Influence of Recycled Concrete Powder (RCP) and Recycled Brick Powder (RBP) on the Physical/Mechanical Properties and Durability of Raw Soil

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Abstract: The influence of recycled concrete powder (RCP) and recycled brick powder (RBP) on the dry density, optimal water content, and compressive strength of raw soil materials was investigated in this study. Moreover, the following resistance of freeze–thaw cycles was also considered. Additionally, X-ray diffraction (XRD) and scanning electron microscope (SEM) were selected to detect its mineral composition and observe the microstructure, further revealing the mechanism of performance change. The mass ratios of recycled concrete powder and recycled brick powder were 2~14%. Results showed that the dry density decreased and the optimal water content increased with the increasing dosage of recycled concrete powder and recycled brick powder. When the dosage of RCP or RBP was lower than 14%, raw soil with RCP showed higher optimal water content and lower dry density. However, when the dosage was higher than 14%, the result was the opposite. The addition of recycled concrete powder and recycled brick powder was able to decrease the compressive strength of raw soil, except for 10% of recycled brick powder. Raw soil with recycled brick powder presented higher compressive strength than that of raw soil with recycled concrete powder. RBP could improve the freeze–thaw cycles’ resistance of specimens; however, RCP led to decreasing the resistance of freeze–thaw cycles. These research findings can provide reference to the recycling of construction waste.

Keywords: recycled concrete powder; recycled brick powder; dry density; optimal water content; compressive strength; freeze–thaw cycles; water absorption

1. Introduction

The source of building materials is very extensive. Artificial construction building materials, such as cement and other binder materials, release large amounts of harmful gas during production. For eco-environmental production needs, construction building materials should be manufactured without harmful substances. Raw soil is clean production produced by natural, undisturbed soil as the main raw material. The raw soil can be used in house construction through simple processing without high-temperature treatment [1,2]. Compared with modern building materials, raw soil materials possess thermal insulation performance, which not only maintains its ecological and natural essence but also can be recycled [3,4]. The history of raw soil architecture can be traced back to 8000 years ago; but its low strength and poor durability restrict its application in modern architectural engineering. How to improve the strength and durability of raw soil material while ensuring its excellent thermal insulation performance is the critical factor to its popularization and application.

Aiming at solving this problem, scholars at home and abroad have made a lot of exploration and research on the modification of raw soil materials [5–25]. The addition
of cement, lime, and fiber can change the mineral composition and microstructure from the perspective of chemistry and physics. Recycled micro powders are powder particles with particle sizes of less than 0.075 mm, obtained from the regeneration treatment of construction waste. This kind of materials is composed of amorphous SiO$_2$ and Al$_2$O$_3$, possessing a micro aggregate effect and certain potential activity. The recycled micro powder is in a trial stage, and it is mostly used as mineral admixture to replace cement in different proportions for concrete and its products [26–28]. Many studies about waste-modified raw soil materials have been reported. Kasinikota et al. [29] reported that brick waste can significantly improve the durability of raw soil materials. Bogas et al. [30] pointed out that the addition of 4% of recycled aggregate can improve the waterproof performance of raw soil materials. Qian et al. [31,32] discovered that desulfurization waste from coal-fired power plants was able to modify raw soil materials and improve the strength of raw soil materials, leading significantly to reducing the drying shrinkage and finally improving the water resistance.

However, the study on the modification of raw soil materials with recycled micro powder has not been reported. Exploring the mechanism of recycled micro powder-modified raw soil materials and the feasibility of an engineering application can support the expansion of the application field of recycled micro powder and improve the green level of raw soil buildings. Moreover, the influence of freeze–thaw cycles on the properties' decay of raw soil has not been reported.

In this study, the influence of the recycled micro powder on the density and mechanical strengths of raw soil materials with recycled concrete powder (RCP) and the recycled brick powder (RBP) is reported. Moreover, the following freeze–thaw resistance, the loss performance, and the influence of recycled micro powders on the microstructures were researched.

2. Experimental Section

2.1. Raw Materials

The raw soil (RS) was provided by Beijing General Research Institute of Building Materials Science Co., Ltd., Beijing, China, possessing the air-drying water content of 1.5%, the plasticity index of 14.44%, and the maximum dry density of 1.79 g/cm$^3$. The recycled micro powder included recycled concrete powder (RCP) and recycled brick powder (RBP), manufactured by Beijing solid waste Tong solid waste resource utilization Co., Ltd., Beijing, China, was used in this research. Table 1 and Figure 1 show the chemical compositions and particle passing percentages of raw soil, RCP, and the RBP. The particle size was obtained by a Mastersizer 3000 Laser Particle Size Analyzer (Malvern Instruments Co., Ltd., Malvern, UK). Table 2 shows the mixing proportions of the specimens.

Table 1. Main chemical compositions (%).

| Types | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | CaO | K$_2$O | MgO | Na$_2$O | TiO$_2$ | SO$_3$ |
|-------|---------|-------------|------------|-----|--------|-----|---------|--------|--------|
| RS    | 63.0298 | 17.6545     | 6.7301     | 3.9416 | 3.4703 | 2.2331 | 1.2623  | 0.9268 | -      |
| RBP   | 51.1530 | 12.8542     | 5.3402     | 19.5833 | 2.5918 | 5.2535 | 1.5004  | -      | 0.6033 |
| RCP   | 43.4490 | 9.9166      | 4.5731     | 28.3367 | 2.1488 | 8.5441 | 1.1369  | -      | 0.7135 |
2.2. Samples’ Preparation and Measurement

The maximum dry density and optimal water content were determined by a light compaction method, according to GB/T50123-2019 [33].

The optimal water content and the maximum dry density were determined following these steps:

The basic water content of the soil was 12%. Five samples were prepared for each group with a difference of 2% of water added in turn. The soil was tamped by a BKJ-III multifunctional electric compaction instrument of Beijing tianchangtongda Instrument Co., Ltd., Beijing, China. The Tcy-20 hydraulic electric demolder was used for demolding. The specimens were prepared by tamp forming. The raw materials were poured into the molds at three layers after mixing. Before the tamping of each layer, the tamped surface of the previous layer should have been roughened. After the tamp forming, the specimens with sizes of 40 mm × 40 mm × 40 mm were prepared. All specimens were dried in the DHG-P240B electric constant temperature blast-drying oven at the temperature of 60 ± 5 °C for 24 h to a constant weight. After this step, the samples were used for the measurement of the maximum dry density and the corresponding optimal water content. After that, all specimens were taken out and placed in a room at 20 ± 5 °C for cooling for 20 min. After the cooling, the specimens were placed in the concrete slow-freezing...
box with the pneumatic air melting. Each freeze–thaw cycle included freezing for 2 h at −20 °C and melting for 2 h at 20 °C. When 20 freeze–thaw cycles were finished, the mass and mechanical strengths of the specimens were determined. The water absorption and desorption rates were tested following these steps:

The dried samples were placed in a standard curing room (a temperature of 20 ± 2 °C and a humidity of 95%) and the mass was tested for 24 h; the mass increasing rate was defined as water absorption rates. After the determination of water absorption rates was finished, the samples were removed to the environment with a temperature of 20 ± 2 °C and a humidity of 40%. The method of mass test was the same as that of the determination of water absorption rates. The mass increasing rate was calculated after the mass weighing was finished.

The scanning electron microscopy (SEM) was observed by a JSM-6360LV scanning electron microscope (Japan electron optics laboratory, Tokyo, Japan) and X-ray diffraction (XRD) spectrum was obtained by a D8 discover X-ray diffractometer of Brooke company, Berlin, Germany, respectively. A Gemini SEM 300 field emission scanning electron microscope was selected to observe the microstructure of specimens. Before the XRD measurement, all samples were dried in the electrothermal blower-dryer at the temperature of 60 ± 5 °C for 3 days. After drying, all samples were cooled at room temperature (20 ± 2 °C) for 2 h. The central fragments of samples were taken out and ground into powder by mortar. The ground powder was used for the XRD research after passing a 45-µm square hole sieve-screening treatment. The surfaces of the dried testing samples were sprayed with gold. After that, the samples were used for determination by the Gemini SEM 300 field emission scanning electron microscope.

3. Results and Discussion

3.1. Mechanical Properties

Figure 1 depicts the particle size distributions of raw materials. As shown in Figure 1, the particle sizes of RS, RBP, and RCP were 1–100 µm, 0.5–200 µm, and 0.7–800 µm, respectively. Moreover, the peak values of bulk density of RS, RBP, and RCP corresponded to the particle sizes of 50, 61.2 and 5.4 µm, respectively. As obtained from Figure 1, fineness decreased in this order: RCP > RS > RBP.

Figure 2 shows the maximum dry density and optimal water content of raw soil materials with different dosages of recycled powder. As can be observed from Figure 2, the maximum dry density of raw soil materials decreased with the increasing dosage of recycled powder. Moreover, the optimal water content of RBP and RCP increased obviously with the dosage of recycled powder ranging from 0% to 10% or 20%. However, when the dosage of recycled powder increased from 10% to 30% or increased from 20% to 30%, the optimal water content of RBP and RCP reached stable values. When the content of recycled powder was lower than 10%, the RBP showed lower maximum dry density and higher optimal water content. However, when the content of recycled powder was equal to or higher than 10%, the result was the opposite. The increasing dosage of micro powder could lead to decreasing the pore barrier in the material, which affects the electrostatic attraction and Van der Waals force between particles. At the same time, the sliding friction between micro powder and soil particles in the process of reorientation and arrangement decreased, resulting in the reduction of maximum dry density [34]. As can be obtained from Figure 2, the relationships of the maximum dry density and the optimal water content corresponded to the cubic function. The fitting degrees of all curves were higher than 0.90, indicating the rationality of fitting results.
Figure 2. The maximum dry density and optimal water content of raw soil materials.

Figure 3 shows the compressive strength of recycled micro-powder raw soil materials. All specimens were cured at the temperature of 20 ± 2°C and relative humidity of 40 ± 2% for 3, 7, and 28 days, respectively. As depicted in Figure 3, the compressive strength decreased with the increasing dosages of RBP and RCP (besides the condition of raw soil materials with 10% RBP cured for 28 days). However, the compressive strength of soil materials increased with the increasing curing age. Furthermore, the soil materials with RBP demonstrated higher compressive strength than that with RCP. This was attributed to the fact that the RBP showed higher activity, which could promote the hydration of raw materials, leading to forming more hydrated calcium silicates and calcium hydroxides, thus increasing the compressive strength of soil materials [35–37].
3.2. Durability

Figure 4 depicts the mass of specimens during this time. As illustrated in Figure 4, the mass of specimens increased rapidly with the time ranging from 1 to 7 days (the moisture absorption rate was higher than 5%). Meanwhile, when the time increased from 7 to 16 days, the mass of specimens varied stably. When the time was 13 days, the mass of specimens reached the maximum values. This was attributed to the fact that a lot of micro pores and micro gaps on the surface of raw soil materials and inside raw soil particles. The water absorption process was mainly surface physical adsorption within 7 days, and the water absorption rate was fast, which accounted for the main part of the water absorption quality of raw soil materials. However, when the time was higher than 7 days, the surface physical adsorption was finished and the mass of specimens rarely changed. At this stage, the hydration process was the main reason for the mass variation of specimens [38]. When the time was 13 d, the hydration process was basically complete and the mass of specimens reached the maximum value. However, when the time increased from 13 to 16 days, the mass decreased slowly due to some damages in the raw soil. When the dosage of RBP or RCP ranged from 2% to 10%, the mass of absorbed water decreased due to the filling effect. However, when the dosage of RBP or RCP increased from 10% to14%, the absorbed water decreased due to damage of water absorption expansion. Raw materials with RCP showed higher water absorption performance.

Figure 5 shows the mass and compressive loss rates of recycled micro powder raw soil materials. As illustrated in Figure 5, the mass and compressive strength loss rates increased with the increasing dosage of recycled powder due to the surface spalling and inner cracks of raw soil materials [39,40]. As can be observed from Figure 5, the compressive strength loss rates of raw soil materials with RCP were higher than that with RBP. This was attributed to the fact that RBP with higher activity led to more adequate hydration and compactness of raw soil materials [41]. Moreover, the granularity of RBP was more similar to that of RCP, resulting in a better filling effect of raw soil. Therefore, the frozen-heave stress was decreased, thus improving the resistance of freeze–thaw cycles.
3.3. Microscopic Analysis

Figure 6a shows the XRD images of RBP-10%, RCP-10%, and RS-100% cured for 28 days. Figure 6b,c shows RBP-10% with different curing ages and RCP-10% with different curing ages, respectively. The boxes in the figures indicate the same chemical compound. As illustrated in Figure 6a, Compared with RS-100%, the characteristic peaks of Ca(OH)$_2$, SiO$_2$, and AFt of RCP-10% were more obvious, while RCP-10% showed the highest characteristic peaks of Ca(OH)$_2$, SiO$_2$, and CaCO$_3$ than that of RS-100%. It can be observed from Figure 6b that the characteristic peaks of Ca(OH)$_2$, AFt, and CaCO$_3$ increased with the curing ages.
However, when the curing age increased, the characteristic peak of SiO$_2$ rarely changed. This was attributed to the higher activity of RBP and the carbonization of Ca(OH)$_2$. As seen in Figure 6c, the increase of curing ages resulted in higher characteristic peaks of Ca(OH)$_2$ and Aft [42–44]. However, with the increasing curing ages, little change occurred to the characteristic peaks of CaCO$_3$.
The microstructures of specimens with 100% RS, 10% RBP, and 10% RCP were clearly observed by SEM images, as shown in Figure 7. As illustrated in Figure 7, the structure of specimens with 100% RS, formed by the bonding of soil particles, was relatively loose and the pores were unevenly distributed. The structural units distributed around the pores and soil particles were embedded within each other [45]. It can be observed in Figure 7 that specimens with 10% RCP contained more cracks than the specimens with 10% RBP and specimens with 100 RS, indicating that the specimens with 10% RCP possessed lower mechanical strength.

4. Conclusions

In this study, the physical and mechanical properties and durability of raw soil with recycled concrete powder and recycled brick powder were investigated. The conclusions are summarized as follows.

The dry density of raw soil decreased in quadratic function with the increasing dosage of recycled concrete powder and recycled brick powder. However, the relationships
between the dosages of recycled concrete powder/recycled brick powder and the optimal water content were positive quadratic functions.

When the dosage of recycled concrete powder or recycled brick powder was lower than 14%, the raw soil with recycled concrete powder showed higher water content and lower dry density. However, when the dosage was higher than 14%, the result was the opposite.

The recycled concrete powder and recycled brick powder led to decreasing the compressive strength of raw soil, except 10% recycled brick powder. The compressive strength of raw soil with recycled brick was higher than that of raw soil with recycled concrete powder.

The freeze–thaw cycles’ resistance of specimens was the best, while the addition of recycled concrete powder could result in decreasing the resistance of freeze–thaw cycles. The water absorption rates of raw soil with 10% recycled brick powder or recycled concrete powder were the highest of all dosages. The raw soil with recycled concrete powder showed higher water absorption than that with recycled brick powder. These research findings can provide reference to the recycling of construction waste.

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