization approaches for red mud have been investigated. Notably, red mud has been studied as a binder material in geotechnical engineering applications [2,3] and has demonstrated significant potential in environmental remediation efforts, such as wastewater treatment and soil rehabilitation [4,5]. Zhang et al.

have pointed out that red mud with a mass ratio of 15% by mass of binder materials can increase the compressive strengths of pile foundation material by a rate of 22% [6]. Furthermore, Venkatesh et al. have found that red mud can improve the 180-day compressive strength of cement concrete by a rate of up to 28.96% [7–13]. Despite the role of red mud in resource utilization, the application of red mud in cement concrete can consume a small amount of red mud.

In addition to red mud, various industrial by-products such as sludge, construction waste, phosphogypsum, and furnace ash have been utilized in the fabrication of unfired bricks, yielding compressive strengths of 12.9 MPa, 15.4 MPa, 17.6 MPa, and 14.7 MPa, respectively. Beyond mechanical properties, thermal insulation represents a crucial parameter for building materials. The thermal conductivities of these bricks were observed to decrease by up to 19.4%, 27.6%, 34.9%, and 23.7%, respectively [14–16]. Red mud has been confirmed to be used as unfired brick. The compressive strength varies from 8.6 MPa to 21.8 MPa with the mass ratio of red mud ranging from 10% to 50%. While, the corresponding thermal conductivity decreases from 0.59 W/(m·K) to 0.32 W/(m·K) [15–17].

However, masonry is a material that is prone to cracking; therefore, fibers are needed to delay the development of its cracks. Straw fibers are an excellent choice for resisting the expansion of masonry cracks [16,18–22]. Several researchers have pointed out that straw fibers have been used for delaying the cracking of masonry [23–26]. Little research has been paid to the mechanical properties and temperature-related properties of red mud straw fiber unfired bricks. This paper targets the aforementioned problems. Recycled functional unfired bricks were prepared with red mud and straw fibers as raw materials and the material properties of unfired bricks as well as the temperature regulation performance of simulated houses were systematically investigated.

The slump flow, the initial setting time and the mechanical strengths of red mud unfired bricks were investigated in this research. The investigation considered red mud proportions ranging from 5% to 40% and straw fiber contents between 0.5% and 2.5%. The autoclave curing environment was used to cure the specimens for 1 day after hardening and formwork removal. The flexural strength, compressive strength, splitting strength and rebound value were determined. The optimal proportion of unfired bricks with the best mechanical properties has been selected and then the influence of stearic acid on its properties is investigated. Stearic acid is used as a kind of phase change material. Straw fibers are used for enhancing the crack resistance of red mud unfired bricks. The temperature variation law of the simulated cabin has also been studied in the article. The mechanism of the specimens' properties is revealed with the assistance of X-ray diffraction (XRD) curves and scanning electron microscopy (SEM). This study will provide a reference for the recycling of red mud and straw fibers [27,28].

2. Materials and Methods

2.1. Raw Materials

The ordinary portland cement (OPC) with a strength grade of 42.5 MPa was supplied by Xiangshan Conch Cement Co., Ltd., Ningbo, China. This cement exhibited a specific surface area of 357 m²/kg. The initial setting time and final setting time of OPC were 203 min and 250 min, respectively. Class II fly ash (FA), with a density of 2.3 g/cm³, was provided by Jiuqi Building Materials Co., Ltd., Weifang, China. Meanwhile, red mud (RM), an insoluble residue solid generated from the Bayer process for alumina production, was furnished by Shandong Xinfu Group Co., Ltd., Rongcheng, China, with a density of 2.66 g/cm³. River sand served as the fine aggregate in this work, consisting of three particle size fractions: (0.68–1.21) mm, (0.33–0.61) mm and (0.14–0.31) mm, which were blended at a mass ratio of 1:1.5:0.8. The straw fibers were biomass organic short fibers made

from agricultural and forestry solid waste, which were provided by Yikesaier Agricultural Development Co., Ltd., Suqian, China. The straw fibers have a filamentous bundle structure, rich internal pores, high surface hydroxyl content, strong hydrophilicity and significant water absorption expansion. The chemical components and particle size distributions of all raw materials are shown in Tables 1 and 2, respectively.

Table 1. The particle size distributions of the cementitious materials (%).

Types	Particle Size/ μm						
	0.3	0.6	1	4	8	64	360
RM	0.07	1.77	6.26	23.93	32.75	80.21	100
OPC	0	0.33	2.66	15.01	28.77	93.59	100
FA	31.2	58.3	82.3	100	100	100	100

Table 2. The chemical compositions of the cementitious materials (%).

Types	SiO ₂	Al ₂ O ₃	Fe _x O _y	MgO	CaO	SO ₃	K ₂ O	Na ₂ O	P ₂ O ₅	Cr ₂ O ₃	ZrO ₂	MnO	TiO ₂	Loss on Ignition
RM	16.16	22.52	33.41	0.03	3.32	0.14	0.19	8.64	0.14	0.10	0.18	0.09	5.50	9.58
OPC	20.87	4.14	5.12	4.08	62.66	2.74	0.28	0.11	-	-	-	-	-	-
FA	48.85	35.72	4.33	0.86	4.28	0.15	0.70	0.33	0.14	0.01	0.03	0.05	1.37	3.02

2.2. The Preparation of Specimens

All raw materials were accurately measured in accordance with the mix proportions presented in Table 3. In order to ensure the reliability of the experimental data, six samples were prepared for each mix ratio. Cement, red mud, fly ash (FA) and sand were introduced into the UJZ-15 mortar mixer (Shanghai Rongjida Instrument Technology Co., Ltd., Shanghai, China). The mixture was dry-mixed at a speed of 140 ± 5 revolutions per minute (r/min) for 60 s to obtain uniform composition. Straw fibers were uniformly dispersed by volume proportion, followed by the addition of cement, red mud and fly ash, until the straw fibers were no longer visible to the naked eye. Subsequently, pre-mixed water was gradually incorporated, and mixing proceeded at 285 ± 10 r/min until a total mixing duration of 420 s was attained. A constant water-to-binder ratio (W/B) of 0.35 was maintained throughout the process. Upon completion of mixing, the fresh paste was allocated for various tests: a portion was utilized for the slump flow test; another portion was cast into cubic molds measuring $150 \times 150 \times 150 \text{ mm}^3$ for splitting tensile strength evaluation; and the remaining paste was poured into oil-coated molds of dimensions $200 \times 100 \times 50 \text{ mm}^3$ to produce unfired bricks. After demolding, all specimens underwent autoclave curing at 180°C and 1.0 MPa for 8 h, following the guidelines stipulated in the Chinese standard GB/T 11945-2019 [29]. Red mud (RM) was used to replace ordinary Portland cement (OPC) at a mass ratio of 0%–40% relative to the total binder materials. This gradient design aimed to recycle industrial red mud waste and reveal how RM dosage affects mechanical strengths. A 20% RM replacement ratio was screened as the basic formula for subsequent modification. On the basis of the 20% RM system, stearic acid (SA) was introduced at gradient dosages ranging from 0% to 20% by mass of river sand aggregate.

Table 3. The mixing proportions of unfired brick with red mud (kg/m^3).

Water	OPC	RM/Binding Materials (%)	RM	FA	River Sand	SA/River Sand (%)	Stearic Acid (SA)
427.7	1110.9	0%	0	111.1	977.9	0%	0
427.7	1049.8	5%	61.1	111.1	977.9	0%	0
427.7	988.7	10%	122.2	111.1	977.9	0%	0

Table 3. Cont.

Water	OPC	RM/Binding Materials (%)	RM	FA	River Sand	SA/River Sand (%)	Stearic Acid (SA)
427.7	927.6	15%	183.3	111.1	977.9	0%	0
427.7	866.5	20%	244.4	111.1	977.9	0%	0
427.7	805.4	25%	305.5	111.1	977.9	0%	0
427.7	744.3	30%	366.6	111.1	977.9	0%	0
427.7	683.2	35%	427.7	111.1	977.9	0%	0
427.7	622.1	40%	488.8	111.1	977.9	0%	0
427.7	866.5	20%	244.4	111.1	977.9	5%	61.1
427.7	866.5	20%	244.4	111.1	977.9	10%	122.2
427.7	866.5	20%	244.4	111.1	977.9	15%	183.3
427.7	866.5	20%	244.4	111.1	977.9	20%	244.4

2.3. Measuring Procedure

2.3.1. Slump Flow and Initial Setting Time

The slump flow test was carried out using an NLD-3 cement mortar fluidity tester manufactured by Shaoxing Zhekun Instrument Co., Ltd., Shaoxing, China. The detailed test procedures are described as follows. Firstly, the prepared fresh mortar mixture was poured into the standard slump cone of the fluidity tester to half the cone height, followed by 15 compaction tamping strokes to eliminate internal voids and achieve uniform material compaction. Afterwards, the slump cone was fully filled with the residual mortar mixture, and the identical tamping compaction operation was repeated again. After finishing filling and compaction, the slump flow value was recorded and measured strictly in compliance with the Chinese national standard GB/T 219-2005 [30]. The setting time was tested with a ZKS-100 tester, which was supplied by Beijing Zhongjiaojianyi Technology Development Co., Ltd., Beijing, China. The initial setting time was determined following the standard JGJ70-2009 [31]. The penetration resistance value during the setting time was calculated by Equation (1) and the setting time was defined as the moment when f_p reached 0.7 MPa.

$$f_p = \frac{N_p}{A_p} \quad (1)$$

where f_p refers to the penetration resistance and N_p is the static pressure when the penetration depth reaches 25 mm. A_p denotes the cross-sectional area of the penetration needle.

2.3.2. Mechanical Strengths

The splitting tensile and compressive strengths of the cured prismatic specimens (40 m × 40 m × 160 m) were tested with a WAW-600C microcomputer-controlled electro-hydraulic servo universal testing machine, which was manufactured by Jinan Shijin Group Co., Ltd., Jinan, China. Cubic specimens with dimensions of 150 m × 150 m × 150 m were adopted for splitting tensile strength measurement. Prior to loading, wooden cushion strips with a thickness of 2~3 mm were padded on the splitting fixture to avoid local stress concentration. The cubic specimens were placed on the fixture along the preset splitting plane, and continuous loading was conducted until the specimens fractured. The splitting tensile strength was determined at a constant loading rate of 0.05 MPa/s in accordance with GB/T 50081-2019 [32]. As for compressive measurement, the original RM unfired bricks (200 m × 100 m × 50 m) were split into two halves along the central axis and stacked together for axial loading. Cement paste was applied on the contact interface between the two halved bricks for bonding and leveling. Meanwhile, the top and bottom bearing surfaces of the specimens were leveled with cement paste ≤ 3 mm thick. The specimens were cured for 4 h in an unventilated environment at a temperature above 10 °C. After that, the compressive strength of each specimen was measured by applying an axial load at a

rate of 2.4 kN/s. For each formulation of red mud unfired bricks, three replicate splitting tensile tests and six replicate compressive tests were conducted and the average value was taken as the final strength index. The whole testing process was performed in accordance with the Chinese standard GB/T 17671-2021 [33].

2.3.3. Thermal Conductivity

The thermal conductivity test was performed using a DRL-III thermal conductivity tester manufactured by Xiangtan Xiangyi Instrument Co., Ltd., Xiangtan, China. Prior to testing, prism-shaped specimens with dimensions of 200 mm × 200 mm × 20 mm were cut from cured red mud unfired brick samples for subsequent thermal property characterization. The thermal conductivity value of each specimen was calculated via the equation presented below.

$$k = \alpha \rho C_p \quad (2)$$

where k is the thermal conductivity, α represents the thermal diffusivity coefficient, ρ is the density of the test samples, and C_p stands for the specific heat capacity. The density of the samples was measured by the Archimedes method, and the specific heat capacity was determined via modulated temperature differential scanning calorimetry (MTDSC).

2.3.4. Temperature Measurement in the Experimental Cabin

Nine house models with uniform dimensions of 1500 mm × 1300 mm × 900 mm were assembled by stacking red mud-based unfired bricks. The brick specimens were prepared with stearic acid dosages varying from 0 wt.% to 20 wt.% relative to the total mass of binder materials, whereas the dosages of red mud, straw fibers, fly ash (FA), river sand and mixing water remained constant across all groups. All assembled house models were placed inside an enclosed environmental chamber maintained at $-8\text{ }^{\circ}\text{C}$ and a relative humidity of 35%. The internal temperature of each model was raised linearly from $-8\text{ }^{\circ}\text{C}$ to $40\text{ }^{\circ}\text{C}$, after which the specimens underwent natural cooling to ambient conditions. PT1000 temperature sensors were mounted to record real-time temperature variations in the model walls, and the sensor layout is illustrated in Figure 1.

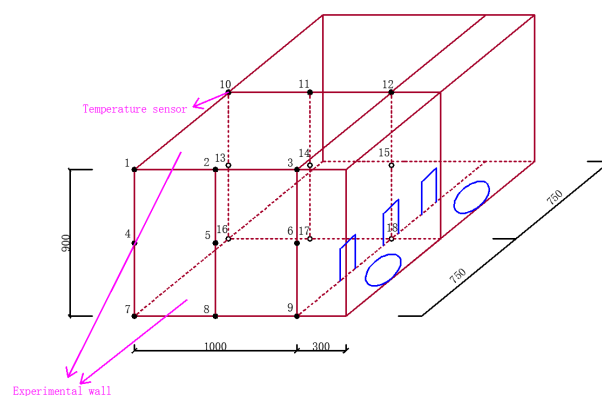


Figure 1. Simulation room temperature test process.

2.3.5. Microscopic Measurement

X-ray diffraction (XRD) and scanning electron microscopy coupled (SEM) were employed to investigate the fundamental mechanisms involved. Prior to analysis, all specimens were subjected to oven drying. For SEM examination, small, flat fragments were carefully extracted from the interior of the unfired red mud bricks, coated with a thin layer of gold via sputtering, and observed under vacuum conditions using a COXEM EM-30AX Plus scanning electron microscope (Coxem Co., Ltd., Seoul, Republic of Korea) at an accelerating voltage of 15 keV. For XRD analysis, the remaining samples were pulverized

into fine powders and characterized using a D8 ADVANCE X-ray diffractometer (Bruker (Beijing) Technology Co., Ltd., Beijing, China) operated at 40 kV and 40 mA, with a scanning speed of 0.6° per minute across a 2θ range of 5° to 90° . A schematic representation of the experimental methodology is provided in Figure 2. The Olympus DSX-500 provided by Shimadzu Technology Co., Ltd., Wuxi, China, was used for the ultra depth-of-field microscope scanning experiment. To obtain a flat and undamaged sample surface, the sample cross-section was polished. The sample was placed under the microscope to observe and analyze the microstructure, surface texture, and distribution of the sludge particles.

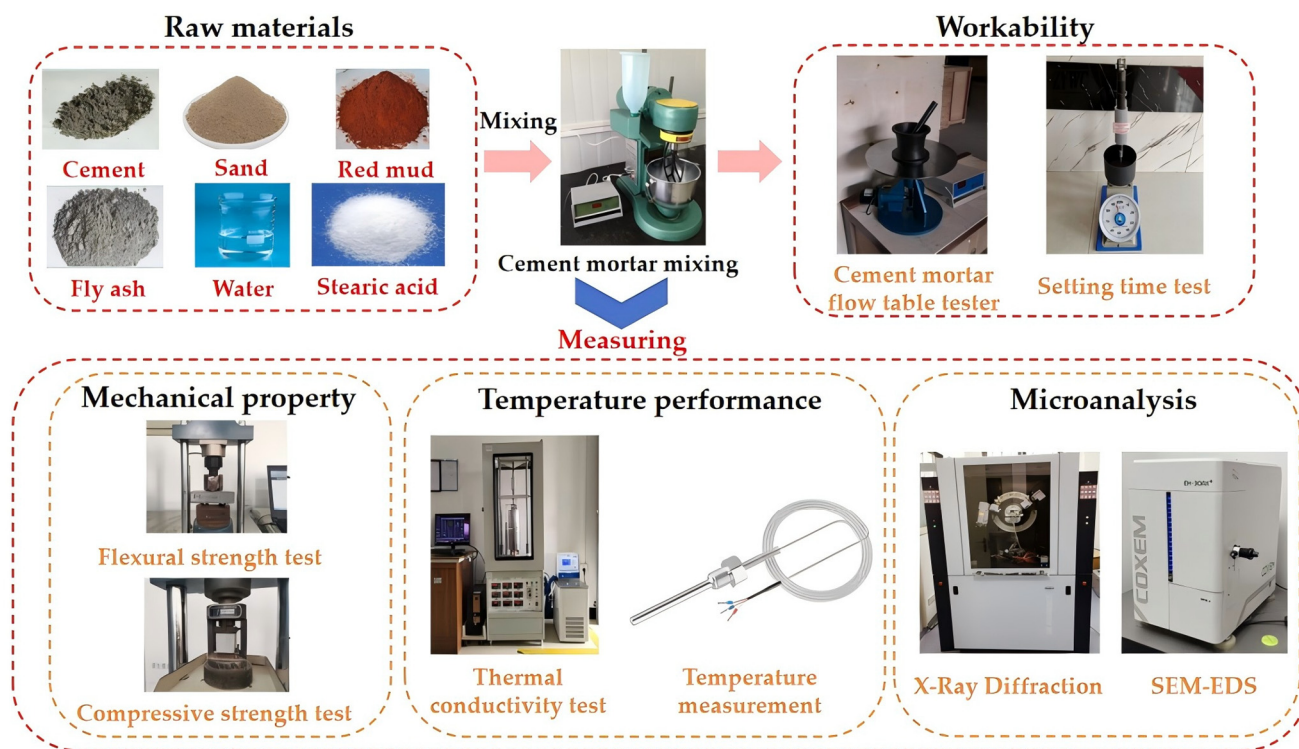


Figure 2. The flowchart of experimental details.

3. Results and Discussion

3.1. The Slump Flow of Fresh Red Mud Unfired Bricks

Figure 3 illustrates the slump flow behavior of unfired bricks incorporating red mud (RM) as a function of RM content and straw fiber dosage. The regression analysis results correlating slump flow with RM mass ratio are detailed in Table 4. As depicted in both Figure 3 and Table 4, the slump flow exhibits a cubic increase with rising RM content, with coefficients of determination (R^2) ranging from 0.99 to 1.00, indicating a highly accurate fit. Specifically, when the RM content is elevated from 5% to 40%, slump flow consistently increases by 0% to 23.7% across all experimental groups. This enhancement is attributed to the ball-bearing effect of the fine red mud particles, which diminishes inter-particle friction and thereby improves the fluidity of the fresh mixture. On one hand, fine RM grains fill particle gaps to optimize grading and release free water; on the other hand, the negative surface charge of alkaline RM produces electrostatic repulsion to weaken particle agglomeration, jointly lowering paste yield stress [34,35]. In contrast, at a constant RM content, the addition of straw fibers negatively impacts workability. As shown in Figure 3, the presence of straw fibers reduces slump flow by up to 12.8%, with the greatest reduction observed at 40% RM content. This decrease is primarily ascribed to the fibers' higher water absorption capacity and the resultant increase in internal friction within the mixture [36,37].

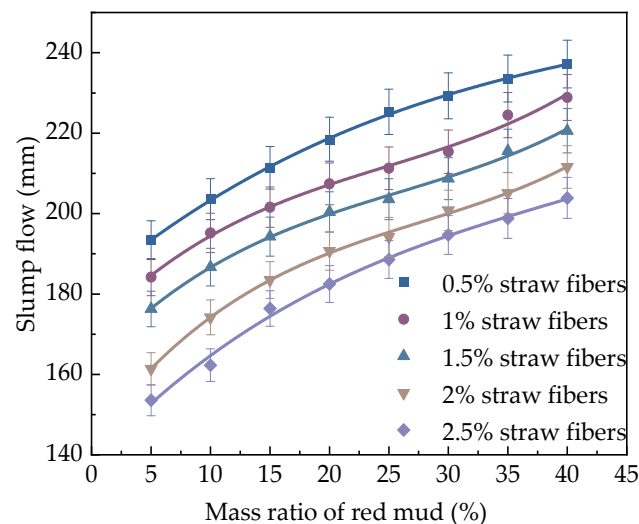


Figure 3. Slump flow of specimens with straw fibers and red mud.

Table 4. The fitting results of slump flow (S) and volume ratio of straw fibers (%).

Equation	Straw Fibers	a	b	c	d	R ²
$S = aM^3 + bM^2 + cM + d$	0.5%	2.20×10^{-4}	−0.036	2.48	181.96	1.00
	1%	1.17×10^{-3}	−0.087	3.07	171.31	0.99
	1.5%	1.12×10^{-3}	−0.087	3.15	162.71	1.00
	2%	1.32×10^{-3}	−0.110	3.97	144.18	1.00
	2.5%	4.69×10^{-4}	−0.057	3.15	138.40	1.00

3.2. The Mechanical Strengths of Red Mud Unfired Bricks

Figure 4 illustrates the mechanical strengths of the specimens as functions of the straw fibers volume fraction and red mud (RM) mass fraction, with the corresponding regression analyses detailed in Table 5. As depicted in Figure 4a, the mechanical strengths across all sample groups exhibit cubic trends in response to increasing RM content, with coefficients of determination (R^2) exceeding 0.80 (Table 5), thereby validating the robustness of the fitted models. At a constant straw fiber content, the mechanical strengths initially increase and subsequently decrease as the RM content rises. Specifically, for low to moderate RM levels ($\leq 20\%$), the strengths demonstrate a steady enhancement with increasing RM dosage. The highest compressive strength recorded was 36.7 MPa at 20% RM combined with 2.5% straw fibers, representing a 32.7% improvement relative to the control mixture. Similarly, the maximum splitting tensile strength of 6.1 MPa was observed under the same compositional conditions. This improvement is ascribed to the synergistic interaction between the physical filling effect of RM and the crack-bridging capability of straw fibers: RM particles contribute to pore structure refinement and increased matrix density, while straw fibers inhibit microcrack propagation, collectively enhancing both compressive and splitting tensile strengths [38–40]. Among the fiber content groups, the 2.5% straw fiber dosage yielded the most pronounced strength enhancement, whereas the 0.5% fiber group exhibited the most consistent performance, likely due to the less disruptive influence on the cementitious matrix at lower fiber concentrations.

Conversely, when the RM content surpasses 20% (notably beyond 25%), both compressive and splitting tensile strengths decline significantly. This degradation is attributed to two primary factors. Firstly, excessive RM content hinders the hydration process of the cementitious matrix, thereby diminishing the formation of calcium silicate hydrate (C-S-H) gel [41–43]. Secondly, higher RM concentrations increase porosity and weaken the interfacial transition zone (ITZ) between RM particles and the surrounding matrix [44–46].

Therefore, the optimal mechanical performance was attained at a composition of 2.5% straw fibers and 20% RM, where the synergistic effects of RM's filling action and fiber-induced crack bridging collectively optimize microstructural refinement and enhance mechanical properties.

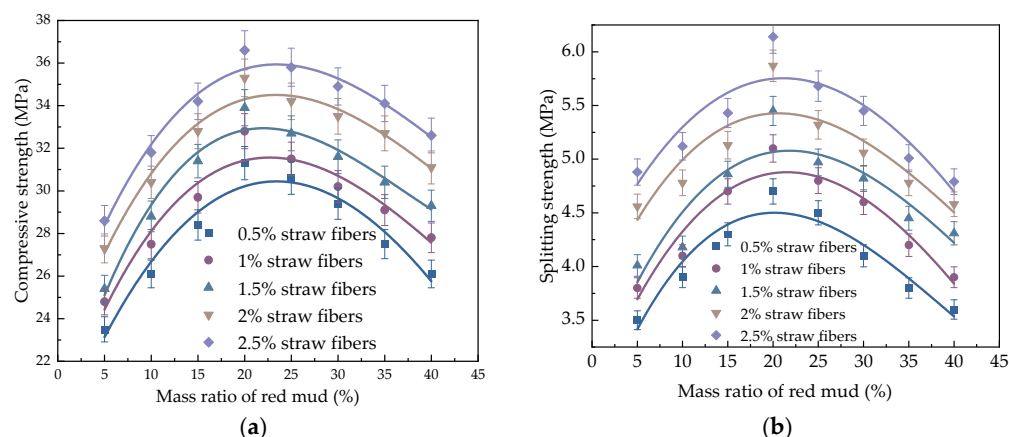


Figure 4. Mechanical strengths of specimens with straw fibers and red mud: (a) compressive strength; (b) splitting strength.

Table 5. The fitting results of mechanical strengths and straw fibers' volume ratio (%).

Equation	Straw Fibers	a	b	c	d	R ²
$f_{cu} = aM^3 + bM^2 + cM + d$	0.5%	1.27×10^{-4}	−0.028	1.11	18.27	0.95
	1%	2.71×10^{-4}	−0.036	1.24	19.11	0.93
	1.5%	4.34×10^{-4}	−0.048	1.50	18.75	0.96
	2%	2.73×10^{-4}	−0.036	1.24	21.73	0.97
	2.5%	2.83×10^{-4}	−0.037	1.26	22.94	0.97
$f_{st} = aM^3 + bM^2 + cM + d$	0.5%	6.46×10^{-5}	−0.0077	0.23	2.5	0.92
	1%	3.64×10^{-5}	−0.0061	0.21	2.79	0.91
	1.5%	4.99×10^{-5}	−0.0068	0.22	2.90	0.80
	2%	4.61×10^{-5}	−0.0062	0.20	3.60	0.86
	2.5%	2.34×10^{-5}	−0.0049	0.18	4.01	0.81

3.3. The Rebound Value of Red Mud Unfired Bricks

Figure 5 illustrates the variation in rebound value of red mud unfired bricks with different dosages of red mud and straw fibers. While Table 6 shows the corresponding fitting functions. The results show that the rebound value of all groups followed cubic functions with the increasing RM ratio. The fitting coefficients of determination (R^2) are 0.91~0.96, confirming the high accuracy of the correlation. At a fixed straw fiber ratio, the rebound value of all groups first increased and then decreased with the rise in RM content. When RM content was less than 20%, the rebound value increased steadily with increasing RM dosage. The highest rebound value of specimens with 20% RM and 2.5% straw fibers reached the maximum value with an increasing rate of 18.7%. Specific analysis is as follows: Moderate RM (<20%) releases active Si/Al and alkali to form compact C-S-H/C-A-H gels via secondary hydration, densifying the matrix and raising surface hardness chemically and physically [47]. Excess RM limits gel production and induces microcracks, reducing rebound performance. Appropriately incorporated straw fibers bridge microcracks to sustain structural integrity under impact loads, further optimizing rebound hardness [48]. Similar mechanical trends have been validated in existing red mud-fiber composite research.

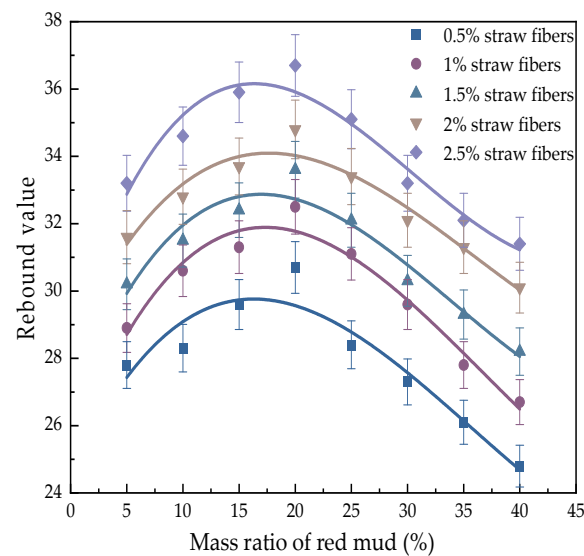


Figure 5. Rebound value of specimens with straw fibers and red mud.

Table 6. The fitting results of rebound value (R) and volume ratio of straw fibers (%).

Equation	Straw Fibers	a	b	c	d	R ²
$R = aM^3 + bM^2 + cM + d$	0.5%	2.62×10^{-4}	−0.028	0.71	24.56	0.91
	1%	2.97×10^{-4}	−0.033	0.87	25.16	0.96
	1.5%	3.27×10^{-4}	−0.033	0.85	26.49	0.93
	2%	2.51×10^{-4}	−0.027	0.72	28.44	0.94
	2.5%	4.77×10^{-4}	−0.043	1.04	28.71	0.94

3.4. The Thermal Conductivity of Red Mud Unfired Bricks

Figure 6 shows the thermal conductivity variation in the specimens with varying volume ratio of straw fibers and red mud (RM) mass ratio. In parallel, as shown in Table 7, the thermal conductivity of all groups follows a cubic function trend with the increasing RM mass ratio. The coefficients of determination (R^2) are at least 0.81, verifying the reliability of the fitting model. The thermal conductivity first increased and then decreased with the rise in RM content. More precisely, when the RM dosage is not higher than 20%, the thermal conductivity is enhanced progressively with increasing RM dosage. Specimens with 20% RM and 0.5% straw fibers reach the peak thermal conductivity. The maximum increasing rate is 27.0%. Moderate RM promotes hydration to generate dense C-S-H gels that reduce isolated pores. Additionally, fewer air voids cut off thermal insulation channels and raise solid-phase heat transfer efficiency [49]. Excessive RM causes loose interfacial pores, and straw fibers introduce stagnant air inside the matrix, both lowering thermal conductivity [50]. This pore structure-dependent heat transfer rule is consistent with previous solid waste brick research.

Table 7. The fitting results of thermal conductivity (λ) and volume ratio of straw fibers (%).

Equation	Straw Fibers	a	b	c	d	R ²
$\lambda = aM^3 + bM^2 + cM + d$	0.5%	1.01×10^{-6}	4.23×10^{-4}	0.019	0.89	0.90
	1%	9.49×10^{-6}	1.05×10^{-3}	0.032	0.78	0.89
	1.5%	3.23×10^{-6}	7.13×10^{-4}	0.027	0.74	0.96
	2%	3.43×10^{-6}	6.96×10^{-4}	0.025	0.71	0.92
	2.5%	-7.27×10^{-6}	3.38×10^{-5}	0.011	0.73	0.79

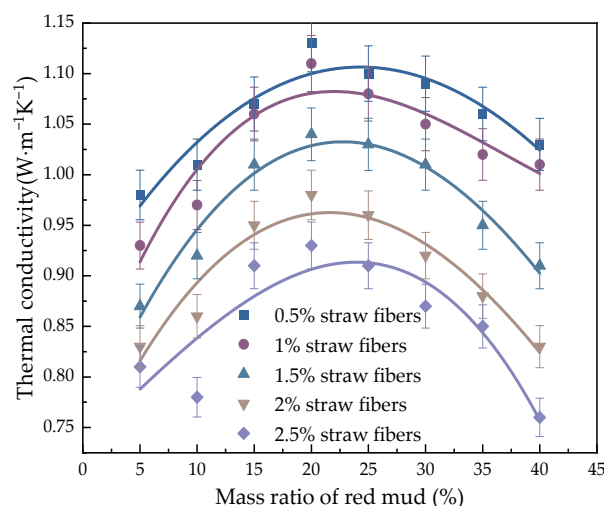


Figure 6. Thermal conductivity of specimens with straw fibers and red mud.

3.5. The Influence of Stearic Acid

Stearic acid is cost-effective and readily available, with good compatibility of mineral lightweight admixtures when incorporated into cement-based thermal regulation blocks, outperforming other fatty acids without deteriorating block-forming performance. Rather than regulating cement hydration, stearic acid acts as a phase-change medium for thermal buffering. It melts and absorbs excess heat in summer to slow indoor temperature rise, and crystallizes to release stored latent heat in winter to prevent rapid indoor cooling, realizing thermal insulation. Moreover, adsorbed stearic acid forms hydrophobic films on pore walls to refine pore structure and lower thermal conductivity, further reducing indoor-outdoor heat exchange and improving the thermal stability and durability of the blocks. Figure 7 illustrates the relationship between the compressive and splitting tensile strengths of the specimens and the dosage of stearic acid (SA). Both mechanical properties exhibit a decreasing trend that follows cubic functions as the SA content increases, with coefficients of determination (R^2) equal to 1.00, indicating a highly precise fit of the data to the proposed models. Specifically, when the SA mass ratio is elevated from 0% to 20%, the compressive strength declines progressively by 0% to 15.6%, while the splitting tensile strength similarly decreases by 0% to 19.7%. This reduction in strength is attributed to the hydrophobic characteristics of stearic acid. The addition of SA results in the formation of a weak hydrophobic film on the surface of the cementitious matrix, which hinders the hydration process of cement and diminishes the interfacial bonding between the aggregates and the matrix. Consequently, these effects lead to a decrease in both compressive and splitting tensile strengths [51–53].

Figure 8 illustrates the relationship between rebound value and the dosage of stearic acid (SA). The rebound value exhibits a cubic decline as the SA content increases, with a coefficient of determination (R^2) equal to 1.00, indicating an exceptionally precise fit of the model. Specifically, when the mass ratio of SA rises from 0% to 20%, the rebound value decreases progressively by up to 15.5%. This decline is attributed to the interaction between stearic acid and free calcium ions (Ca^{2+}) during the cement hydration process, resulting in the formation of insoluble calcium stearate. The generated hydration products hinder the normal hydration of cement and create a hydrophobic film on the surfaces of particles, thereby compromising the microstructure near the surface and leading to a reduction in the rebound value [54,55].

Figure 9 illustrates the relationship between the thermal conductivity of the specimens and the dosage of stearic acid (SA). The thermal conductivity exhibits a cubic decline as the SA content increases, with a coefficient of determination (R^2) equal to 1.00, indicating a highly

precise fit of the model. Specifically, when the mass ratio of SA increases from 0% to 20%, the thermal conductivity decreases progressively by 0% to 23.7%. This decrease is primarily attributed to the hydrophobic characteristics of stearic acid. Functioning as a surfactant, SA forms a hydrophobic layer on the surface of cementitious particles, which inhibits the hydration process and leads to increased porosity. The presence of air voids with low thermal conductivity consequently diminishes the compactness of the matrix and reduces heat transfer efficiency, thereby resulting in a continuous reduction in thermal conductivity [56–58].

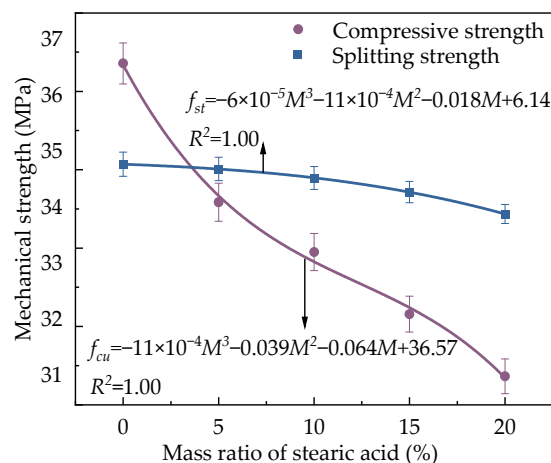


Figure 7. Mechanical strength of specimens with stearic acid.

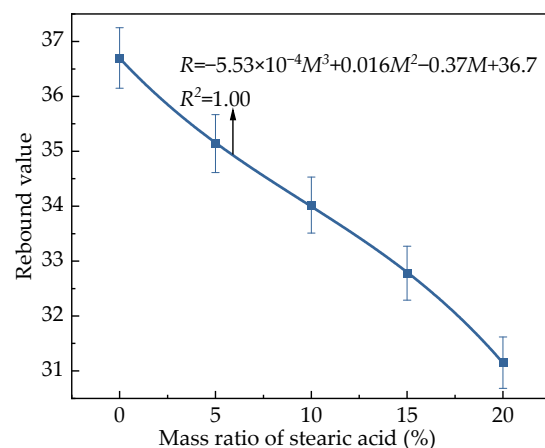


Figure 8. Rebound value of specimens with stearic acid.

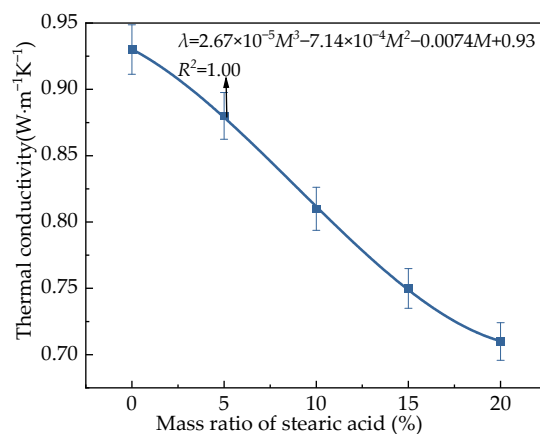


Figure 9. Thermal conductivity of specimens with stearic acid.

The overall performance of unfired bricks is governed by the coupled chemical reactions among ordinary Portland cement (OPC), fly ash (FA), red mud (RM), and stearic acid (SA). The hydration of OPC generates $\text{Ca}(\text{OH})_2$, which activates the pozzolanic phases present in FA and RM. The inherent alkalinity of RM accelerates secondary hydration, promoting the formation of dense C-S-H and C-A-H gels; an RM content of 20% yields the densest matrix, whereas further RM addition leads to calcium deficiency, insufficient gel products, and widespread microcracking [47]. SA undergoes esterification with hydration products to form hydrophobic films on pore walls, thereby reducing water absorption. However, excessive SA encapsulates solid particles and retards hydration, while an appropriate SA dosage converts interconnected pores into closed voids, thus lowering thermal conductivity [49].

Cubic polynomial functions were employed to model the relationship between performance indicators and red mud content, as depicted in Figures 3–9, for two primary reasons. Firstly, certain properties—such as slump flow, rebound hardness, and thermal conductivity—exhibit a non-linear trend characterized by an initial increase to a peak followed by a subsequent decline, a pattern that cannot be accurately captured by linear or quadratic models. Secondly, the coefficients of the cubic polynomial possess meaningful physical interpretations linked to intertwined internal physicochemical mechanisms: the linear coefficient represents the advantageous effects of lubrication and densification occurring at low red mud concentrations; the quadratic coefficient accounts for the deterioration in properties due to calcium deficiency at higher red mud levels; the cubic coefficient reflects further negative influences arising from the presence of entangled straw fibers and increased porosity; and the constant term denotes the baseline performance corresponding to the control samples [59,60].

3.6. The Temperature Measurement

The temperature of the wall made of red mud non-fired bricks in the simulation room is shown in Figure 10. As observed in Figure 10, the temperature increases with the heating time. The increasing rate of temperature becomes slower with the increasing dosage of phase change materials. Moreover, when the heating stopped, the temperature remained at the temperature of 16.67°C – 18.03°C for 17.26°C – 18.82°C . The increasing mass ratio of phase change material can extend the time for flat temperature. Meanwhile, the phase change material delays the rate of temperature drop. Phase change materials (PCMs) absorb latent heat through a solid–liquid phase transition during heating, thereby suppressing temperature rise; during cooling, the stored latent heat is released to maintain a stable wall temperature and retard heat loss [61]. A higher PCM content provides greater latent heat storage capacity, prolonging the constant-temperature plateau and mitigating temperature fluctuations, which is consistent with the thermal regulation mechanism of PCM-incorporated building walls reported in previous studies.

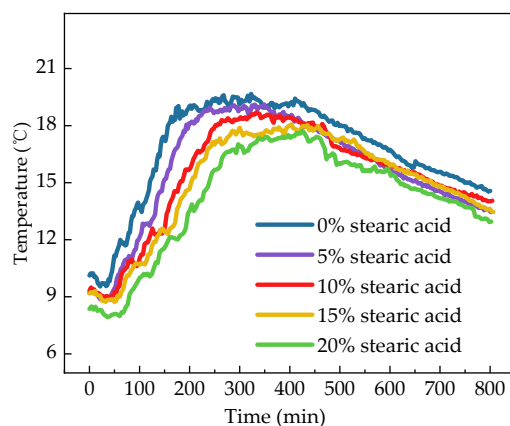


Figure 10. The temperature of a wall made of red mud non-fired bricks in the simulation room.

3.7. The Microscopic Analysis Results

Figure 11 presents the SEM micrographs of red mud unfired bricks incorporating 5 wt.%, 20 wt.%, and 40 wt.% red mud, and all images were captured at a magnification of 10,000 times. Flocculent calcium silicate hydrate (C–S–H) and calcium aluminosilicate hydrate (C–A–S–H) gels constitute the dominant binding phase in all samples. The matrix of the 5% red mud specimen exhibits abundant microcracks. As the red mud content increases from 5% to 20%, the microcracks diminish markedly while the dense hydration gel phases become more prevalent, a consequence of the enhanced pozzolanic reaction of red mud that effectively fills micro-defects. Upon further increasing the red mud dosage to 40%, a slight reduction in microcracks is observed; however, excess unreacted red mud particles disrupt the continuity of the gel network [62,63]. Accordingly, the specimens containing 20% red mud develop the densest microstructure and optimal mechanical properties, which is consistent with existing microstructural investigations of red mud-based building materials.

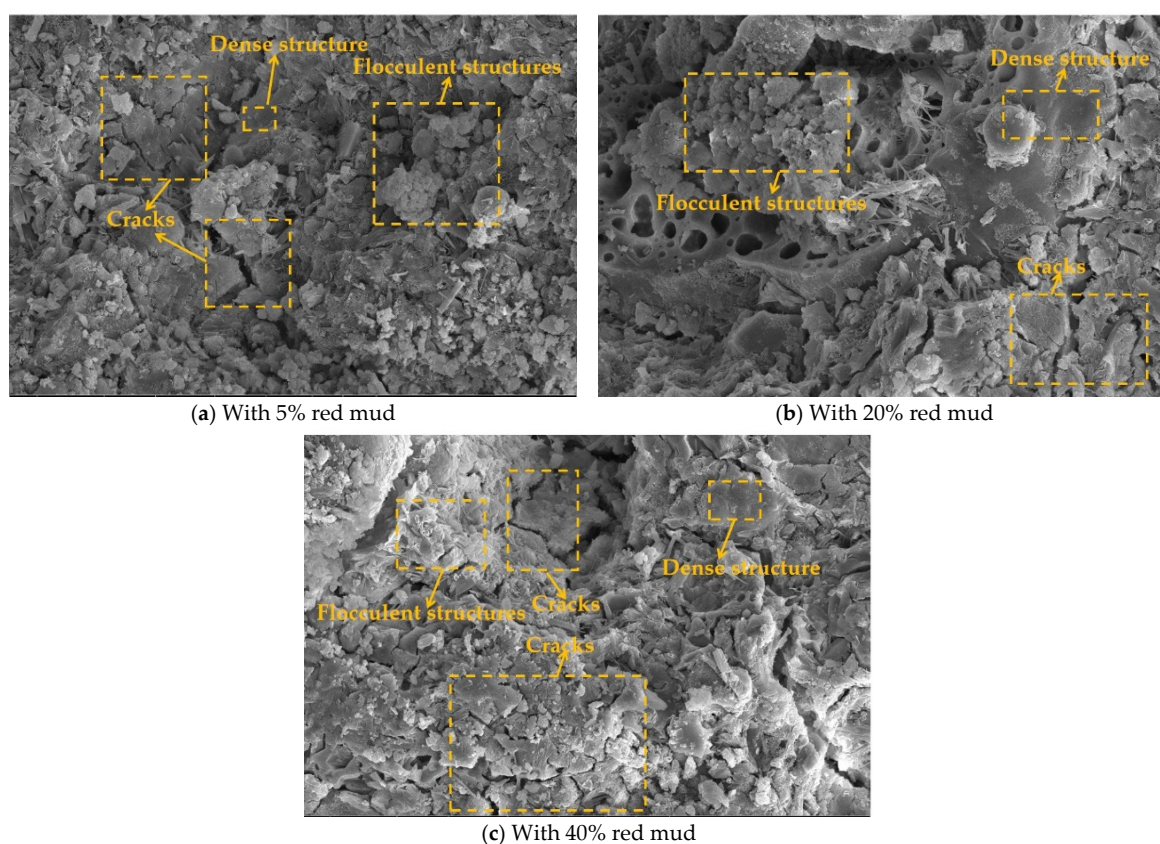


Figure 11. The SEM photos of red mud unfired brick.

The X-ray diffraction curves are shown in Figure 12. As depicted in this Figure, the crystals of dolomite and ettringite (AFt) are mainly observed. Meanwhile, minor phases including the crystals of dicalcium silicate (C_2S) and calcium carbonate ($CaCO_3$) exist. This affirms that the sulfoaluminate cement mortar is composed of unhydrated materials (C_2S) and hydrated products (AFt, $CaCO_3$, Dolomite). The added red mud demonstrates an increasing effect on the crystals of AFt, $CaCO_3$, and dolomite. Meanwhile, the crystals of C_2S are decreased. This confirms that the red mud at a dosage of 20% can improve the hydration process of C_2S and dolomite, thus increasing the hydration products of AFt, $CaCO_3$, and dolomite. However, when the mass ratio of red mud is 40%, the crystals of dolomite are decreased, ensuring that the red mud with a mass ratio of 40% can decrease the hydration products of AFt, $CaCO_3$, and dolomite.

Figure 13 reflects the matrix compactness and pore characteristics with different red mud (RM) and 1.5% straw fibers. At 5% RM, moderately active phases form dense hydration products wrapping straw fibers, with limited connected pores and low porosity. Specimens with 20% RM show the densest matrix and minimal isolated micropores, as sufficient alkali-activated gels optimize interfacial bonding between fibers and binder, corresponding to the lowest porosity and optimal macro performance. For 40% RM, calcium shortage suppresses pozzolanic reactions; prominent cracks and large pores appear around fibers, drastically raising porosity and deteriorating mechanical and thermal properties. The observed pore evolution directly interprets the nonlinear performance variation with RM.

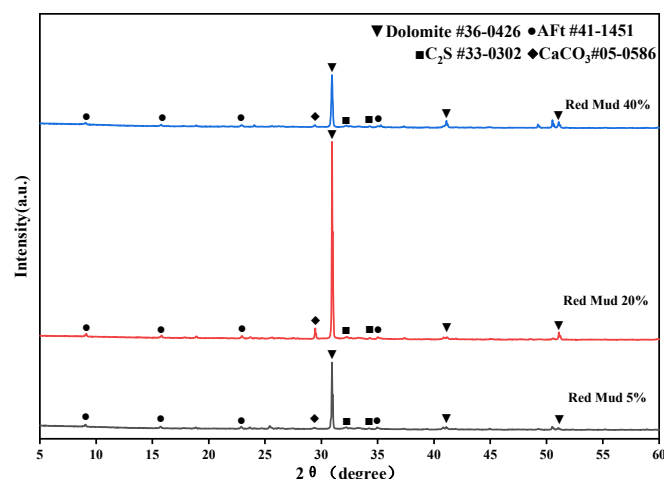


Figure 12. The XRD photos of red mud unfired brick.

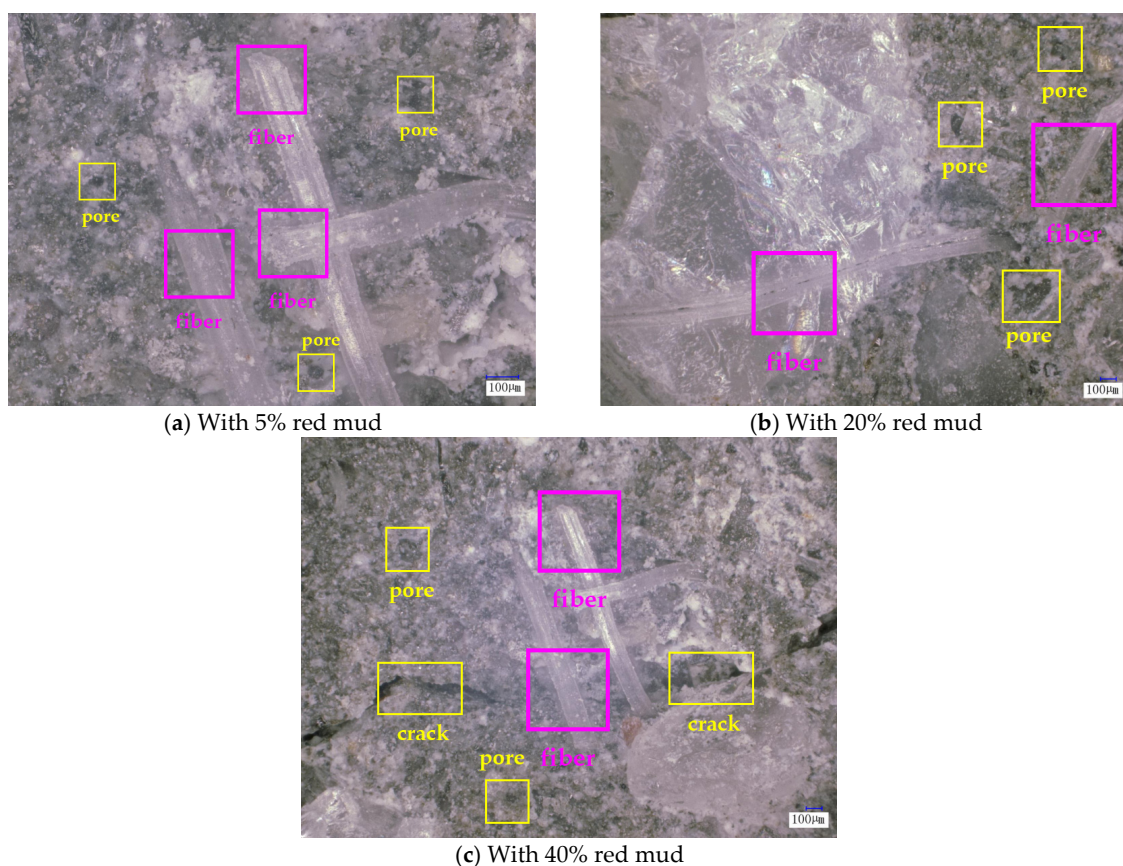


Figure 13. The section scanning diagram of red mud unfired brick.

4. Conclusions

After systematically studying a series of properties of unburned red mud bricks, the conclusions are obtained as follows.

The slump flow of unfired bricks exhibits positively correlated cubic functions with the mass ratio of red mud. The corresponding initial setting time and the mechanical strengths vary as cubic functions with the red mud's mass ratio. The unfired bricks' mechanical strengths reach their highest when the mass ratio is 20%. The red mud increases the compressive strength, the splitting strength and the rebound of unfired bricks by rates of 28.1%, 29.2% and 15.9%.

The compressive strength, the splitting strength and the rebound of the unfired bricks are increased by rates of 32.7%, 32.6% and 18.7% with the addition of straw fibers. The compressive strength, the splitting strength, the rebound and the thermal conductivity decrease in the form of cubic functions with the mass ratio of stearic acid. The corresponding decreasing rates are 15.6%, 19.7%, 15.5% and 23.7%.

The SEM results show that the cracks decrease with the increase in red mud content from 5% to 20%. However, as the amount of red mud increases from 20% to 40%, the cracks inside the hydration products decrease. Therefore, the specimen with 20% red mud content showed the highest mechanical properties.

The crystals of dicalcium silicate (C_2S), ettringite (Aft), calcium carbonate ($CaCO_3$), and dolomite are found in the specimens. The addition of red mud can increase the crystals of dolomite and decrease the corresponding C_2S .

Increasing stearic acid dosage slows the temperature rise in red mud unfired brick walls, prolongs their temperature plateau interval at 16.67–18.03 °C after heating termination, and suppresses the subsequent cooling rate, demonstrating favorable thermal regulation capacity.

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