buildings

Article

Experiment on the Performance of Recycled Powder of Construction Waste on Adobe Materials

Mei Zeng [1], Huanan Huang [1] and Xianggang Zhang [2,*]

[1] Department of Civil Engineering, Henan College of Industry & Information Technology, Jiaozuo 454000, China; 17603918036@163.com (M.Z.)
[2] School of Civil Engineering, Henan Polytechnic University, Jiaozuo 454000, China
* Correspondence: xgzhang1986@163.com

Abstract: With the widespread use of adobe materials in buildings, their durability can deteriorate under harsh weather conditions such as long-term low temperatures and rainfall, which can easily lead to safety accidents. This article takes adobe material mixed with construction waste recycled powder as the research object and adds the prepared construction waste recycled concrete powder and recycled brick powder to the adobe material in different proportions to study the mechanical and durability properties of the adobe material. The results indicate that under normal temperature curing conditions, the compressive strength of the adobe sample significantly increases with the increase in the recycled powder content, and then decreases. Under high-temperature conditions, with the increase in the recycled powder content, the compressive strength of the adobe sample first significantly increases and then decreases. When the powder content is within the range of 6% to 10%, good moisture absorption and desorption performance can be achieved. When the content of recycled powder is between 2% and 10%, the effect on the dry–wet cycling performance of the adobe is weakest. When the content of grade I/II recycled brick powder is between 2% and 6%, and the content of grade I recycled concrete powder is between 2% and 6%, the negative impact on the freeze–thaw cycle performance is relatively weak. The research results provide theoretical data support for the mixed-use of recycled powder and adobe materials.

Keywords: construction waste; recycled powder; adobe material; compressive strength; durability

check for updates

Citation: Zeng, M.; Huang, H.; Zhang, X. Experiment on the Performance of Recycled Powder of Construction Waste on Adobe Materials. *Buildings* **2023**, *13*, 1358. https://doi.org/10.3390/buildings13051358

Academic Editors: Xudong Zhang, Bingxiang Yuan, Yong Liu and Yonghong Wang

Received: 30 March 2023
Revised: 27 April 2023
Accepted: 19 May 2023
Published: 22 May 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

With the rapid development of infrastructure construction in China, the consumption of building materials is increasing day by day. Facing the serious shortage of resources and the impact of conventional building reinforced concrete building materials on the environment, adobe materials have attracted great attention because of their green environmental protection [1]. During the production and use of reinforced concrete, the average carbon content per cubic meter is 635 kg. Although the production of adobe is very simple, it only needs to mix clay and water, but the average hidden carbon content per cubic meter is 345 kg. Considering its carbon footprint, adobe is a good choice for buildings [2]. Adobe materials are mainly natural raw materials, which only need simple low temperatures and routine maintenance. They have the characteristics of good thermal insulation, thermal performance, adjustable humidity, and simple construction technology [3]. The wall built with adobe materials has the characteristics of thermal insulation, ventilation, and fire prevention; low energy consumption; pollution-free; and renewable, and is an ideal green building material for sustainable utilization. At present, about one-third of the world's population still lives in adobe buildings, and adobe materials in China are also widely used as building materials, such as caves in the Loess Plateau, Hakka earth buildings, and adobe houses with curved roofs in Xinjiang [4]. However, adobe building materials have the disadvantages of poor water resistance and low strength. When affected by external factors such as rain, freezing, and thawing, the mechanics and durability of adobe building materials are greatly reduced, and the service life is also greatly shortened [5]. Therefore, it improving the properties of raw materials and enhancing their water resistance and mechanical properties has become a hot topic.

Construction waste refers to the waste produced in construction, maintenance, and demolition projects, mainly including waste concrete, clay bricks, and muck [6]. Figure 1 shows the proportion of various construction wastes, in which waste concrete and waste bricks account for more than 70% of the total construction wastes, and they are the construction wastes with the largest output [7]. With the large-scale development of infrastructure projects, the annual treatment volume of construction waste in China is increasing rapidly. By 2021, it will reach 2.1 billion tons, of which 95% will be treated by on-site stacking or backfilling and buried in other places, resulting in soil and groundwater pollution and making it easy to form a construction waste siege [8]. Therefore, it is urgent to improve the recycling rate of construction waste and study the preparation of recycled products such as recycled powder.

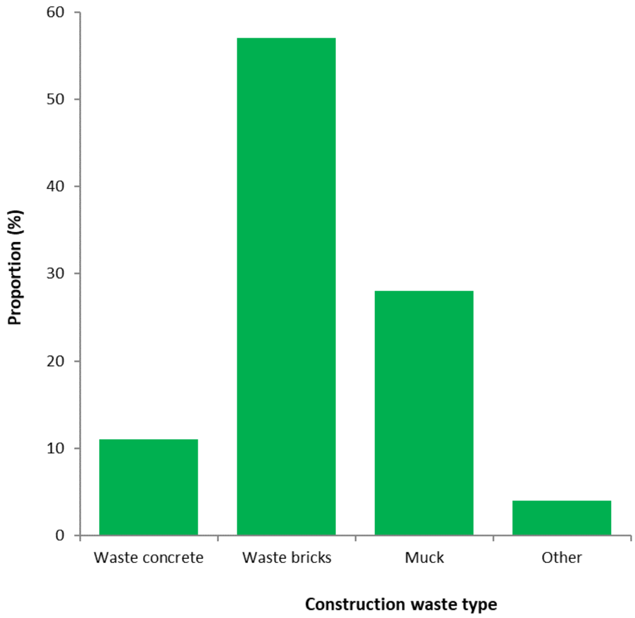

Figure 1. Proportion of various construction wastes.

Some research achievements have been made on improvements in the properties of adobe materials. Some researchers have studied the mechanical properties of adobe materials under different ratios by mixing cement and cement special mixture materials [9]. The results show that when the water/solid ratio is 1:5, the cement content reaches 20%, the cement special mixture material content is 2%, the adobe material content is 80%, the compressive strength reaches 12 MPa, and the flexural strength reaches 3.2 MPa after 56 days of curing [10].

Some researchers have studied adding cement, lime, and mineral admixtures to improve the strength of raw materials [11]. When cement is added to raw materials alone, the hydration products of $Ca(OH)_2$ and C-S-H have a cementation effect, which promotes the strength of samples to increase. When lime is added to the raw material alone, the hydration products of $Ca(OH)_2$ greatly fill the gaps between the particles of the raw material, which makes the material denser and improves the compressive strength of the sample. When cement or lime and mineral admixture are mixed into the adobe materials, the secondary hydration reaction of the mineral admixture greatly improves the compressive strength of time [12].

Some researchers use the plasticity index to add cement and waterproofing agents to raw materials and analyze their water resistance and frost resistance [13]. The results show that when the plasticity index of raw materials is 6–9, the samples prepared by adding cement alone or mixing cement and a waterproofing agent have higher water and frost resistance. When the plasticity index of adobe materials is 9–19, the samples prepared by adding cement alone have better water and frost resistance [14]. Some researchers have studied the effects of cement, slag, lime, fly ash, and gypsum on the durability of raw materials. The results show that when cement, slag, lime, fly ash, and gypsum are added to raw materials, their water and frost resistance can be improved [15].

Some researchers use recycled brick powder in different proportions instead of cement to prepare various mortars [16]. When the quality of the recycled brick powder is less than 20%, the content of powder has little effect on the elastic modulus and compressive strength of adobe materials, but it improves its durability. Based on the grey relational index, some researchers quantitatively analyzed the performance changes in concrete mixed with recycled powder and concluded that with the increase in the amount of powder, the permeability of concrete gradually decreased, but the wear resistance gradually increased and the carbonation resistance gradually weakened [17].

To avoid being used as filling material for roadbeds and quarries after the end of the life cycle of concrete structures, some researchers have proposed using the Eco Concrete tool to conduct a Partial Life Cycle Assessment (LCA) of concrete made from fine recycled concrete aggregates [18]. To understand the impact of admixtures on the properties of transparent concrete, some researchers have conducted experimental studies on the physical and mechanical properties and structure of the materials. Research has shown that the developed material has a compressive strength of 30 MPa, strong interlayer adhesion (which is tested to damage the material through concrete matrix testing), and sufficient light transmittance [19].

Researchers have utilized their experience in using crushed concrete in civil engineering (mainly geotechnical engineering) to introduce and summarize selected social, technical, and economic case studies, including the energy consumption required for the proposed technology and the dynamic effects of ground-transmitted vibrations and noise [20]. A study introduced the overall conditions for abandoned underground mining operations in selected areas of Russia, as well as some experiences collected at many construction sites in Poland, in an attempt to encourage the concept of sustainable development. This is necessary to shift from purely protective measures to planned management of natural resources and establish mathematical models of the impact of geotechnical engineering on the environment [21].

Through the summary and analysis of the current research status of adobe improvement, it is found that in the current research on adobe improvement, materials that undergo chemical reactions can better improve the mechanical and durability properties of adobe. However, in terms of the construction costs and applications, the adobe is mostly used in economically backward and remote areas, and the market prices of active materials such as cement, lime, and gypsum are relatively high, which is not conducive to promotion. The recycled powder can replace cementitious materials such as cement or be used as an active material alone. The amorphous SiO_2, Al_2O_3, and CaO contained in the recycled powder undergo chemical reactions, which can improve the performance of adobe. This article investigates the mechanism of changes in the mechanical properties of adobe by adding the active recycled powder to the material. Taking mixed recycled construction waste powder as the research object, different proportions of recycled concrete powder and recycled brick powder were added to the adobe, and their mechanical properties and durability experiments were conducted.

The innovation of this paper is to provide theoretical support for the use of recycled powder mixed with adobe through the mechanism study of the difference between mechanical properties and durability, give play to the advantage of the low market price of recycled powder, improve the utilization rate of solid waste, reduce or even eradicate the use of cement and other cementitious materials, and reduce the construction costs and facilitate promotion.

2. Materials and Methods

2.1. Material Preparation

The recycled powders used in this paper are mainly recycled brick powder and recycled concrete powder, which are mainly prepared from waste clay bricks and waste concrete from construction waste recycling stations. Adobe material comes from the Loess Plateau in the Shaanxi section of the Yellow River. Its chemical composition is measured by an X-ray fluorescence spectrometer. Table 1 gives the main parameters of the adobe.

Table 1. Main parameters of adobe (%).

Chemicals	SO_3	Fe_2O_3	CaO	SiO_2	Al_2O_3	Other
Proportion (%)	0.3	7.7	1.9	66.2	17.8	6.1

The preparation process of recycled brick powder and recycled concrete powder is as follows: Waste brick aggregate and waste concrete aggregate are treated by a 1 cm square hole sieve to remove impurities such as broken plastics and sawdust, as shown in Figure 2. The mechanical grinding method of the ball mill is used to prepare and stimulate the activity of recycled brick powder and recycled concrete powder, and its activity is improved by increasing the specific surface area of the powder. The recycled powder after grinding is shown in Figure 3. The left side is recycled brick powder, and the right side is recycled concrete powder. Referring to JG/T 573-2020, "Recycled powder for Concrete and Mortar", the recycled brick powder and recycled brick powder are divided into two grades, I and II, respectively, based on their different grinding times. The fineness and sieve residue of different grades are shown in Table 2.

Figure 2. Waste concrete coarse aggregate (**left**) and waste brick coarse aggregate (**right**).

Figure 3. Recycled powder.

Table 2. Fineness and sieve residue of recycled brick powder and recycled concrete powder.

Item	Grade	Fineness (%)	45 µm Sieve Residue (%)
Recycled brick powder	I	≤30	19.5
	II	≤45	30.5
Recycled concrete powder	I	≤30	24.5
	II	≤45	35.5

The particle size distribution of recycled powder was analyzed by a laser particle size analyzer. From Table 3, it can be seen that, regardless of whether recycled brick powder or recycled concrete powder is used, the particle size distribution of grade I is more inclined toward a smaller particle size range than that of grade II. In existing studies, it has been found that the higher the content of cement particles with a particle size less than 40 µm, the higher the activity. The higher the content greater than 100 µm, the lower the activity test. The finer the particle content, the higher the activity. So, the grade I activity of recycled brick powder and recycled concrete powder is higher than the grade II activity.

Table 3. Particle size distribution of grade I/II recycled brick powder and recycled concrete powder (%).

Item	<10 µm	<25 µm	<45 µm	<60 µm	<75 µm	<90 µm	<110 µm	<150 µm
Recycled brick powder-I	31.63	53.32	70.65	78.77	86.47	89.67	94.08	96.24
Recycled brick powder-II	26.7	43.51	60.33	68.45	76.81	80.83	88.06	97.50
Recycled concrete powder-I	45.75	63.28	79.55	85.10	90.35	92.28	94.28	96.59
Recycled concrete powder-II	32.5	48.77	62.75	69.09	75.59	78.74	84.54	93.27

At present, the compaction method is mainly used for adobe materials; that is, the bulk of adobe materials are compacted to a dense state by external force, which meets the requirements of geotechnical experiments. When preparing adobe samples in this paper, firstly, the optimum water content and the corresponding maximum dry density of adobe mixed with recycled powder are calculated, and then the compaction method is adopted. The main steps are as follows:

(1) To avoid situations where the sample is not easy to de-mold and the demolding angle is missing, a plastic film is paved in the mold in advance;
(2) The adobe materials, which are mixed evenly according to a certain proportion, are divided into three layers and filled into the mold from bottom to top, and each layer is compacted five times for a total of fifteen times in three rounds.
(3) Before each layer is compacted, roughen the compacted surface of the lower layer, increase the concave and convex points, and increase the roughness and bonding force of the interlayer contact surface.

The sample size is 40 mm × 40 mm × 160 mm, and it is covered with plastic film to keep moisture, as shown in Figure 4. After standing for 48 h, the mold is removed and the sample is cured in a constant temperature and humidity curing box with humidity of 45% and temperature of 15–25 °C for 7 days, 14 days, and 28 days, respectively, and the compressive strength and durability of each group of samples are tested.

2.2. Experimental Methods

The mechanical performance experiment of recycled concrete blocks shall be carried out according to the method specified in the "Standard for Mechanical Performance Experiment Methods of Ordinary Concrete" GB/T50080-2002. The unconfined compressive strength experiment is mainly used for the compressive strength of samples, and the loading speed of the pressure testing machine is set to 2 kN/s to test the compressive strength of samples in different curing periods. The softening coefficient of the sample mainly represents the water resistance of the material. In this paper, the ratio of the sample's compressive strength soaked in water for 1 day to the compressive strength after 28 days of standard curing shows that the greater the softening coefficient of the sample, the stronger its water resistance. The hydration products and mineral components of the samples were mainly determined by an X-ray diffractometer. The wavelength of the equipment was set to 0.16 nm, the scanning speed was set to 110°/min, and the scanning range was 5–90°. The mineral components of the samples after different improvements were analyzed. The pore structure and morphological characteristics of the samples were mainly tested by scanning electron microscope. The pore structures of different samples were compared by taking electron microscope pictures of different samples. In testing concrete strength, 3 days, 7 days, and 28 days are commonly used testing time points. The 28-day testing time determines the final strength of the concrete. The test results can help determine the strength development trend of concrete and whether measures need to be taken to enhance its strength. In this experiment, after 28 days, the strength development curve of the adobe sample began to enter a plateau period.

Figure 4. Preparation of concrete block.

Moisture absorption and desorption performance experiment: place the sample cured at normal temperature for 28 days in an electric blast drying oven at 55–65 °C, and keep it dry for 3 h at a stable weight. Take out the sample and place it in a room at 15–25 °C for 20 min until it is cooled, and then place it in a constant temperature and humidity curing box with a temperature of 18–22 °C and relative humidity of 95% to simulate the high humidity environment. Record the quality of the sample after moisture absorption once every 24 h until the quality fluctuation of the sample is less than 0.05 g and then stop recording. After that, take out the sample after moisture absorption and place it in a constant temperature and humidity curing box at 23–27 °C and 35–45% relative humidity to simulate the natural environment of water loss. Additionally, record the quality of the sample after water loss every 24 h until the quality fluctuation of the sample is less than 0.03 g and then stop recording.

Dry–wet cycle experiment: place the sample cured at normal temperature for 28 d in an electric blast drying oven at 55–65 °C, and keep it air-dried for 3 h until it reaches a stable weight. Take it out and cool it indoors at 15–25 °C for 20 min, and record the quality of the sample. Then, put it in a water tank with a water surface that is 30 mm higher than the upper surface of the sample and a temperature of 15–25 °C. After 5 min, take it out and dry it indoors at 20 °C for 30 min. Soak the sample in water for 5 min, dry it for 30 min, dry it for 7 h 15 times, and record the quality and compressive strength of the sample after the cycle.

Freeze–thaw cycle experiment: place the sample cured at normal temperature for 28 days in an electric blast drying oven at 55–65 °C for 3 h at a constant weight, and then take it out and cool it at 15–25 °C for 20 min. Record the quality and place it in the concrete slow-freezing box. Using pneumatic thawing, set the machine parameters to slow freeze for 2 h at −20 °C and melt for 2 h at 20 °C, as one cycle. Record the quality and compressive strength at the end of the cycle after 20 cycles.

3. Results and Discussion

3.1. Compressive Strength of Samples under Normal Temperature Curing Conditions

There are few studies on the performance of adobe with the single addition of recycled powder, but similar studies are more common for cement-based materials. Some studies [22] used a ball mill to grind the powder to below 45 μm and mixed it into the concrete as an active material. It was found that the recycled brick powder and recycled concrete powder contained clay minerals, and unhydrated cement particles had good activity performances. Some studies [23] further ground the powder into three ranges of 0–45 μm, 45–75 μm, and 75–150 μm, and also added it as an active material into cement for testing. The results showed that recycled brick powder and recycled concrete powder have good pozzolanic activity. In addition, it was found that the fineness of the powder has a significant impact on its activity, and the compressive strength of recycled concrete powder with particle sizes ranging from 0 to 45 at 28 days is higher than the other two particle sizes.

The above research shows that the activity of recycled powder increases with the decrease in fineness. In this experiment, no other active materials were used to assist in the reaction of adobe with recycled powder, and the activity of the powder was only stimulated by its activity and the alkaline environment inside the soil. The total amount of raw soil is kept at 100% by referring to the commonly used recycled powder separately, and the external mixing method is adopted [5]. Additionally, adobe was set as the control group.

Compression experiments were conducted on adobe obtained by mixing recycled powder treatment. The concrete was cured from the completion of pouring, and the compressive strength growth rate was the fastest in the first seven days of this cycle. During the following 7–14 days, its growth rate slowed down. At 28 days, it reached over 100%, but after 18 days, its growth rate became very slow. Therefore, a strength of 28 days is generally used as the standard strength. After 28 days, the development curve of concrete strength began to enter a plateau period. The experimental results show that, from the perspective of age and powder type, the compressive strength of adobe treated with recycled brick powder under room temperature conditions shows a significant increase compared to the untreated group at each age. Among them, during the aging period of 7 days to 28 days, the increase in the use of grade I and grade II powders reached 32% to 53% and 30% to 57%, respectively.

The 28-day compressive strength relationship curve of adobe obtained by mixing recycled powder treatment is shown in Figure 5. According to Figure 5, it can be observed that the combination of recycled brick powder shows a decreasing inflection point when the dosage is 10%. However, compared to the latter, the former has a higher compressive strength at different dosages, regardless of whether it is grade I or grade II powder. The larger the dosage, the greater the difference between the two. This also indicates that both grade I and II recycled brick powder have better composite effects when mixed with adobe. To optimize the dosage of powder on this basis, the experimental results should be compared and analyzed with the control group.

Then, the 28-day compressive strength of the adobe and control groups obtained from the mixed treatment was measured. Compared with the control group, the compressive strength of the mixed recycled brick powder group showed a certain degree of increase. The growth rate of the grade I powder group was 26% to 52%, while the growth rate of the grade II powder group was 18% to 41%. In addition, the compressive strength of the composite recycled concrete powder group also increased to a certain extent. Mixing recycled brick powder at room temperature had a significant effect on improving the compressive strength of the adobe. Among them, the 28-day strength increase in the adobe was the highest when 6–14% of grade I/II recycled brick powder and 2–10% of grade I/II recycled concrete powder were added. In addition, the recycled brick powder also had a promoting effect on improving the compressive strength of adobe with only cement added. The effect was most significant when the grade I dosage was 6–14% and the grade II dosage was 10%.

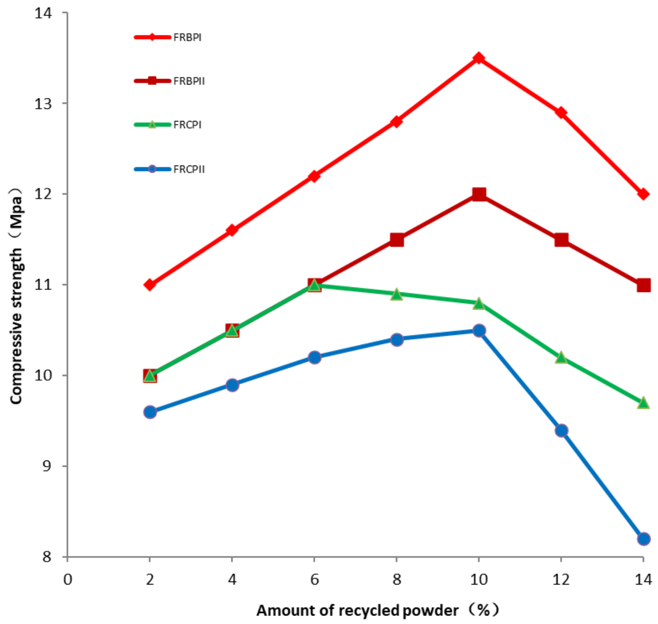

Figure 5. Compressive strength of adobe material mixed with recycled powder and cured at normal temperature for 28 days.

3.2. Compressive Strength of Samples under Hot Curing Conditions

The compressive experiment was carried out on the samples made of adobe materials mixed with recycled brick powder and recycled concrete powder. Figure 6 shows the compressive strength of adobe materials mixed with recycled powder after 28 days of hot curing. From Figure 6 and the experimental results, it can be seen that through the analysis of the curing age of the samples and the types of powder, the compressive strength of the adobe materials mixed with recycled brick powder increased obviously at each curing age under hot conditions, and the compressive strength of the samples mixed with grade I and grade II recycled brick powder increased by 15–2% and 7–18% within the curing age of 7–28 days. In hot conditions, the compressive strength of the samples mixed with recycled concrete powder of grade I and grade II increased by 7–10% and 2–6% within the curing period of 7–28 days, which were both lower than the compressive strength of the samples mixed with recycled brick powder of the same dosage for the same curing period. Therefore, mixing recycled powder plays an effective role in the compressive strength of the raw materials under hot conditions, and the effect of recycled concrete powder is not obvious. With the increase in the content of recycled brick powder, the compressive strength of the sample first increased and then decreased, and the turning point occurred when the content of the recycled brick powder of grade I and II was 10%. With the increase in the content of recycled concrete powder, the compressive strength of the sample also increased at first and then decreased. The turning point occurred when the content of the recycled concrete powder was 6%, which fully shows that the adaptability of recycled brick powder to temperature is weak and the content can be more, while the adaptability of recycled concrete powder to temperature is obvious, which is not suitable for adding a large number of adobe materials.

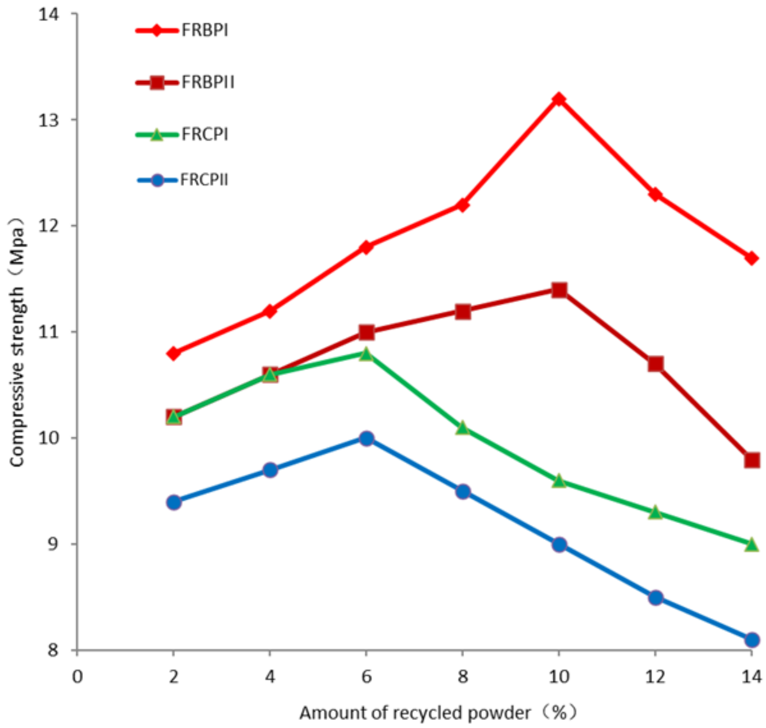

Figure 6. Compressive strength of adobe material mixed with recycled powder after 28 days of hot curing.

To ensure the curing effect of adobe under hot conditions, it should be compared with the room temperature curing group. Research has found that, compared to the group under room temperature conditions, the composite recycled brick powder group reach its peak at a dosage of 6%. After exceeding this dosage, there is a small range of decreases in variation. Among them, the decrease in grade I powder is 1% to 3%, and the decrease in grade II powder is 5% to 8%. The composite recycled concrete powder group also reaches its peak at a dosage of 6%. After exceeding this dosage, it shows a wide range of decreasing changes. Among them, the reduction in grade I powder is 5–9%, and the reduction in grade II powder is 4–12%. This also indicates that under hot conditions, the effect of adding the powder to adobe with cement on its 28-day compressive strength is relatively small when the content of grade I/II recycled brick powder is between 2% and 14%, the content of grade I recycled concrete powder is between 2% and 14%, and the content of grade II recycled concrete powder is between 2% and 6%.

3.3. *Durability*

Durability refers to the ability of a material to remain non-cracking and non-collapsing due to non-destructive external forces such as environmental changes during long-term use. Specifically, it refers to the ability of the material forming the structure to maintain its original characteristics without being damaged during use [24]. During its use, adobe will face the effects of rainwater erosion, dry–wet cycling, freeze–thaw cycling, and other factors. Depending on the region, it will also face the effects of temperature differences and humidity changes. Therefore, compared to mechanical properties, the durability of adobe should be a top priority in the study of the properties of recycled powder mixed with adobe.

3.3.1. Moisture Absorption and Desorption Performance

Using only the water absorption rate and water resistance delay index cannot fully characterize the water resistance performance of adobe, let alone reflect the specimen's moisture absorption and release performance in actual usage environments. Therefore, it is necessary to introduce other characterization methods to improve the evaluation criteria for water resistance, so the moisture absorption and desorption performance will be used as another indicator to measure the water resistance performance of the adobe. This study also pointed out that the moisture absorption and release performance experiment is closer to the actual use scenario [25].

In the experiment of moisture absorption and desorption characteristics of the samples, the quality of adobe materials mixed with recycled powder is maintained in the process of rapid growth in the first 7 days of sample curing, the quality increases slowly after 7 days of curing, and the moisture absorption quality of samples reaches the peak on the 13th day of curing. In this paper, the quality of the sample's cured for 13 days will be regarded as the stable moisture absorption quality of the sample. Figure 7 shows the experiment results of the moisture absorption and desorption performance of adobe materials. As can be seen from Figure 7, when the content of recycled powder is 6–10%, the moisture absorption rate of the sample is low, which is much lower than other contents of recycled powder, and the natural drying rate of the sample is also lower than other contents of recycled powder, which is mainly because the powder cannot fill the intergranular pores of the dense adobe material when the content of recycled powder is low. When the content of recycled powder is high, a large number of pores will be produced in the soil-based materials, which will lead to the deterioration of the moisture absorption and desorption properties of the materials. Therefore, when the content of recycled powder is 6–10%, the soil material has a good moisture absorption and desorption performance.

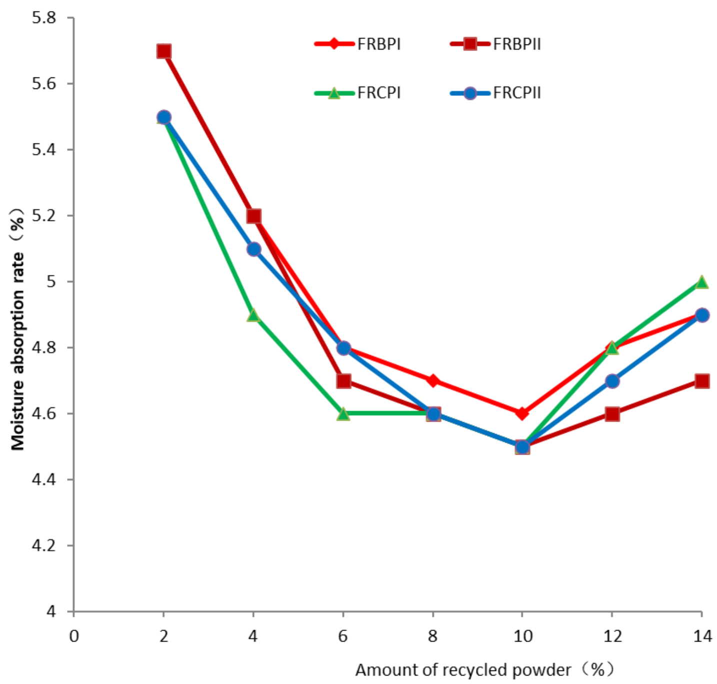

Figure 7. Experiment results of moisture absorption and desorption performance of adobe materials.

3.3.2. Dry–Wet Cycle Performance

Based on the research on the durability performance of rammed earth walls [26], researchers conducted 12 dry–wet cycle experiments on adobe according to the American Society for Materials standard [27], and provided reference values for the maximum mass loss after 12 cycles. Referring to the above content, the number of dry and wet cycles set in this experiment was 12.

In the dry–wet cycle experiment of the sample, the experiment results of the dry–wet cycle performance of adobe materials are given in Figure 8. As can be seen from Figure 8, for the adobe materials doped with recycled powder, when the content of recycled powder exceeds 2%, the quality loss rate of the samples shows a gradual upward trend. Compared with recycled concrete powder, the quality loss rate of the samples mixed with I/II recycled brick powder is higher, and the difference in the quality loss rate of the samples is larger with the increase in the mixing amount. At the same time, it is found that the strength loss rate of the sample increases gradually when the content of recycled powder exceeds 2% and the overall change is not significant, which shows that the mixing of recycled powder has an impact on the dry–wet cycle performance of the raw material, and the impact on the dry–wet cycle performance of the raw material is the weakest when the content of recycled powder is 2–10%.

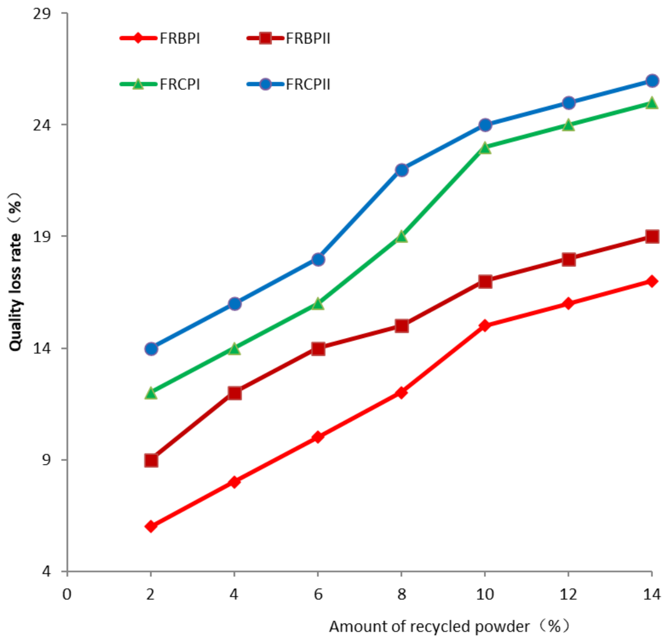

Figure 8. Experiment results of dry–wet cycle performance of adobe materials.

3.3.3. Freeze–Thaw Cycle Performance

According to the relationship between the amount of powder added and the quality loss rate in adobe, it can be found that, for the groups containing recycled brick powder and recycled concrete powder, when the amount of powder added is higher than 2%, the corresponding quality loss rate shows an increasing trend and is far lower than the control group, meeting the limit requirement of less than 5%. In addition, when the powder content is greater than 6%, compared to the recycled brick powder group, the mass loss rate of the recycled concrete powder group under grade I/II powder is lower. Additionally, with the increase in the dosage, the mass loss rate corresponding to the two types of grade I/II powders is closer to the control group. Taking into account the relationship between the amount of powder added and the strength loss rate in adobe, for the groups containing recycled brick powder and recycled concrete powder, the strength loss rate gradually increases after the amount exceeds 2%, and is overall higher than the control group. When the dosage exceeds 10%, the corresponding strength loss rate does not meet the corresponding requirements for the strength loss rate. This also indicates that adding recycled brick powder and recycled concrete powder will cause negative changes in the freeze–thaw cycling performance of adobe. When the content of recycled brick powder in grade I/II is between 2% and 6%, and the content of recycled concrete powder in grade I is between 2% and 6%, this effect is relatively weak.

4. Conclusions

This paper takes the adobe material mixed with the recycled powder of construction waste as the research object, adds the prepared recycled concrete powder and recycled brick powder of construction waste into the adobe material according to different mixing ratios, adopts the compaction process and carries out standard curing to prepare the adobe sample, and studies the mechanical and durability properties of the adobe material. The main research results are as follows.

(1) Under normal temperature curing conditions, with the increase in recycled powder, the compressive strength of the adobe material sample shows a significant increasing trend, with a turning point of around 10%.
(2) Under high-temperature conditions, with the increase in recycled powder, the compressive strength of the adobe sample first significantly increases and then decreases. The turning point is about 10% for recycled brick powder and 6% for recycled concrete powder.
(3) Good moisture absorption and desorption performance can only be achieved when the powder content is within the range of 6% to 10%.
(4) The addition of recycled brick powder and recycled concrete powder will cause changes in the dry–wet cycling performance of adobe. This effect is relatively weak when the dosage is within the range of 2% to 10%.
(5) The addition of recycled brick powder and recycled concrete powder will cause negative changes in the freeze–thaw cycling performance of single cement adobe. When the content of recycled brick powder in grade I/II is between 2% and 6%, and the content of recycled concrete powder in grade I is between 2% and 6%, this effect is relatively weak.

Author Contributions: Conceptualization, M.Z. and H.H.; methodology, X.Z.; software, X.Z.; validation, M.Z., H.H. and X.Z.; formal analysis, M.Z.; investigation, M.Z., H.H. and X.Z.; resources, M.Z., H.H. and X.Z.; data curation, M.Z., H.H. and X.Z.; writing—original draft preparation, M.Z., H.H. and X.Z.; writing—review and editing, M.Z., H.H. and X.Z.; visualization, M.Z.; supervision, X.Z.; project administration, X.Z.; funding acquisition, H.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Key R&D and Promotion Projects in Henan Province (212102310288).

Data Availability Statement: The tables used to support the findings of this study are included in the article.

Acknowledgments: The authors would like to show sincere thanks to those who have contributed to this research.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Salih, M.M.; Osofero, A.I.; Imbabi, M.S. Critical Review of Recent Development in Fiber Reinforced Adobe Bricks for Sustainable Construction. *Front. Struct. Civ. Eng.* **2020**, *14*, 839–854. [CrossRef]
2. Sipahi, S.; Kulözü-Uzunboy, N. A Study on Reducing the Carbon Footprint of Architectural Buildings Based on Their Materials under the Guidance of Eco-Design Strategies. *Clean Technol. Environ. Policy* **2021**, *23*, 991–1005. [CrossRef]
3. Muñoz, P.; Letelier, V.; Muñoz, L.; Bustamante, M.A. Adobe Bricks Reinforced with Paper & Pulp Wastes Improving Thermal and Mechanical Properties. *Constr. Build. Mater.* **2020**, *254*, 119314. [CrossRef]
4. Costa, C.; Cerqueira, Â.; Rocha, F.; Velosa, A. The Sustainability of Adobe Construction: Past to Future. *Int. J. Archit. Herit.* **2019**, *13*, 639–647. [CrossRef]
5. Gandia, R.M.; Gomes, F.C.; Corrêa, A.A.R.; Rodrigues, M.C.; Mendes, R.F. Physical, Mechanical and Thermal Behavior of Adobe Stabilized with Glass Fiber Reinforced Polymer Waste. *Constr. Build. Mater.* **2019**, *222*, 168–182. [CrossRef]
6. Wang, Q.; Chen, L.; Hu, R.; Ren, Z.; He, Y.; Liu, D.; Zhou, Z. An Empirical Study on Waste Generation Rates at Different Stages of Construction Projects in China. *Waste Manag. Res.* **2020**, *38*, 433–443. [CrossRef]
7. Li, X.; Qin, D.; Hu, Y.; Ahmad, W.; Ahmad, A.; Aslam, F.; Joyklad, P. A Systematic Review of Waste Materials in Cement-Based Composites for Construction Applications. *J. Build. Eng.* **2022**, *45*, 103447. [CrossRef]
8. Loizou, L.; Barati, K.; Shen, X.; Li, B. Quantifying Advantages of Modular Construction: Waste Generation. *Buildings* **2021**, *11*, 622. [CrossRef]

9. Akinwande, A.A.; Adediran, A.A.; Balogun, O.A.; Adesina, O.S.; Owa, A.F.; Ademati, A.O.; Olorunfemi, B.J.; Emmanuel, A. Recycling of Synthetic Waste Wig Fiber in the Production of Cement-Adobe for Building Envelope: Physio-Hydric Properties. *Int. J. Eng. Res. Afr.* **2022**, *59*, 57–75. [CrossRef]
10. Ige, O.; Danso, H. Experimental Characterization of Adobe Bricks Stabilized with Rice Husk and Lime for Sustainable Construction. *J. Mater. Civ. Eng.* **2022**, *34*, 04021420. [CrossRef]
11. Dormohamadi, M.; Rahimnia, R. Combined Effect of Compaction and Clay Content on the Mechanical Properties of Adobe Brick. *Case Stud. Constr. Mater.* **2020**, *13*, e00402. [CrossRef]
12. Jokhio, G.A.; Al-Tawil, Y.M.Y.; Mohsin, S.M.S.; Gul, Y.; Ramli, N.I. Compressive and Flexural Experiments on Adobe Samples Reinforced with Wire Mesh. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *318*, 012030. [CrossRef]
13. Lara-Ojeda, R.A.; Miranda-Vidales, J.M.; Narváez-Hernández, L.; Lozano-de Poo, J.M. A New Mixture Criterion for the Improvement of the Compressive Strength of Adobe Using Zeolite as Stabilizer. *KSCE J. Civ. Eng.* **2022**, *26*, 3549–3559. [CrossRef]
14. Zaidi, A.; Izemmouren, O.; Taallah, B.; Guettala, A. Mechanical and Durability Properties of Adobe Blocks Filled with Date Palm Wastes. *World J. Eng.* **2021**, *19*, 532–545. [CrossRef]
15. Olacia, E.; Pisello, A.L.; Chiodo, V.; Maisano, S.; Frazzica, A.; Cabeza, L.F. Sustainable Adobe Bricks with Seagrass Fibres. Mechanical and Thermal Properties Characterization. *Constr. Build. Mater.* **2020**, *239*, 117669. [CrossRef]
16. Yue, J.; Zhang, Y.; Li, P.; Zhang, J.; Huang, X.; Yue, Y.; Han, Z. Experimental Study on the Mix Ratio of Restored Heritage Building Adobe. *Materials* **2022**, *15*, 4034. [CrossRef]
17. Bertelsen, I.M.G.; Belmonte, L.J.; Fischer, G.; Ottosen, L.M. Influence of Synthetic Waste Fibres on Drying Shrinkage Cracking and Mechanical Properties of Adobe Materials. *Constr. Build. Mater.* **2021**, *286*, 122738. [CrossRef]
18. Evangelista, L.; De Brito, J. Environmental Life Cycle Assessment of Concrete Made with Fine Recycled Concrete Aggregates. In *Portugal SB07—Sustainable Construction, Materials, and Practices: Challenge of Industry for the New Millenium*; IOS Press: Amsterdam, The Netherlands, 2007; pp. 789–794. [CrossRef]
19. Pilipenko, A.; Bazhenova, S.; Kryukova, A.; Khapov, M. Decorative Light Transmitting Concrete Based on Crushed Concrete Fines. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *365*, 32046. [CrossRef]
20. Kawalec, J.; Kwiecien, S.; Pilipenko, A.; Rybak, J. Application of Crushed Concrete in Geotechnical Engineering—Selected Issues. *IOP Conf. Ser. Earth Environ. Sci.* **2017**, *95*, 22057. [CrossRef]
21. Ivannikov, A.L.; Kongar-Syuryun, C.; Rybak, J.; Tyulyaeva, Y. The Reuse of Mining and Construction Waste for Backfill as One of the Sustainable Activities. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *362*, 12130. [CrossRef]
22. Xiao, J.; Ma, Z.; Sui, T.; Akbarnezhad, A.; Duan, Z. Mechanical Properties of Concrete Mixed with Recycled Powder Produced from Construction and Demolition Waste. *J. Clean. Prod.* **2018**, *188*, 720–731. [CrossRef]
23. Hussain, M.; Levacher, D.; Leblanc, N.; Zmamou, H.; Djeran-Maigre, I.; Razakamanantsoa, A.; Saouti, L. Reuse of Harbour and River Dredged Sediments in Adobe Bricks. *Clean. Mater.* **2022**, *3*, 100046. [CrossRef]
24. Reyes, J.C.; Yamin, L.E.; Hassan, W.M.; Sandoval, J.D.; Gonzalez, C.D.; Galvis, F.A. Shear Behavior of Adobe and Rammed Earth Walls of Heritage Structures. *Eng. Struct.* **2018**, *174*, 526–537. [CrossRef]
25. Sajid, S.; Chouinard, L. Impulse Response Test for Condition Assessment of Concrete: A Review. *Constr. Build. Mater.* **2019**, *211*, 317–328. [CrossRef]
26. Medvey, B.; Dobszay, G. Durability of Stabilized Earthen Constructions: A Review. *Geotech. Geol. Eng.* **2020**, *38*, 2403–2425. [CrossRef]
27. *ASTM D 559-03*; Standard Method of Test for Wetting-and-Drying Test of Compacted Soil-Cement Mixtures. ASTM International: West Conshohocken, PA, USA, 2003.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.