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Preparation Method and Benefit Analysis for Unburned Brick Using Construction Solid Waste from Residue Soil

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Abstract: Highly efficient resource utilization of construction solid waste has significant environmental and socioeconomic benefits. In this study, a fabrication method and process optimization of unburned brick from construction residue soil were investigated based on experiments. The effects of cementing the material content, the raw material treatment process, the brick moisture content, and the molding method on the compressive strength of unburned brick were studied and discussed. The experimental results show that 5–20% of ordinary cement can produce a strength grade of 5 MPa–20 MPa for unburned brick, and the utilization rate of the residue soil is greater than 80%. In the case of well-dispersed residual particles, complete drying and rolling are not necessary, and soil particle size within 5 mm is beneficial for obtaining proper sand grading and low mud content, which will improve the strength of unburned brick. The pressure for the press forming of unburned brick should be 10 MPa, and the optimal moisture content of the residue-soil mixture is about 13%. The proposed residue-soil unburned brick has remarkable environmental and economic benefits with low carbon emissions, low cost, and high profit. The methods proposed and optimized in this study can provide important technical support for realizing the large-scale production of residue-soil unburned brick.

Keywords: construction residue soil; unburned brick; raw material process; molding method; moisture content

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1. Introduction

With the continuous advancement of urbanization and the ongoing improvement of infrastructure construction, such as the construction of subways and the excavation of underground integrated pipeline corridors, the volume of construction residue soil is increasing significantly [1]. At present, the method for dealing with the huge volume of construction residue soil is mainly to transport it to landfill sites. Only a small portion of this residue soil is used for site backfilling. However, the capacity of residue-soil landfill sites is limited, and improper stacking may lead to major engineering safety accidents [2]. Most landfills occupy land, which not only causes adverse effects or even damage to the environment and resources but also causes safety hazards, such as landslides. Transporting residue soil to landfills causes serious problems, such as high cost and energy consumption and damage to urban roads, affecting the appearance of the city. Therefore, resource utilization of residue soil, especially on-site resource utilization, is the best way to solve the problem of residue soil and has important economic, environmental, and social benefits.

Currently, methods for the resource utilization of construction residue soil include site backfill, subgrade filler, sintered ceramics [3], sintered bricks [4,5], and unburned bricks [6–10]. Although a significant amount of residue soil is generated at construction sites, the quantity that can be effectively utilized for backfill and subgrade fill is very limited. Sintered bricks and sintered ceramics have the disadvantages of high energy consumption and substantial carbon emissions [11,12]. Fired clay bricks have been banned in many

places in China. By contrast, unburned bricks offer a promising solution for solidifying residue soil using inorganic cementing materials. Making unburned brick is the residue-soil resource utilization method with the most potential, characterized by low costs (details in Section 7.2), small equipment area, and the convenience of on-site production. Furthermore, the residue-soil utilization rate of unburned brick is extremely high.

At present, green building materials and technologies have been extensively and deeply studied [13–15]. However, research on the resource utilization of residue soil is in its initial stages. The existing research focuses on the material mix proportions. Mostly, the mineral compositions of soil waste are inactive. However, the addition of cementitious materials can make them achieve adequate curing strength to meet the requirements of service performance. By this means, all waste soil, such as red mud [6–8], fly ash [8–10], tailings [10,16], clay [17,18], slag [9,19], silt from river dredging [20], sediments from reservoirs and ports [21], bottom ash and dust from thermal power plants [22], solid waste from building construction [17], industrial production [9], etc., can be recycled and used for construction of infrastructure. Obviously, there are various types of soil waste that come from different sources, with diverse mineral compositions and different physicochemical properties. Therefore, the determination of cementitious materials is very important and complicated. Portland cement-based materials are the most widely used cementitious materials for unburned bricks [17,20,22]. Portland cement has many advantages, such as good performance. However, the production of cement results in larger CO_2 emissions. Environment-friendly materials from soil waste, such as geopolymers, are encouraged to be used for unburned brick [16]. In order to obtain the optimal material compounding, additive materials, such as gypsum, lime, magnesium oxide, slag, and coal fly ash, are usually used to improve performance and reduce the cost of unburned brick from construction soil waste [17,20]. Uchida et al. [23] studied an unburned brick formula for unburned MgO-C bricks with added aluminum powder and silicon powder.

Besides the mixture material components and proportions, fabrication techniques such as molding and curing methods also significantly influence the strength and other performance factors of unburned brick. The unconsolidated mixture (residue soil, cementitious material, and moisture) should be compacted under a certain pressure load [8,10,18]. The curing method for unburned brick highly depends on the cementitious materials. For unburned brick from cement-based material, natural curing, water curing, steam curing, and autoclaved curing are commonly used methods [8,10,18]. Wang et al. [20] discussed the production process and curing methods for unburned brick and emphasized a substantial impact on the performance of the brick, highlighting the importance of optimizing the production process and curing methods for unburned brick production. Nong et al. [24] investigated the influence of mud in residue soil on the compressive strength of unburned brick. In general, the technology of residue-soil unburned brick is still in the stage of experimentation and exploration. Large-scale, standardized, and industrialized construction–residue-soil production lines for unburned brick are few at present [25]. Therefore, exploring the material composition and production processes suitable for actual production needs, thereby improving production efficiency and reducing costs, is of great importance to the practical application of residue-soil unburned brick technology.

This study carried out research on the resource utilization technology for construction solid waste from residue soil and proposed a method to transform the residue soil into unburned bricks, thereby effectively turning residue-soil waste into valuable resources and products. In this paper, the material formula for residue-soil unburned bricks is examined using a single-factor research method with compressive strength as the index. To obtain an optimal formula that meets the strength requirements while being cost-effective, a preparation method for unburned brick from the four aspects of the cementing material content, the residue-soil raw material treatment process, the molding method, and the moisture content was studied experimentally, subsequently optimizing the production process. This study also explores the influence of residue soil on the compressive strength of unburned bricks and identifies key factors influencing their strength. At last, the environmental and

economic benefits of the proposed unburned brick are analyzed and discussed. This study can provide important technical references and practical suggestions for the production of residue-soil unburned bricks and will promote the large-scale production of residue-soil unburned brick and its further promotion application.

2. Materials and Methods

2.1. Materials

Residue-soil unburned brick is a commonly used construction product. It is obtained by solidifying residue soil using appropriate inorganic cementing materials, which can meet the performance requirements for engineering applications. The materials required for producing residue soil from unburned bricks mainly include construction residue soil, cementing materials, and water.

(1) Construction residue soil

The construction residue soil used in this study was obtained from the excavation of a large transportation hub project in South China. The type of this residue soil is silty clay found in alluvial soil layers. According to the geological survey report, the average values for the main physical and mechanical properties of the geotechnical tests are as follows: w = 29.3%; e = 0.867; IL = 0.48; a1–2 = 0.40 MPa^{-1}; Es1–2 = 4.75 MPa. In these indicators, w represents the soil's moisture content, e is the porosity ratio of the soil, IL signifies the liquid index of the soil, a1–2 denotes the compression coefficient of the soil, and Es1–2 represents the compression modulus of the soil. The main physicochemical parameters of the residue soil were tested and analyzed. The chemical composition of the residue soil was obtained by the XRF test technique, which is presented in Table 1. The primary components of the residue soil are SiO_2 and Al_2O_3, accounting for over 85% of the mass of the soil sample. The ignition loss of the residue soil is 5.42%, indicating material stability.

Table 1. Chemical compositions of the construction residue soil (%).

SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	MgO	Other	Loss of Ignition
71.87	16.82	1.77	0.01	3.42	0.06	0.63	5.42

SiO_2 exists widely in nature, is one of the main components of rocks, and is also the main component of silicate minerals, such as granite and quartz. Al_2O_3 is an important inorganic compound with high hardness, high wear resistance, high fire resistance, high electrical insulation, and high chemical stability. Many minerals in nature contain Al_2O_3, such as kaolin. Fe_2O_3 is a common iron oxide that exists widely in nature; it is one of the main components of iron ore. K_2O is a white solid, has a strong hygroscopic, and can react with water to produce potassium hydroxide. Natural potassium minerals are illite, muscovite, and potassium feldspar. Oxides of calcium and magnesium are widely distributed in nature and are important mineral components. Calcium and magnesium carbonate minerals are also widely distributed in nature.

The construction residue soil was sampled, and XRD (X-ray diffraction) analysis was conducted to determine its mineral composition. X'pert Powder produced by PANalytical was used for XRD testing. As shown in Figures 1 and 2, the mineral composition was mainly quartz stone, accounting for 55.8%, followed by 21.7% of kaolinite and 22.5% of illite. Through analysis, there is no chemical reaction in the soil with the cement [26,27]. Furthermore, the test results of the residue-soil mud content (particle content with sizes less than 0.075 mm) and sand particle size distribution of the project are presented in Table 2. The mud content is 35%, and the sand gradation is in Zone 3 according to the national standard of the People's Republic of China (PRC) GBT14684-2022 [28]. The preliminary investigation and analysis show that the residue soil of this project is typical in South China and suitable for unburned brick fabrication.

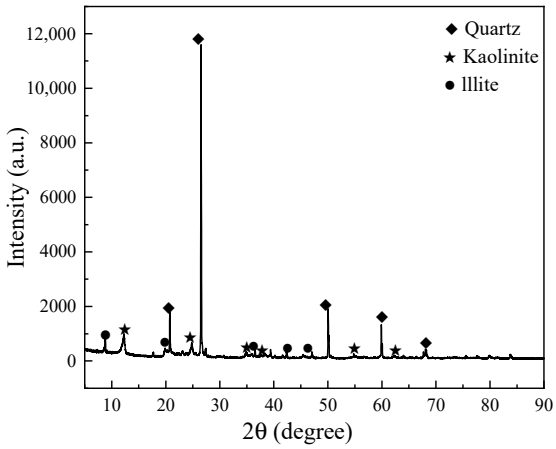


Figure 1. XRD testing results.

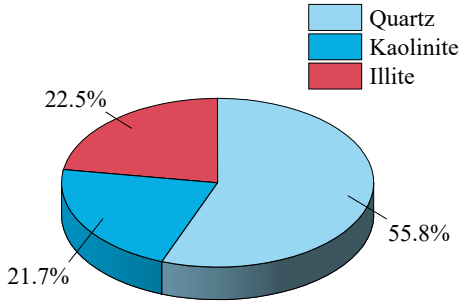


Figure 2. Mineral composition.

Table 2. Particle size (mm) distribution and mud content (%) of construction residue soil.

Particle Size	2–0.18	1.18–0.6	0.6–0.3	0.3–0.15	0.15–0.075	Mud Content
Mass ratio	4	13	26	13	9	35

(2) Cementing material

To facilitate practical engineering applications and reduce the complexity and cost of material ratios, ordinary cement is used as the cementing material. In this study, ordinary Portland cement with a strength grade of 42.5, labeled as P·O 42.5, produced by Guangzhou Shijing Cement Company, was used for the fabrication of residue-soil unburned bricks.

(3) Water

Ordinary tap water was used for unburned brick making in this experiment.

2.2. Method of Making Unburned Brick

The production process of residue-soil unburned bricks is mainly divided into three stages: raw material process, unburned brick production, and unburned brick curing. The manufacturing process of residue-soil unburned brick is illustrated in Figure 3.

(1) Raw material treatment process of residue soil

The residue soil raw material treatment process is shown in Figure 4. First, the air-dried residue soil is placed into a rotary dryer to dry until the moisture content is less than 1%. Next, the dried residue soil is milled using a wheel mill. Then, the ground residue soil is sieved using a sieve shaker with a 2 mm sieve. The residue soil with a particle size less than 2 mm is sifted out for unburned brick making.

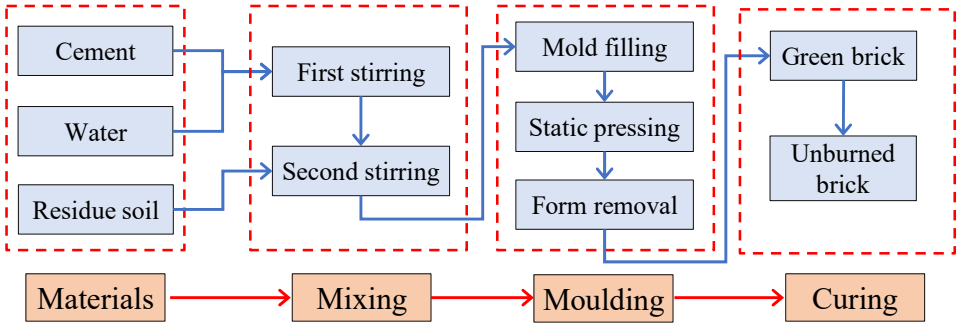


Figure 3. Production process of the residue-soil unburned brick.

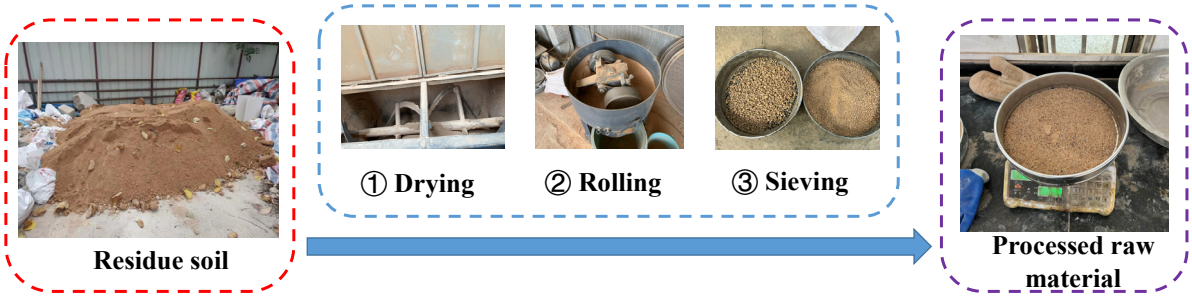


Figure 4. Processing of the residue soil.

(2) Mixing of residue-soil composite

All the materials, such as cementitious material, residue soil, and water, are weighed according to the material ratio designed in the experiment. Using the method of wet mixing, including two steps, water and cementitious material are first put into a mixer for 1 min of stirring, and then the residue soil is added while stirring for 3 min.

(3) Molding of unburned brick using the press-forming method

The mixed material is loaded into the self-made mold, and the hydraulic jack is used for static pressing and molding brick. After releasing the pressure and removing the mold, standard residue-soil unburned bricks with dimensions of 240 mm × 115 mm × 53 mm are obtained.

(4) Curing of unburned brick

The pressed bricks were put into the curing box. The curing box is an ordinary wooden cabinet made of wood templates and covered with plastic film. After the green, unburned bricks are placed in the curing box, they are watered and cured for the first three days and then allowed to cure naturally for a total of 14 days. After curing, the residue-soil unburned bricks are suitable for testing of strength and other performances.

2.3. Test Method for Compressive Strength of Unburned Brick

The compressive strength test was carried out according to the PRC National Standard GB/T2542-2012, test methods for wall bricks [29]. The test process is shown in Figure 5. The compressive test was conducted on the WA-600kE electro-hydraulic servo test machine in the Laboratory of Civil Engineering Materials at South China University of Technology. The specific method involves cutting the brick into two halves and overlapping the two halves with their cut openings facing opposite directions. The length of the overlapping part should not be less than 100 mm. The brick is then placed flat in the center of the pressing plate, perpendicular to the pressing surface, and loaded at a speed of 2–6 kN/s

until failure occurs. The failure load of the brick is recorded, and the compressive strength is calculated. The calculation formula for compressive strength is as follows:

$$R_p = \frac{P}{L \times B} \quad (1)$$

where R_p represents the compressive strength (MPa); P is the maximum failure load (N); and L and B denote the length and width (mm) of the compression surface (superimposed surface) of the brick.



Figure 5. Compressive strength testing process of the unburned brick.

3. Experiment of Cementing Material Content

3.1. Experimental Program

Under the static pressing method at 10 MPa, the effects of different amounts of cementing materials (5%, 10%, 15%, and 20%) on compressive strength were comparatively studied. The experimental design parameters of the mix proportions are presented in Table 3. Five specimens were prepared for each experimental group, resulting in a total of 20 specimens being made.

Table 3. Mix proportions of the materials for unburned brick fabrication (%).

Specimen	Cement	Residue Soil	Moisture Content
P1-J5	5	95	15
P1-J10	10	90	15
P1-J15	15	85	15
P1-J20	20	80	15

3.2. Experimental Results and Discussion

In this experiment, the manufacturing methods described in Section 2 were used to produce unburned brick with different cementing material content. Natural curing was conducted for 14 days, after which the compressive strength of the bricks was tested.

The relationship between the amount of cementing material in construction residue-soil unburned bricks and the compressive strength of unburned bricks is depicted in Figure 6. The ratio of cementing material plays a crucial role in determining the compressive strength of unburned bricks and is a key factor in establishing their compressive strength grade. A positive correlation is observed between the amount of cementing material and the compressive strength of unburned bricks. Greater use of cementing material results in higher compressive strength. This is because the hydration reaction products increase with the increase of cementing material content, leading to improved bonding with the residue soil. When using the 10 MPa static pressing method, unburned bricks with 5%, 10%, 15%, and 20% cement as the cementing material can meet the compressive strength grade requirements of MU5, MU10, MU15, and MU20, respectively. The utilization rate of residue soil is remarkably high, ranging from 80% to 95%.

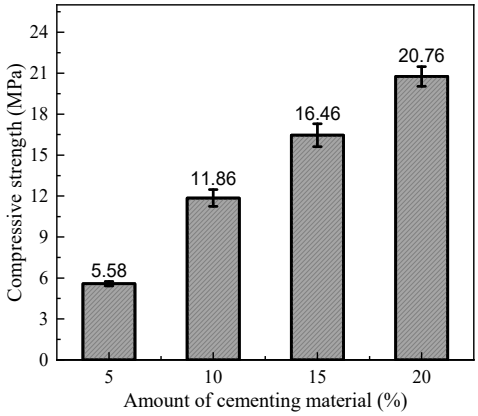


Figure 6. Effect of the cementing material content on the compressive strength.

According to China specification JG/T575-2020 Non-sintered regenerated product of construction waste [30], four grades of compressive strength of unburned brick are defined as MU5, MU10, MU15, and MU20. For instance, MU10 indicates that the average compressive strength of the brick is not less than 10 MPa.

4. Process Method of the Raw Material of Residue Soil

4.1. Experimental Program

The two main control parameters for the residue-soil treatment process are the particle size and moisture content of the residue soil. To meet experimental requirements and obtain smaller residue-soil particles while accurately controlling the molding moisture content, drying and grinding the residue soil are necessary. However, such fine processing may not be feasible or necessary in practical engineering applications. The residue-soil treatment process was therefore optimized to simplify the residue-soil treatment process, reduce energy consumption and cost, and enhance its suitability for on-site production. In addition to achieving these objectives, the factors affecting the compressive strength of residue-soil unburned bricks were also explored. On the basis of the raw material treatment process described in Section 2 (Figure 4), three optimized processes are proposed. The study of bricks with different process methods also helps in understanding the influencing factors of brick compressive strength. The four types of residue-soil treatment processes are as follows:

(1) Process method 1 (PM-1)

This process method for residue-soil raw material has been described in Section 2.2, and the treatment process is shown in Figure 4. The raw residue soil is processed in order as follows: natural drying, mechanical drying, mechanical grinding, and screening through sieve size of 2 mm.

(2) Process method 2 (PM-2)

This method includes process steps of drying and 2 mm sieve size screening, as the same as the process method PM-1. However, the grinding process for the residue soil is eliminated, improving residue-soil treatment efficiency and reducing cost.

(3) Process method 3 (PM-3)

Drying and 5 mm sieve size screening. On the basis of process method PM-2, the particle size screening is extended to 5 mm, increasing the residue-soil utilization rate, adjusting the particle size distribution of residue soil, and further enhancing residue-soil treatment efficiency.

(4) Process method 4 (PM-4)

Natural air drying and 5 mm sieve size screening. On the basis of process method PM-3, natural air drying is used instead of mechanical drying. While ensuring the performance

and production feasibility of unburned brick, the maximum moisture content in the residue soil was studied. This approach reduces the operation time required for residue-soil drying equipment and saves external watering during residue-soil mixing. These lead to reduced energy consumption, improved production efficiency, and cost savings. The moisture content of the residue soil is gradually increased, ensuring that it remains below 9% to maintain the dispersion of the residue soil during the mixing process.

The particle size distribution and mud content of the residue soil obtained by these four treatment processes are shown in Table 4. The residue soil treated by PM-4 has the lowest mud content, and the particle size distribution of sand is wider.

Table 4. Particle size distribution and mud content of the processed residue soils (%).

Process Method	The Range of Residue-Soil Particle Size (mm)						Mud
	4.75–2.36	2.36–1.18	1.18–0.6	0.6–0.3	0.3–0.15	0.15–0.075	≤0.075
PM-1	-	4	13	26	13	9	35
PM-2	-	5	16	27	11	8	33
PM-3	5	7	14	26	12	8	28
PM-4	5	8	16	24	11	9	27

4.2. Experimental Results and Discussion

The unburned bricks were produced using the residue-soil material obtained from the four treatment processes described earlier. A mass ratio of 10% cement was used as the cementing material, and 10 MPa was utilized for press forming of the unburned brick. Five specimens were prepared for each set of conditions, resulting in a total of 20 brick specimens. The specimens were initially cured by watering and covering with a film coating for 3 days, followed by natural curing for up to 14 days. Then, the compressive strength of unburned brick was measured. The compressive strength test results of unburned bricks made of residue soil by different material treatment processes are shown in Figure 7.

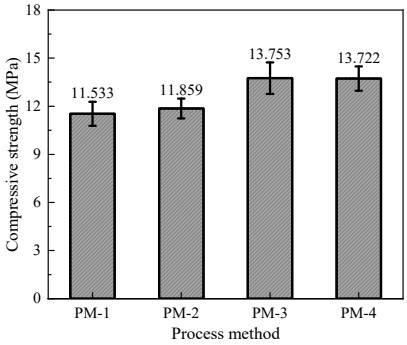


Figure 7. Compressive strength of unburned brick with different material-processing methods.

The results indicate that the compressive strength of the unburned bricks is improved by the three optimized processes. Compared to the original process method PM-1, the strength of PM-2 increased from 11.533 MPa to 11.859 MPa, a relative increase of 2.83%. Likewise, compared with PM-1, the strength of PM-3 increased from 11.533 MPa to 13.753 MPa, resulting in a relative increase of 19.25%. Finally, compared to PM-1, the strength of PM-4 increased from 11.533 MPa to 13.722 MPa, demonstrating a relative increase of 18.98%.

In comparison with PM-1, PM-2 reduces the content of fine particles in the treated residue soil by eliminating the rolling step. An increase in fine particles weakens the strength of unburned brick; reducing the content of fine particles can thus improve the compressive strength of unburned brick. By contrast, PM-3, compared with PM-1, significantly enhances the compressive strength of residue-soil unburned bricks by increasing the sifting particle size to 5 mm. This is due to the substantial influence of particle composition, particle size distribution, and mud content of the residue soil on the strength of residue-

soil unburned brick. Construction residue soil can be divided into two parts: reclaimed sand (particle size 0.075–4.75 mm) and mud material (particle size below 0.075 mm). The gradation of reclaimed sand can be evaluated according to the gradation area outlined in PRC national standard GB/T14684-2022 [28]. Sand for Construction and the specific data are shown in Table 5 and Figure 8.

Table 5. Grading zone and mud content of residue soil using different treatment processes.

Sieve Size (mm)	Cumulative Screen Margin in Sand Grading Area (%)			Cumulative Screen Allowance of Residue-Soil Treatment Process (%)			
	Zone 1	Zone 2	Zone 3	PM-1	PM-2	PM-3	PM-4
4.75	10–0	10–0	10–0	0	0	0	0
2.36	35–5	25–0	15–0	0	0	7	7
1.18	65–35	50–10	25–0	6	7	17	16
0.60	85–71	70–41	40–16	26	30	36	40
0.30	95–80	92–70	85–55	66	75	72	71
0.15	100–85	100–80	100–75	86	88	89	88
0.075	-	-	-	35	33	28	27

Note: (1) Reclaimed sand is artificial sand, so the cumulative sieve balance of 150 μm sieve size in Zone 1 can be relaxed to 100–85, that in Zone 2 can be relaxed to 100–80, and that in Zone 3 can be relaxed to 100–75. (2) Evaluation criteria of sand particle grading: when the cumulative sieve residue soil of sand is in any of the grading areas, the continuity of particle grading is qualified.

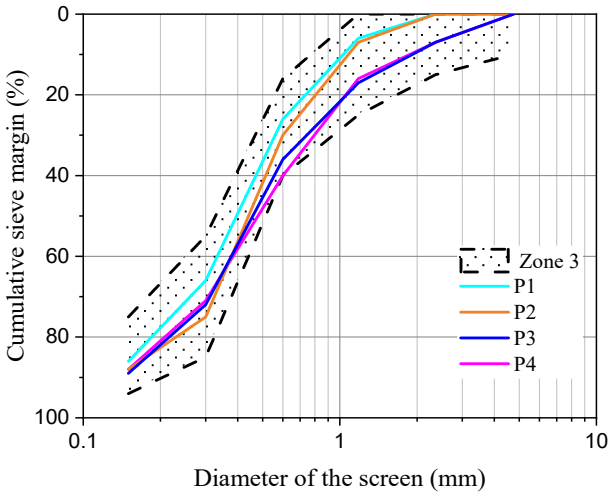


Figure 8. Gradation curve of residue soil with different treatment processes.

The results presented in Table 5 and Figure 8 show that the reclaimed sand portions of residue-soil raw material treatment processes PM-1 and PM-3 are in zone 3, indicating that the particle gradation is acceptable and the particle size distribution of residue-soil particles is generally fine. Method PM-3 enlarges the sieved particle size to 5 mm. This can adjust the overall particle size distribution of residue soil, including adjusting the mud content to reduce the proportion of fine particles. More fine particles lead to higher mud content, necessitating additional cementing material to achieve the target strength of residue-soil unburned brick. Therefore, reducing the proportion of fine particles appropriately ensures the continuity of particle grading and allows the cementing material to perform better, consequently improving the compressive strength of unburned brick. Under the condition of qualified residue-soil grading, the two key factors affecting the strength performance of residue-soil brick are the particle size distribution of residue soil and the mud content. Coarser particle size distribution of residue soil and lower mud content result in higher compressive strength of the residue soil.

Comparing and analyzing the experimental results of PM-3 and PM-4, it can be seen that the mixing effect of residue soil was not affected under a certain moisture content.

Therefore, the residue soil does not need to be completely dried as long as the residue soil and cementing material can be thoroughly and uniformly mixed. In actual production processes, if the particle composition, particle size distribution, and mud content of the residue soil are favorable, PM-4 can be adopted for the actual production of residue-soil unburned brick. PM-4 eliminates the rolling process, reduces the drying time, and only requires the residue soil to be dried to a certain moisture content of about 9%. This process can greatly simplify the residue-soil treatment process, improve production efficiency, and reduce production costs.

5. Molding Method of Unburned Brick

5.1. Experimental Program

Two different methods of molding residue-soil unburned bricks were analyzed in this experiment: machine forming using a YB-2 type unburned brick machine and static press-forming method using a hydraulic machine. The YB-2 machine shapes the unburned brick using the vibration-press-molding method, as shown in Figure 9a. The residue-soil composite materials with a certain moisture content and sufficient mixing are loaded into the brick machine mold. After activating the motor, the composite materials in the mold are vibrated and vertically compressed to form brick billets. By contrast, static pressing uses a hydraulic press to directly compress the composite residue-soil materials in the steel mold to form bricks, as illustrated in Figure 9b. Excessive molding pressure will increase production costs and reduce production efficiency. For instance, if the hydraulic brick machine can produce 24 bricks at a time when using molding pressures of 5 MPa and 10 MPa, the hydraulic press needs to provide about 153 t and 612 t of force, respectively. If a pressure of 20 MPa is used, the requirements for the equipment will be higher. Hence, the static pressure in this experiment was set at 5 MPa and 10 MPa. The effects of 10% and 20% cementing material on the compressive strength of residue-soil unburned bricks were studied under these two different molding methods. In this experiment, the raw materials were treated by process 1, and the unburned bricks were made and the curing for 14 days, and then the compressive strength of the bricks was measured. The experimental design parameters for considering the effects of different molding methods for unburned brick are shown in Table 6. Five specimens were produced for each test group, for a total of 30 residue-soil unburned bricks prepared.



(**a**) (**b**)

Figure 9. Molding method: (**a**) YB-2 unburned brick machine. (**b**) Press-forming equipment.

Table 6. Material mix proportions and forming methods (%).

Number	Cement	Residue Soil	Moisture	Forming Method
1	10	90	16.50	Machine
2	20	80	16.50	Machine
3	10	90	16.50	5 MPa
4	20	80	16.50	5 MPa
5	10	90	16.50	10 MPa
6	20	80	16.50	10 MPa

5.2. Experimental Results and Discussion

The compressive strength of unburned bricks under three different molding methods and two cementing material contents is presented in Figure 10. When the cementing material content is 20%, the compressive strength of unburned bricks produced through vibration pressing is 14.29 MPa, while that of the 5 MPa static pressing method is 20.21 MPa, marking a 41.43% increase. Unburned bricks formed by 10 MPa static pressing exhibit a compressive strength of 20.64 MPa, which is 2.11% higher than that of the bricks formed using the 5 MPa static pressing method. When the cementing material content is 10%, the compressive strength of unburned bricks produced through vibration pressing is 9.81 MPa, while that of the 5 MPa static pressing method is 12.36 MPa, indicating a 26% increase. Unburned bricks formed by 10 MPa static pressing exhibit a compressive strength of 13.83 MPa, which is 11.90% higher than those formed by 5 MPa static pressing. These results clearly demonstrate that the static pressing method significantly outperforms the mechanical vibration pressing method for unburned bricks. As the static pressing pressure increases, a moderate but not substantial increase is observed in the compressive strength of unburned bricks. The effect of increasing molding pressure on the compressive strength of unburned brick with low cementing material content is better than that of high cementing material. Therefore, a static pressure with a high pressure, such as 20 MPa, may have a very limited effect on the strength of unburned brick, making its use unnecessary.

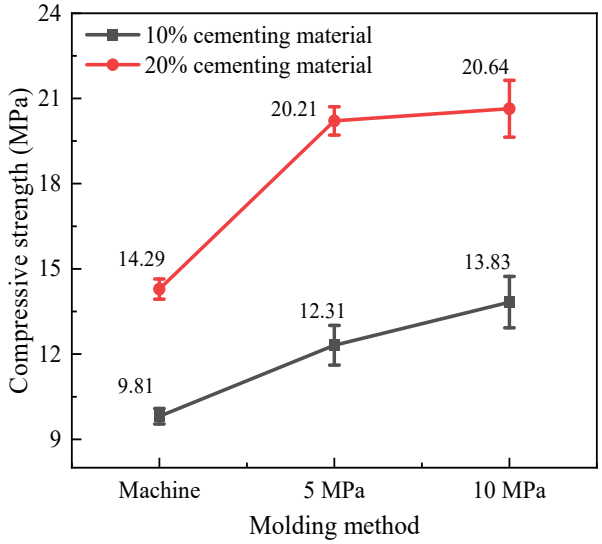


Figure 10. Effect of molding method on compressive strength of unburned brick.

The unburned brick machine primarily relies on vibration to compact the mixture. It is suitable for producing and preparing concrete unburned bricks. However, because the residue soil has high mud content and viscosity, it results in more pores in unburned bricks and reduced strength. Therefore, using conventional unburned bricks, vibration pressing is not feasible for making residue-soil unburned bricks. Increasing the pressure from 5 MPa to 10 MPa does not significantly improve the compressive strength of residue-soil

unburned bricks prepared by static pressing. However, considering the actual production demand, unburned bricks produced using 10 MPa static pressing exhibit a denser and harder structure after demolding. This facilitates the transportation and palletizing of unburned bricks. Therefore, using the 10 MPa static pressing method is preferable.

6. Moisture Content of the Residue-Soil Mixture for Unburned Brick Molding

6.1. Experimental Program

P1, P2, P3, and P4 were used to represent the material formulations with cementing material content of 5%, 10%, 15%, and 20%, respectively. Based on these four material ratios, the impact of molding moisture content (11%, 13%, and 15%) on the compressive strength of the residue-soil unburned brick was studied. The method of 10 MPa static pressing was adopted for brick molding, and the compressive strength was measured after 14-day natural curing of the unburned brick. The experimental design parameters of the unburned bricks considering the influence of moisture content are shown in Table 7. Five specimens were produced for each test condition, for a total of 60 specimens prepared.

Table 7. Material mix proportions (%).

Mix Name	Cement	Residue Soil	Moisture
P1-W15%	5	95	15
P1-W13%	5	95	13
P1-W11%	5	95	11
P2-W15%	10	90	15
P2-W13%	10	90	13
P2-W11%	10	90	11
P3-W15%	15	85	15
P3-W13%	15	85	13
P3-W11%	15	85	11
P4-W15%	20	80	15
P4-W13%	20	80	13
P4-W11%	20	80	11

6.2. Experimental Results and Discussion

The compressive strength of unburned bricks under different moisture content and various material mix proportions is illustrated in Figure 11. Under constant molding method and pressure, the compressive strength of unburned bricks for the four material formulations initially increases and then decreases as the molding moisture content rises, and the optimal molding moisture content (the maximum brick strength) is about 13%. This trend occurs primarily because within a certain range, moisture content affects the plasticity of the mixture, and the plasticity is closely related to the molding process and the subsequent strength development of unburned bricks. When the molding moisture content is lower than the optimal level, the mixture becomes dry, resulting in poor plasticity. The reduced water content can also lead to insufficient hydration, which can lead to lower strength. Consequently, residue-soil particles tend to detach from the surface of the unburned bricks after demolding, affecting the later-stage strength development. Conversely, when the molding moisture content exceeds the optimum moisture content, due to the continuous loading of the force in the static pressing molding, the water in the mixture will flow out through the gap in the mold under the action of pressure, and the outflow liquid contains part of the cementitious material, resulting in a reduction of the cementitious material in the unburned bricks and the decrease in the compressive strength. Therefore, only under the appropriate moisture content is the plasticity of the mixture optimal, resulting in denser particles under the action of pressure.

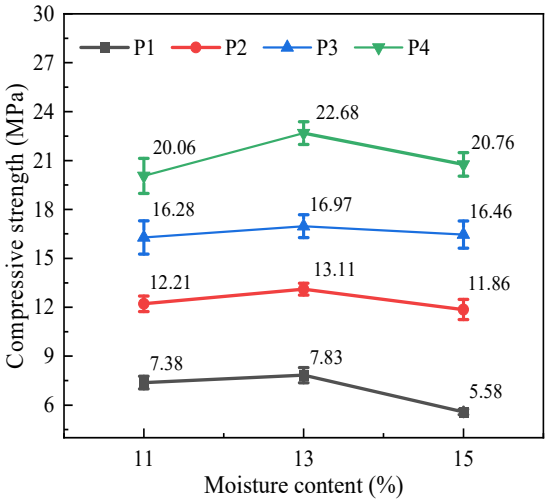


Figure 11. Effect of molding moisture content on compressive strength.

7. Environmental and Economic Benefits Analysis

This paper studies the production method of unburned bricks using engineering residue soil. The materials mainly include cement, residue soil, and water. The percentage of cementitious materials required for different strength grades of unburned bricks varies. Experimental results show that 5%, 10%, 15%, and 10% cementitious material content can successfully produce unburned bricks with strength classes MU5, MU10, MU15, and MU20, respectively. Therefore, the environmental and economic benefits of unburned bricks made from engineering residue soil were analyzed based on the aforementioned mix ratios and strengths. The process of producing unburned bricks can be divided into three parts: (1) raw material treatment: drying, grinding, and sieving of residue soil; (2) molding of unburned bricks: mixing of the materials of residue soil and cement, then static pressure molding to obtain the green bricks; and (3) curing of unburned bricks: using natural curing methods. The main equipment required for the mass production of residue-soil unburned bricks in actual projects is shown in Figure 12, including a drum dryer, vibrating sifter, wheel mill, mixer, and static press brick machine. The production parameters, energy consumption, and costs of these pieces of equipment are listed in Table 8. The cost considers only the production energy consumption and does not account for the cost of equipment acquisition, maintenance, or required operators. The loose bulk density of the residue soil is taken as 1.6 t/m^3. For a standard brick size (240 mm × 115 mm × 53 mm) of unburnt solid bricks, the weight of the mixture (including water) required to produce one brick is approximately 3.5 kg. The price of energy varies cyclically. Here, the cost is calculated with the standard coal price of 1500 CNY/t and the price of industrial electricity at 0.65 CNY/(kw.h). The carbon emission factor of electrical energy is 0.785 kgCO_2/(kw.h), and the carbon emission factor for standard coal is 2.5 kgCO_2/(kw.h).

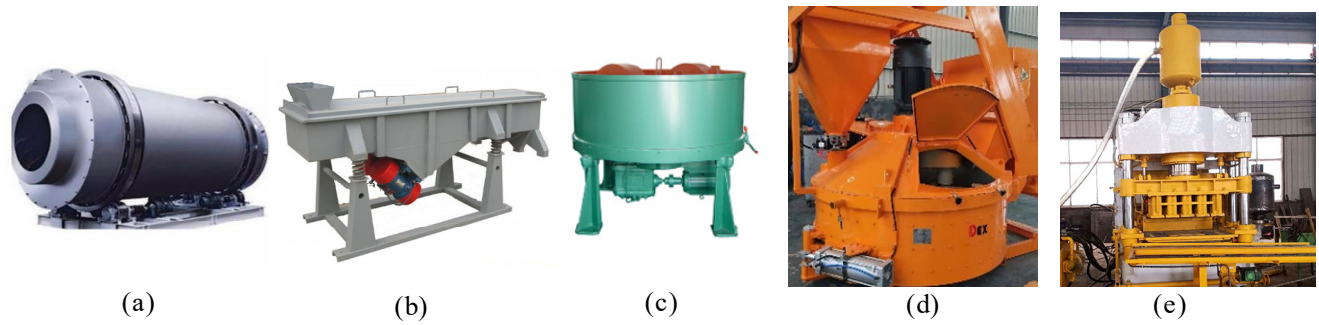


Figure 12. Main equipment used for large-scale production of unburned bricks: (**a**) dryer; (**b**) vibrating sifter; (**c**) wheel mill; (**d**) mixer; (**e**) and brick machine.

Table 8. Production parameters of the main equipment required for the production of free-fired bricks from residual soil.

Equipment	Production Efficiency (t/h)	Power Consumption	Average Carbon Emission CO_2 (kg/t)	Average Energy Cost (CNY/t)
Dryer	13–18	6–8 kg/t (coal) +11 kw/h	18.08	10.980
Vibrating sifter	15	3 kw/h	0.157	0.130
Wheel mill	13–15	22 kw/h	1.234	1.021
Mixer	15	21 kw/h	1.099	0.910
Brick machine	21	37.5 kw/h	1.402	1.161

7.1. Carbon Emission Analysis

Carbon emissions in the cement production process are substantial. According to the PRC national standard GB/T 51366-2019 [31] for calculating carbon emissions of buildings, the carbon emission factor of ordinary silicate cement is 735 $kgCO_2$/(kw.h). For unburned solid bricks of standard size (240 mm × 115 mm × 53 mm), the mixture (including water) for preparing a single brick is 3.5 kg, with the dry mixture accounting for 87% (3.045 kg) and water for 13% (0.455 kg). The carbon emissions of a brick with different strengths, calculated based on the in situ utilization of residual soil, are shown in Table 9. This includes the carbon emissions from the materials and the preparation process of residual soil unburned bricks. Cement, the primary cementitious material for unburned bricks, contributes the largest proportion of carbon emissions, followed by the treatment of raw residue-soil materials. The carbon emissions from the brick molding process are minimal. The carbon emission from the natural curing of residue-soil unburned bricks is zero.

Table 9. Carbon emission analysis of a residue unburned brick (kg).

Brick Grade	Cement		Residual Soil		Brick Molding	Total Carbon Emissions
	Mass	CO_2 Emission	Mass	CO_2 Emission		
MU5	0.149	0.099	2.826	0.055	0.01	0.164
MU10	0.298	0.198	2.677	0.052	0.01	0.260
MU15	0.447	0.297	2.528	0.049	0.01	0.356
MU20	0.596	0.396	2.379	0.046	0.01	0.452

Currently, bricks in the construction industry can be categorized into two types: sintered bricks and unburned bricks. Engineering residue soil can be used to produce sintered bricks, while concrete bricks are the most commonly used unburned bricks. Therefore, this study compares the residue-soil unburned bricks with sintered bricks and concrete bricks to analyze the environmental benefits, mainly examining the carbon emission index. According to the PRC national standard GB/T 51366-2019 standard for calculating construction carbon emissions [31], the carbon emission of a sintered clay solid standard brick is 357 $kgCO_2$/(kw.h), and that of a concrete brick is 336 $kgCO_2$/(kw.h). This translates to 0.521 $kgCO_2$ per sintered brick and 0.49 $kgCO_2$ per concrete brick. Carbon emissions are also generated during the transportation of purchased bricks from the factory to the project site. The carbon emission factor for transportation by medium and light gasoline trucks (2-ton load) is 0.334 $kgCO_2$/(t.km). For a transportation distance of 50 km, the carbon emission per brick transported is 0.058 $kgCO_2$. Therefore, the combined single-brick carbon emissions of outsourced sintered bricks and concrete bricks are 0.579 $kgCO_2$ and 0.558 $kgCO_2$, respectively. Calculations and analysis show that the carbon emissions of residual soil unburned bricks are considerably lower than those of traditional sintered and concrete bricks. The average carbon emission for MU5–MU20 strength-grade residual soil unburned bricks is 0.308 $kgCO_2$ per brick, representing an approximate 50% reduction compared to sintered and concrete bricks. Specifically, the MU20 strength bricks show an average carbon emission reduction of about 30%, while the MU5 strength bricks show a

reduction as high as 60%. The lower the strength grade, the higher the carbon reduction benefit of residue-soil unburned bricks. In summary, residual soil unburned bricks offer remarkable carbon emission reduction benefits, promoting environmental protection and sustainable development.

7.2. Economic Analysis

The in situ resource utilization of residue soil to fabricate unburned bricks primarily involves material and manufacturing costs. The materials for unburned bricks include cement, residue soil, and water, with cement priced at 600 CNY/t, water at 5 CNY/t, and residue soil being free. The production process for unburned bricks can be divided into three main stages: raw residue-soil treatment, brick molding, and brick curing. The treatment of residue soil involves drying, wheel milling, and sieving. The capacity and energy costs of the equipment required for these stages are shown in Table 1. The energy consumption for drying is calculated based on the water content of residue soil, specific heat capacity, and fuel thermal efficiency. Assuming a 20% water content in the residue soil, the average cost of residue-soil treatment for unburned brick preparation is approximately 50 CNY/t. The mixing and molding processes cost about CNY 0.01 per piece. Since unburned bricks are naturally cured, no equipment or energy is needed for this stage. Based on the above data, the cost of a single residual soil unburned brick is shown in Table 10.

Table 10. Costing of a residual soil unburned brick.

Brick Grade	Cement		Residue-Soil Processing		Cost of Water (CNY)	Mixing and Molding Cost (CNY)	Total Cost (CNY)
	Mass (kg)	Cost (CNY)	Mass (kg)	Cost (CNY)			
MU5	0.149	0.0894	2.826	0.1413	0.0023	0.01	0.243
MU10	0.298	0.1788	2.677	0.1338	0.0023	0.01	0.325
MU15	0.447	0.2682	2.528	0.1264	0.0023	0.01	0.407
MU20	0.596	0.3576	2.379	0.1189	0.0023	0.01	0.489

Clay-sintered solid bricks have been gradually banned in China. Here, the cost of residue-soil unburned bricks versus commercially available concrete unburned bricks is comparatively analyzed. Based on a market survey of commonly used standard solid bricks in South China, the prices for MU5, MU10, MU15, and MU20 solid concrete bricks made of construction waste are CNY 0.54, CNY 0.69, CNY 0.79, and CNY 0.89, respectively. The economic benefits of using residue soil to produce unburned bricks at the project site mainly consist of two aspects: (1) preparation at the construction site saves the costs of outward transportation and disposal of residue soil; (2) it saves the cost of purchasing unburned bricks from external sources. Currently, the outward transportation processing cost of construction site residue soil in South China is about 150 CNY/m^3. The most similar brick product commonly used in projects is the construction waste concrete solid brick.

Considering the cost of transportation for residue-soil disposal and the cost of purchasing bricks, the economic benefits of residue-soil unburned bricks are summarized in Table 11. It can be seen that the production cost of residue-soil unburned bricks is considerably lower, about half the price of solid concrete bricks. Compared to traditional methods, using residue soil on-site to produce unburned bricks can save 56–70% of the costs, with economic benefits ranging from 128% to 231%. For bricks within the strength range of MU5–MU20, the average cost saving is about 63%, and the average economic benefit is 175%. For example, a project requiring CNY 1 million of bricks for construction using the on-site utilization of residue soil to produce unburned bricks cost only about half a million CNY. The approach proposed in this paper can save about 330,000 CNY in residue-soil treatment costs, totaling CNY 880,000 in cost savings, which is 175% of the production cost of unburned bricks. Thus, the in situ resource utilization of residual soil for the production of unburned bricks presents considerable cost advantages and economic benefits.

Table 11. Economic benefit analysis of residue-soil unburned bricks.

Brick Grade	Cost of Residual Soil Unburned Brick ①	Cost of Residual Soil Disposal ②	Cost of Purchasing Brick ③	Cost Comparison % ①/(② + ③)	Economic Benefit % (② + ③ − ①)/①
MU5	0.243	0.265	0.54	30.19	231.28
MU10	0.325	0.251	0.69	34.54	189.54
MU15	0.407	0.237	0.79	39.63	152.33
MU20	0.489	0.223	0.89	43.94	127.61
Average value	0.366	0.244	0.7275	37.07	175.180

8. Conclusions

The production method and technology of residue-soil unburned brick will significantly affect the service performances and engineering applications of unburned brick. In this paper, a production method for construction residue-soil unburned brick is proposed. Based on experiments, the material formulation and production process optimization are studied. Compared with conventional brick, the advantages and benefits of residue-soil unburned brick are analyzed. The conclusions are as follows:

(1) For silty clay, ordinary cement is used as a cementing material. The formulation of 5%, 10%, 15%, and 20% cement can produce the construction residue-soil unburned brick meeting the strength grades MU5, MU10, MU15, and MU20, respectively. The utilization rate of the residue soil of the four grades of unburned brick is as high as 80–95%.

(2) The raw material treatment process should be specifically analyzed according to the properties of the residue soil itself. Residue soil with good particle composition, reasonable particle size distribution, and moderate mud content can be directly dried or air-dried to the specified moisture content (about 9%), and particle size within 5 mm can be used for unburned brick manufacturing. This treatment method can significantly improve production efficiency and reduce energy consumption and costs.

(3) Good compactness of brick with adequate pressure compression molding has a significant effect on improving the compressive strength of unburned brick. It is recommended to use a static pressing–molding method with a moisture content of about 13% and a pressure of 10 MPa for molding residue-soil unburned bricks.

(4) Engineering residue-soil unburned brick has remarkable environmental and economic benefits. Compared with existing building brick products, residue-soil unburned brick can reduce carbon emissions by 50%; however, the cost is only 50% of the traditional brick, and the economic benefit of producing unburned brick from an in situ resource of residue soil is up to 175% profit. If the unburned brick can be widely used, it will greatly promote the environmental protection process of the construction industry.

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