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Case study

Mechanical properties of excavated soil waste-based cementitious products at normal condition or after water soaked: A literature review of experimental results

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A R T I C L E I N F O

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A B S T R A C T

Excavated soil waste is one of the construction wastes generated from building foundation pit excavation, tunnel excavation, channel excavation and other engineering excavations. In order to reuse the excavated soil waste in civil engineering, this paper presents a literature review on the feasibility of using excavated soil waste as fine replacements in cementitious products. With the help of existing experiments reported in the literature, a data-driven analysis was conducted on the mechanical properties of excavated soil-based cement mortar, geopolymer, unfired clay bricks and concrete at normal condition (e.g., room temperature and atmospheric moisture) or after water soaked. The influence of excavated soil replacing river sand (i.e., fine aggregate) or binding materials, curing age, thermal treatment, dry sieving process and stabilization process, etc. on the compressive strength, flexural strength and modulus of elasticity of cementitious materials was discussed. The comparative results show that the excavated soil-based products can achieve acceptable mechanical properties when employing physical approaches (e.g., thermal treatment, sieving and grinding) acting on or mixing stabilizer into excavated soil.

1. Introduction

The development of urbanization improves the living standard of human beings and meanwhile generates a large number of construction and demolition wastes (CDW) [1–3]. Excavated soil waste is one of the construction wastes generated from building foundation pit excavation, tunnel excavation and channel excavation, which is characterized with large in quantity, land occupation and environmental damage [4,5]. Zhang et al. [6] characterized the generation and environmental impacts of subway-related excavated soil in China and estimated that the excavated soil construction approximately exceeds 200 million m^3 by 2030. Therefore, it is very meaningful to find a solution to use the excavated soil waste in high value-added cleaner construction products [7–10].

In order to protect nature resources and reduce the environmental impact, numerous research and engineering practices have been conducted on the reuse of excavated soil waste in civil engineering. Karen et al. [11] proposed a methodological flowchart to support

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reuse strategies of soils for urban areas based on current characterization tests. Javier et al. [12] evaluated the lab and in situ mechanical properties of non-selected mixed recycled aggregates containing excavated soil. Their test results show that low quality recycled aggregates can be used as substitutes for natural aggregates as unbound layers. Priyadharshini et al. [13–16] performed experimental studies on the feasibility of using excavated soil waste as fine replacements in cementitious materials considering its particle size characteristic. A series of cementitious products, such as cement mortar [17], geopolymer [18], unfired clay bricks [19–24] and concrete [25,26], were the application objects for use of excavated soil waste to replace fine aggregates or binding materials. Available experimental investigations [13–26] reported the mechanical properties of these cementitious products under normal condition or after various external actions (e.g., water immersion, chloride ions invasion and temperature); and the mechanical properties of excavated soil-based cementitious products are not very stable, which is due to the wide range sources of excavated soil. The discreteness of target properties can lead to increase the difficulty in promoting the application of excavated soil waste in cementitious products. Therefore, it is necessary to summarize and review the current technical merits and deficiencies to gain sufficient confidence to properly reuse this construction waste.

The aim of this paper is to present the feasibility of using excavated soil waste as fine replacements in cementitious products from the perspective of mechanical properties. The methodology employed in this paper is the literature review. The layout of technical details of this investigation can be divided into two sections, that is: *i*) literature review (Section 2); *ii*) conclusions and outlooks (Section 3).

2. Mechanical properties of cementitious products

2.1. Cement mortar

Replacing river sand (i.e., natural fine aggregate) using excavated soil in cement mortar is one of the potential solutions to consume this construction waste. Priyadharshini et al. [13–16] and Wu et al. [17] contributed themselves a lot to this field.

Priyadharshini et al. [14] examined the effect of total replacement of river sand with raw excavated soil on the behavior of cement mortar. Two excavated soils (i.e., excavated soil-1 and excavated soil-2) from different sources were used to replace the river sand. It was reported that excavated soil-2 had a larger plastic nature and exhibited finer particles compared to excavated soil-1. For the reference study, the cement mortar made of river sand was also fabricated and investigated in Priyadharshini et al. [14]'s study. The sequence of plastic nature of fine aggregates can be reached as: river sand<excavated soil-1 <excavated soil-2. Raw excavated soils were finer than river sand. A test variable with respect to mortar mixture, i.e., fine aggregate-to-cement ratio, was considered varying from 3 to 5 by weight. No detailed water content was reported for the mortar mixture. However, the water content required to maintain a constant workability of 110 ± 5% was measured. In each mortar mixture, six cube specimens with 50 mm were prepared to test the compressive strength. Fig. 1 shows the effect of fine aggregate-to-cement ratio on the compressive strength of cement mortar. Regardless of fine aggregate type, increasing the fine aggregate-to-cement ratio leads to a decrease in the compressive strength of cement mortar. This reduction is attributed to the low cement content used for binding the aggregate. Cement mortar made of river sand exhibits the largest compressive strength and the excavated soil-2-based cement mortar has the smallest one, which indicates that the fine aggregate with larger plastic nature is the genesis of lowing the compressive strength of cement mortar.

In order to improve the compressive strength of excavated soil-based cement mortar, Priyadharshini et al. [15]'s adopted the thermal treatment on excavated soil and then manufactured the cement mortar with thermally treated excavated soils. Two types of excavated soils with medium plasticity (MP) and high plasticity (HP) were respectively used. Before fabricating cement mortar, the excavated soils were thermally treated at temperatures of 200 °C, 400 °C, 600 °C, 800 °C, and 1000 °C. For each temperature, the

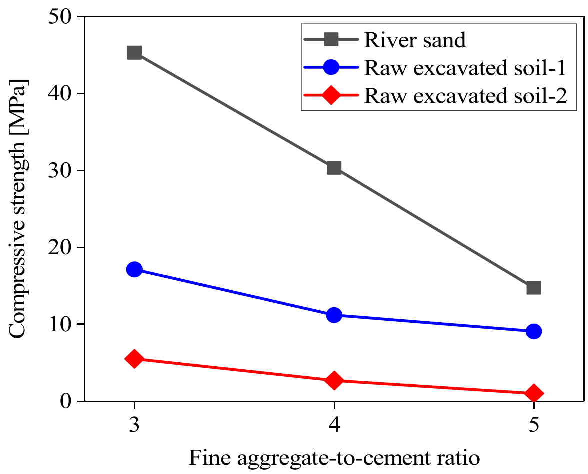


Fig. 1. Effects of fine aggregate-to-cement ratio on compressive strength of cement mortar.
Data from Priyadharshini et al. [14].

duration of thermal treatment varied from 30 to 180 min. River sand and untreated excavation soil were respectively used as the fine aggregate in the benchmark mortar. The ratio of fine aggregate-to-cement in mortar mixture was fixed at 3 by weight. The amount of water required to maintain a constant flow of 110% ± 5% was determined. In each mortar mixture, six cube specimens with 50 mm were prepared to test the compressive strength. Fig. 2 shows the effect of temperature and duration of thermal treatment on the compressive strength of cement mortar containing thermally treated excavated soils. It can be seen that even for the excavated soils after thermal treatment, the compressive strength of cement mortar made of river sand is larger than that of excavated soil-based cement mortar, but increasing the temperature and duration of thermal treatment on excavated soil can help the strength growth approaching to the strength level of river sand-based cement mortar. This is because the plastic nature of excavated soil cannot be totally changed to the nature like river sand even with thermal treatment. Compared to the medium plasticity soil, the high plasticity excavated soil drives to more improvement of the compressive strength of cement mortar after thermal treatment. The reason explained by Priyadharshini et al. [15] is attributed to the temperature requirement to activate illite, which is why there was a marked difference in the effect of duration only at 1000 °C.

Priyadharshini et al. [16] explored other solutions to increase the compressive strength of excavated soil-based cement mortar, including dry sieving process and stabilization process. Excavated soils with low plasticity, medium plasticity and high plasticity were the fine aggregate to manufacture cement mortar. Dry sieving was performed using a sieve with 600 mm size to remove clay and silt. Priyadharshini et al. [16] reported that although dry sieving processing on excavated soils, the adhesive nature of clay to the sand particle cannot be completely removed. Cementitious stabilizer containing reactive silica–alumina with $Ca(OH)_2$ (commercially called GGBS) and hydraulic stabilizer with 97% of $Ca(OH)_2$ (lime) were employed as stabilizers. The respective dosages of lime up to 10% and GGBS up to 20% were used in the mortar mixture. Apart from stabilizers, the basic mixtures of cement mortar were kept same with those presented in Priyadharshini et al. [15]. In each mortar mixture, six cube specimens with 50 mm were prepared to test the compressive strength. Fig. 3 shows the effect of dry density on the compressive strength of cement mortar with dry sieved and stabilized excavated soils. It can be seen from the figure that increasing the dry density results in a larger compressive strength of excavated soil-based cement mortar. This characteristic meets the basic regulation in cementitious materials. Improving the stabilizer dosage increases the compressive strength of cement mortar with stabilized excavated soil. For a certain stabilizer dosage, the medium and high plastic excavated soil-based cement mortars containing slag stabilization have larger compressive strength with reference to the mortar with lime stabilization, which can be explained that the slag contributes to the density increase of mortar due to the formation of dense microstructure. The compressive strength of sieved and stabilized excavated soil-based cement mortar is almost twice higher than that of cement mortar made of unsieved excavated soil. This indicates that in addition to the effect of stabilization, the improvement of particle size (i.e., finer) has a positive influence on the compressive strength.

Wu et al. [17] adopted excavated soil to partially or fully replace the river sand to prepare cement mortar. In Wu et al. [17]'s study, three batches of excavated soil from different construction sites were used to investigate their feasibility in cement mortar, that is: Type I excavated soil, Type II excavated soil and Type III excavated soil. It is worth noting that both Type I and Type II excavated soils were the granite weathered residual soil, and Type III excavated soil was the alluvial diluvial soil. These two series of soils are widely distributed in Southern China. In order to meet the fineness modulus of commonly-used river sand, two treatments including dry-sieving & grinding and dry-sieving were respectively employed to process the granite weathered residual soil and alluvial diluvial soil. The reason of using dry-sieving & grinding method is that the granite weathered residual soil contains a lot of low-strength cohesive soil lumps; and with this method, this soil can be broken down into small particles.

In Wu et al. [17]'s tests, the grade of ordinary Portland cement was 42.5 R, and the water reducing agent was the RPC-H polycarboxylic acid solution by mass fraction equal to 10%. The flexural and compressive loading tests were conducted to the cement mortar prism specimens with a dimension of 40 mm × 40 mm× 160 mm. Different replacement ratios of excavated soil-to-total fine

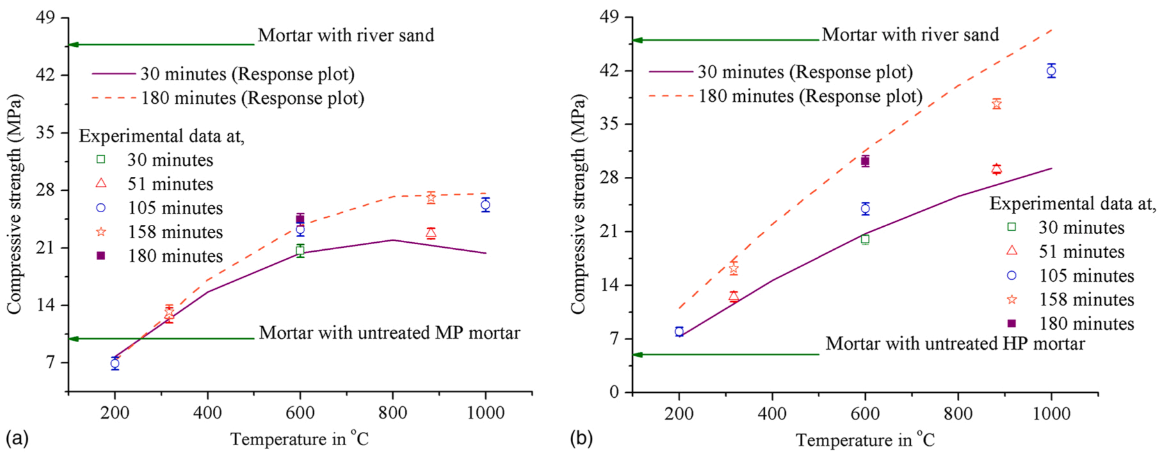


Fig. 2. Effects of temperature and duration of thermal treatment on compressive strength of cement mortar containing thermally treated excavated soils: (a) medium plastic soil; and (b) high plastic soil.
Figure from Priyadharshini et al. [15].

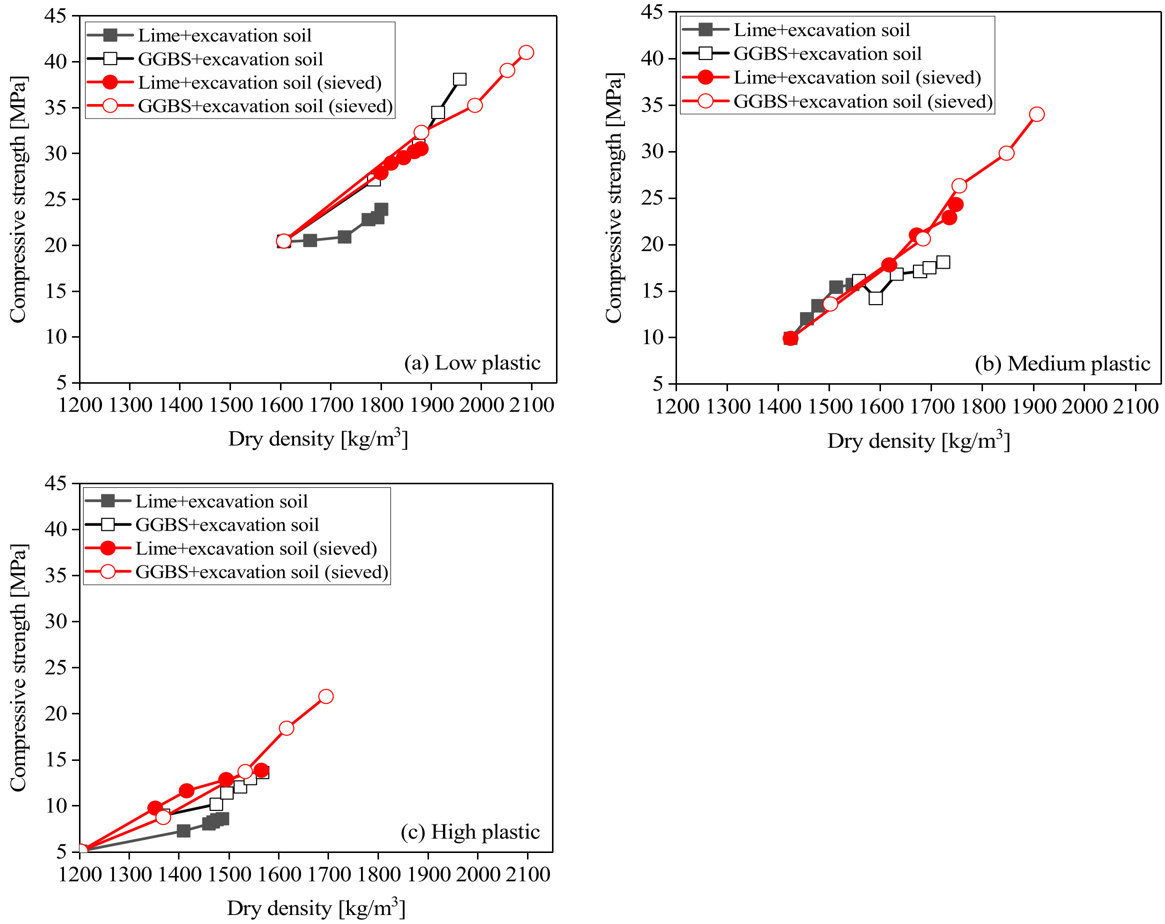


Fig. 3. Effect of dry density on compressive strength of cement mortar with dry sieved and stabilized excavated soils.
Data from Priyadharshini et al. [16].

aggregate by mass (i.e., *R*) were adopted: *i*) for granite weathered residual excavated soil, *R*= 0, 30%, 50% and 70%; *ii*) for alluvial diluvial excavated soil, *R*= 0, 30%, 50%, 70% and 100%. In order to obtain the stable workability of cement mortar, their consistency needs to be controlled to the value varying from 50 mm to 90 mm. Based on this consideration, the dosage of water reducing agent increased with an increase of replacement ratio of excavated soil-to-total fine aggregate. The measured flexural strength, compressive strength and modulus of elasticity of excavated soil-based cement mortar as a function of *R* are presented as follows.

Fig. 4 shows the flexural strength of excavated soil-based cement mortar at different curing ages (i.e., 7d, 14d and 28d). It can be seen that the flexural strength of all excavated soil-based cement mortars with different *R*(s) improves when the curing age increases, indicating that the hydration reaction of cement to fine aggregate becomes larger as time goes on. In the cases of Type I and Type II excavated soils, two different trends can be found in terms of the relationship between flexural strength and *R*, that is: *i*) for *R* no more than 30%, increasing *R* leads to increase the flexural strength; *ii*) for *R* larger than 30%, the flexural strength decreases with an increase of *R*. The reason can be explained by the microstructures recorded by scanning electron microscope (SEM) (see Fig. 5), that is: *i*) the cement mortar made of river sand (i.e., *R*=0) has a lot of C-S-H gel (i.e., the hydration products) and exhibits dense microstructures; *ii*) a large amount of C-S-H gel can still be observed in the cement mortar with *R*= 30%, and the filling effect of excavated soil makes the microstructure of mortar denser, which leads to the decrease of porosity; *iii*) for *R*= 50% and 70%, the hydration products in cement mortar decrease and a certain number of acicular AFt crystals appear with more loose microstructures, which is due to the excavated soil resulting in a negative effect on the cement hydration reaction. In the case of Type III excavated soil, the excavated soil-based cement mortar received a comparable flexural strength with a reference to natural fine aggregate-based cement mortar.

Fig. 6 shows the compressive strength of excavated soil-based cement mortar at different curing ages (i.e., 7d, 14d and 28d). It can be seen that the compressive strength of excavated soil-based cement mortar at any curing age and at a certain *R* has a relationship with fineness modulus of fine aggregate, that is: compressive strength of Type III excavated soil-based cement mortar (i.e., fineness modulus of excavated soil=3.1) > compressive strength of Type I excavated soil-based cement mortar (i.e., fineness modulus of excavated soil=2.4) > compressive strength of Type II excavated soil-based cement mortar (i.e., fineness modulus of excavated soil=2.3). This is because larger fineness modulus of fine aggregate leads to fill the voids of mortar better, i.e., denser. Similar to the flexural strength, increasing the curing age can significantly promote the compressive strength of excavated soil-based cement mortar. In the cases of

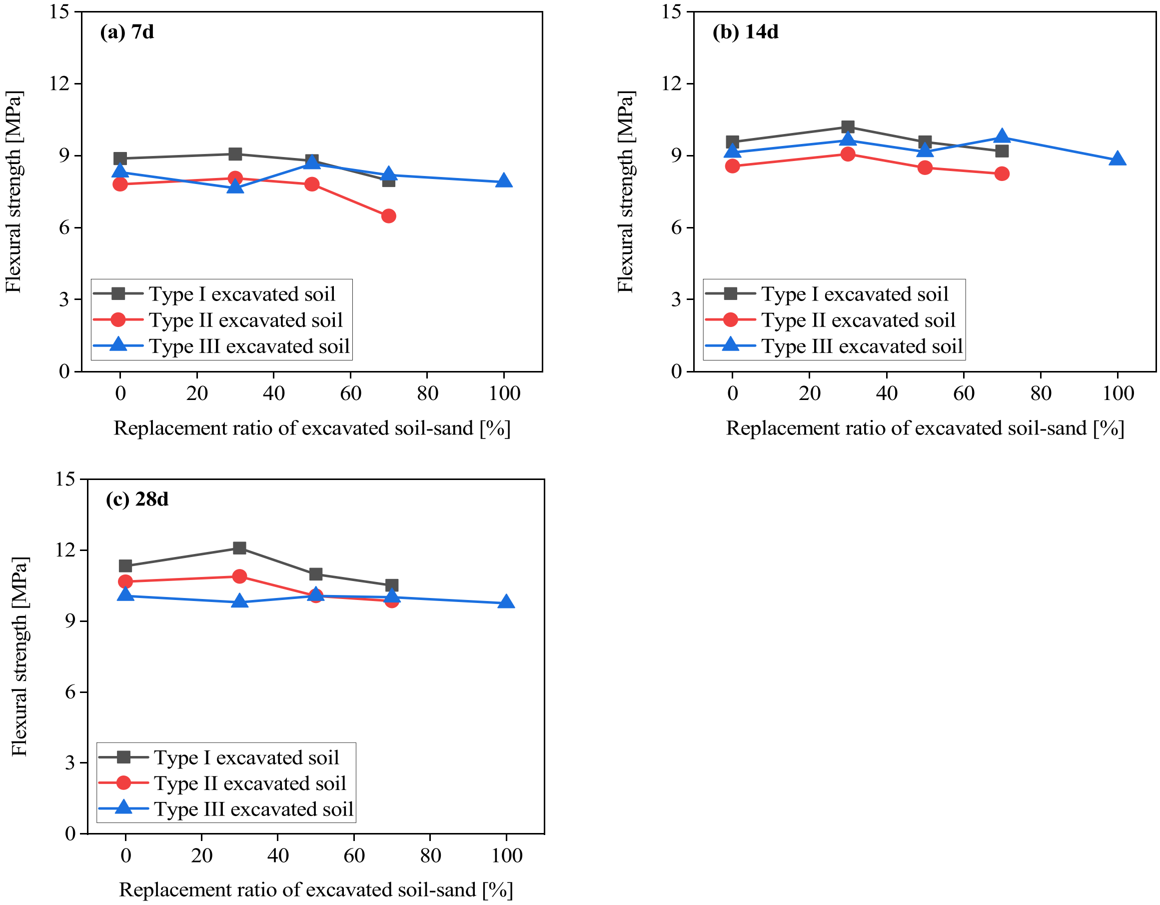


Fig. 4. Flexural strength of excavated soil-based cement mortar (Data from Wu et al. [17]).

Type I and Type II excavated soils, the compressive strength decreases with increasing R; while the cement mortar made of Type III excavated soil exhibits a comparable compressive strength with a reference to natural fine aggregate-based cement mortar. The effects of fineness modulus and R on the modulus of elasticity of excavated soil-based cement mortar are similar to their influence on the compressive strength (see Fig. 7).

From the perspective of flexural strength, compressive strength and modulus of elasticity, the cement mortar made of Type III excavated soil has stable mechanical properties regardless of R, which means that the alluvial diluvial soil replacing river sand is feasible to manufacture cement mortar.

2.2. Geopolymer

Wang et al. [18] employed excavated soil to replace fly ash to manufacture geopolymer. The dosage of mixture of each specimen is shown in Appendix A1. In this test, the used raw materials have the characteristics as follows:

(1) N_aOH were the chemically pure flake samples with a purity over 95%;
(2) Sodium silicate had a baume degree Be of 32°;
(3) Secondary fly ash was used;
(4) The main components of excavated soil were the silicon dioxide, albite, potassium feldspar, anorthite and ferric salts; and the partical size of excavated soil ranges from 5 mm to 10 mm.

Six replacement ratios of excavated soil-to-fly ash plus excavated soil by mass were adopted, that is: 0, 20%, 40%, 60%, 80% and 100%. All specimens were the prism with a dimension of 40 mm × 40 mm× 160 mm. Compressive and flexural loading tests on specimens were conducted after curing 3d, 7d and 28d.

Fig. 8 shows the compressive strength and flexural strength of excavated soil-based geopolymer at different curing ages. It can be seen from Fig. 8**(a)** that: *i*) the reference geopolymer (i.e., replacement ratio=0) at 3d and 7d reaches 86.6%– 94.5% of the 28d-compressive strength, indicating that geopolymer exhibits a high early-strength with a characteristic of rapid prototyping; *ii*) for

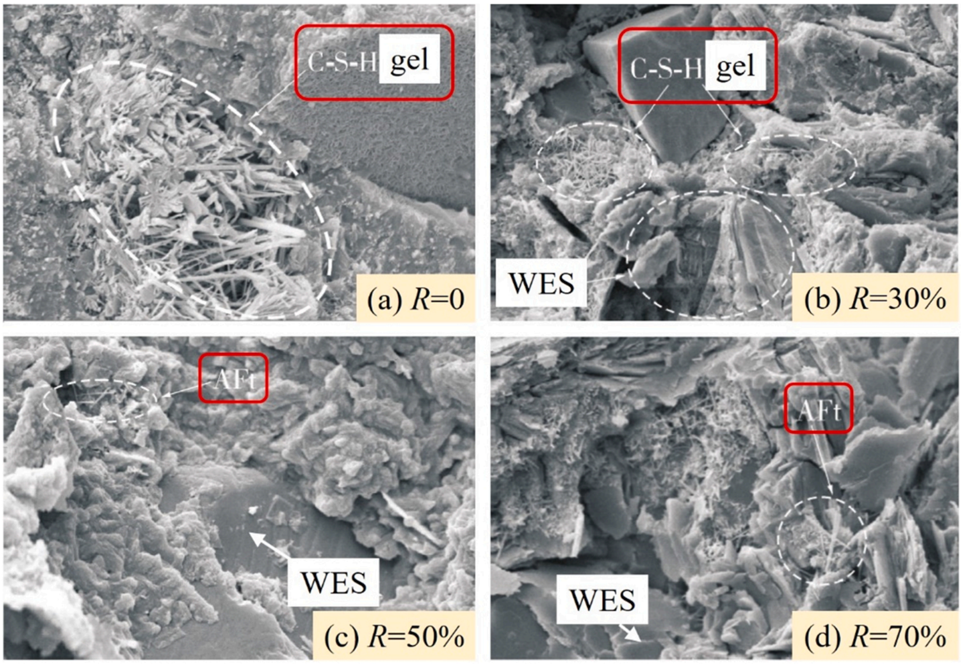


Fig. 5. Microstructures of Type I or Type II excavated soil-based cement mortar.
Images from Wu et al. [17].

the excavated soil-based geopolymer, the 3d-compressive strength is larger than the compressive strength at 7d and 28d, and the 28d-compressive strength is nearly comparable to the 7d-compressive strength; *iii*) increasing the replacement ratio leads to a decrease in the compressive strength regardless of curing age; and in particular, the excavated soil-based geopolymer has no compressive strength in the case of replacement ratio equal to 100%. Similar reduction of flexural strength as a function of replacement ratio can be found in Fig. 8**(b)**.

2.3. Unfired clay bricks

Guo et al. [19], Feng et al. [20] and Yao et al. [21] fabricated unfired clay bricks made of excavated soil and tested their physical and mechanical properties in the normal condition and after water soaked.

In Guo et al. [19]'s test, Portland slag cement with 42.5 MPa strength grade was used; admixture for modified slag cement was composed of alkali sulfate, carbonate and silicate; bonding agent was the polyvinyl alcohol, which was dissolved into 3.5% solution before use. The test specimens were designed as a cylinder with 30 mm in diameter and 30 mm in height. The test variable was the ratio of binding material-excavated soil. Five ratios were considered, that is: 1:12, 1:10, 1:8, 1:6 and 1:4. The briquetting pressure for fabricating cement-based bricks was 10 MPa.

Fig. 9 shows the mechanical and physical properties of excavated soil-based unfired clay bricks. For the normal condition, larger ratio of binding material-excavated soil trends to have higher compressive strength of bricks. At a certain ratio of binding material-excavated soil, increasing the curing age improves the compressive strength. For the bricks after soaked, enlarging the ratio of binding material-excavated soil increases the softening coefficient but decreases the water absorption, which means that larger binding material content helps to sustain the microstructural stability and obstruct the water infiltration in excavated soil-based unfired clay bricks. This is confirmed by the lower strength loss and mass loss under the effect of dense hydration products formed.

In Feng et al. [20]'s test, Portland cement with 42.5 MPa strength grade and high polymer curing agent were used. Excavated soil was taken from a foundation trench in Shenzhen with two-meter depth, and its main composition was red clay without impurities from human activities. The specimens were designed as a block with dimensions of 240 mm × 115 mm× 53 mm. The briquetting pressure for fabricating bricks was 180 MPa. Fresh and sea water were respectively adopted to soak the specimens after cured at different ages (i.e., 4d, 28d, 180d and 360d) to investigate the softening behavior of excavated soil-based unfired clay bricks. It is worth noting that the chloride ion concentration of sea water in Feng et al. [20]'s study was 1.12%. The compressive strength of excavated soil-based unfired clay bricks at room condition is illustrated in Fig. 10**(a)**. Increasing the curing age leads to improve the compressive strength with a linear fashion, which indicates that the hydration reaction in excavated soil-based unfired clay bricks never stops within a year. The softening coefficient of excavated soil-based unfired clay bricks soaked in fresh and sea water is shown in Fig. 10**(b)**. It can be found that: *i*) curing age helps to increase the softening coefficient, which is due to the adequate hydration; *ii*) the growth rate of softening coefficient from 4d to 28d is larger than that from 28d to 360d, indicating that early curing is the most important process for the solidification of excavated soil; *iii*) the softening coefficient at the condition of seawater is larger than that at the condition of

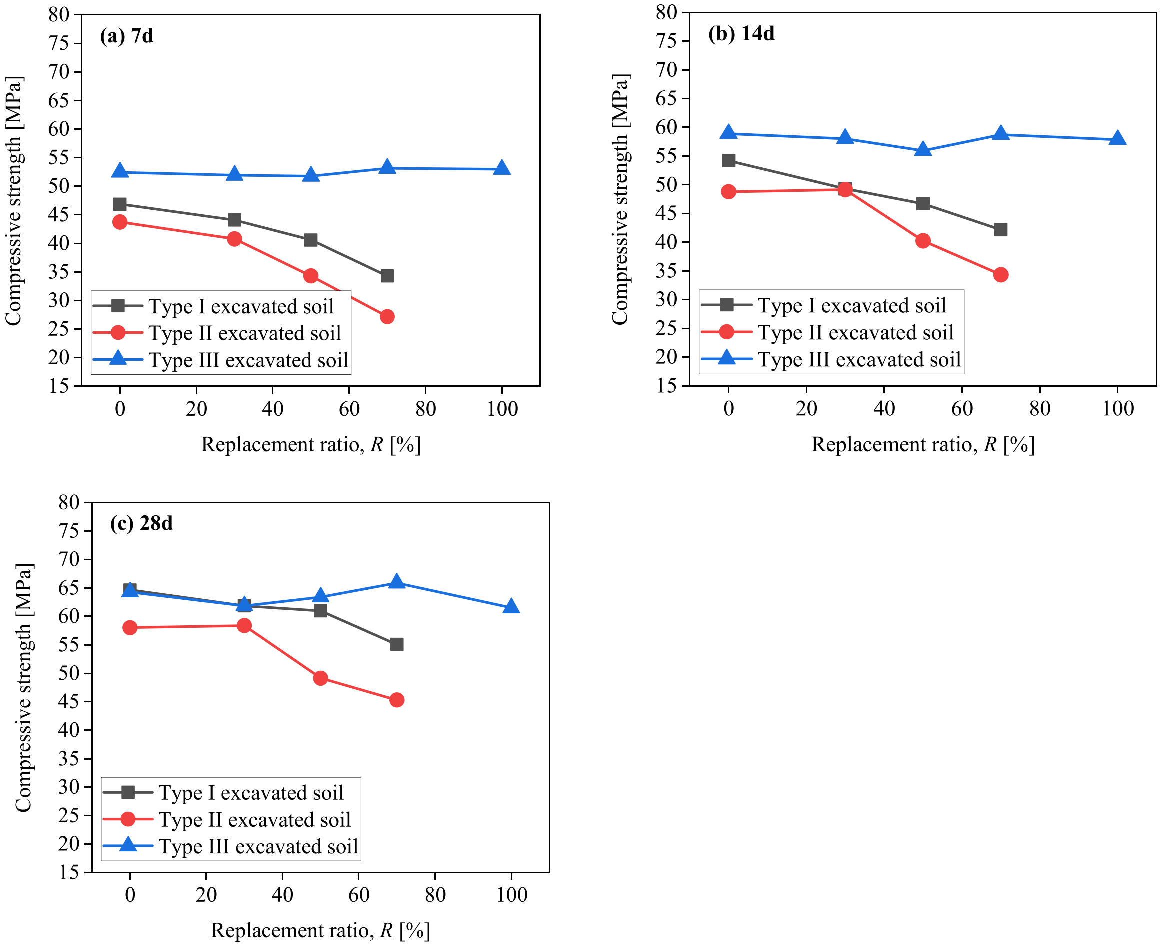


Fig. 6. Compressive strength of excavated soil-based cement mortar (Data from Wu et al. [17]).

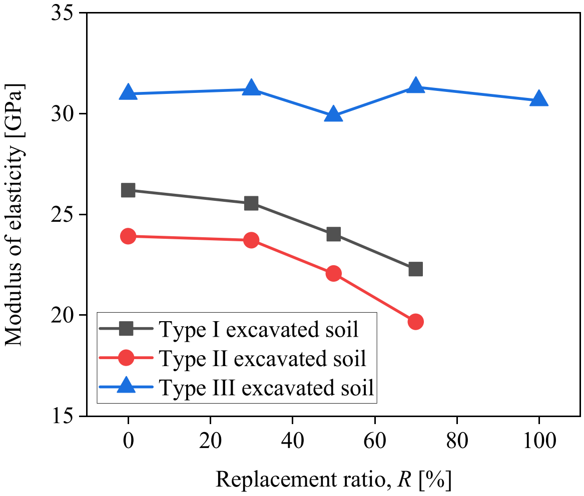
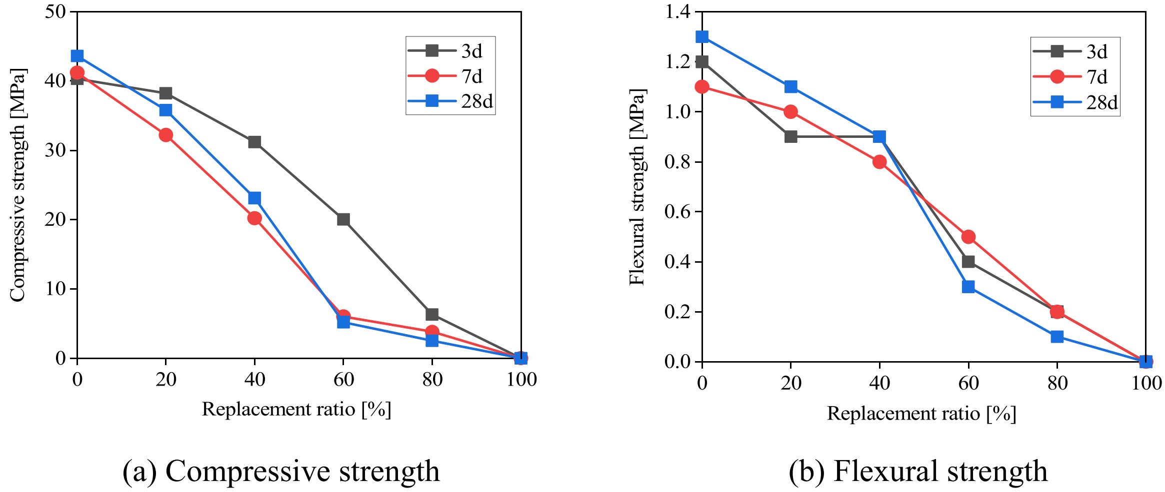
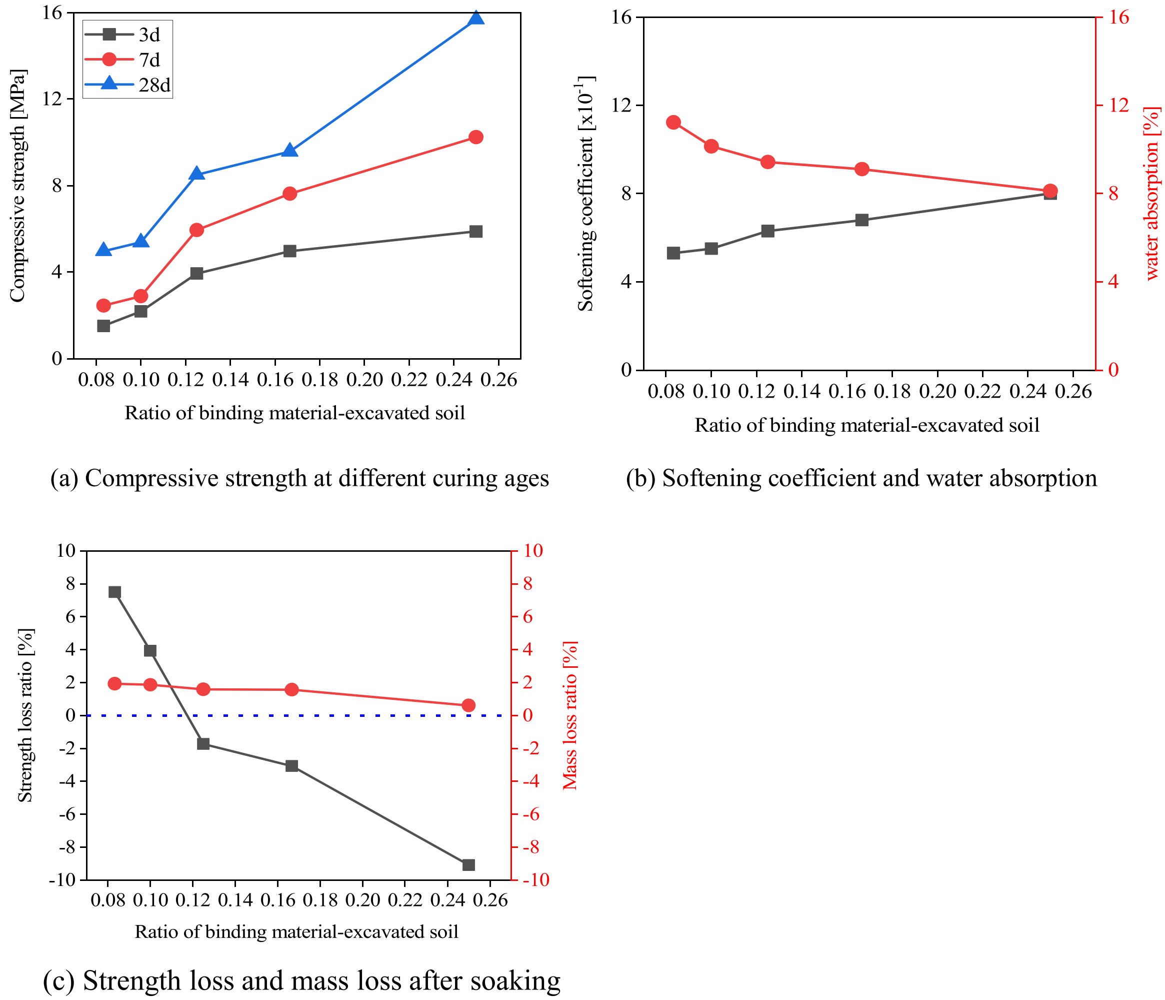


Fig. 7. Modulus of elasticity of excavated soil-based cement mortar.
Data from Wu et al. [17].



(a) Compressive strength (b) Flexural strength

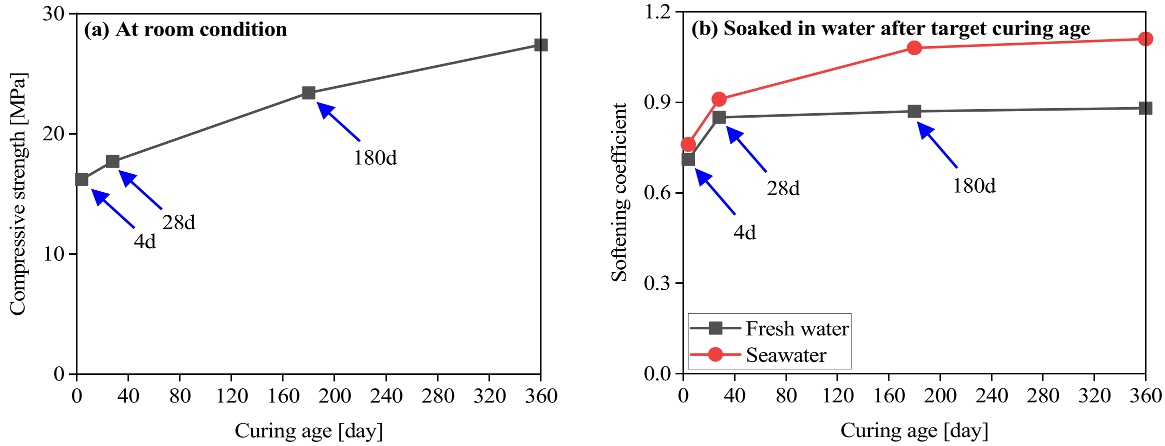
Fig. 8. Strengths of excavated soil-based geopolymer.
Data from Wang et al. [18].



(a) Compressive strength at different curing ages (b) Softening coefficient and water absorption

(c) Strength loss and mass loss after soaking

Fig. 9. Mechanical and physical properties of excavated soil-based unfired clay bricks.
Data from Guo et al. [19].

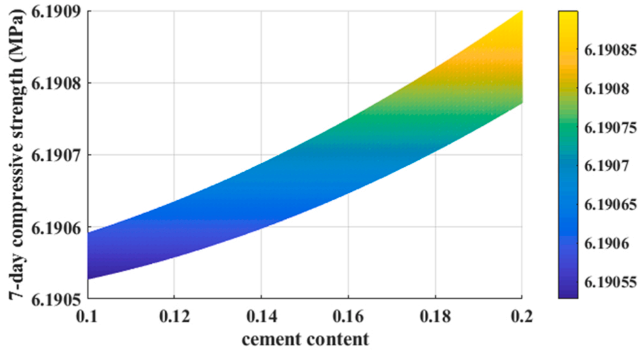


(a) Compressive strength (b) Softening coefficient

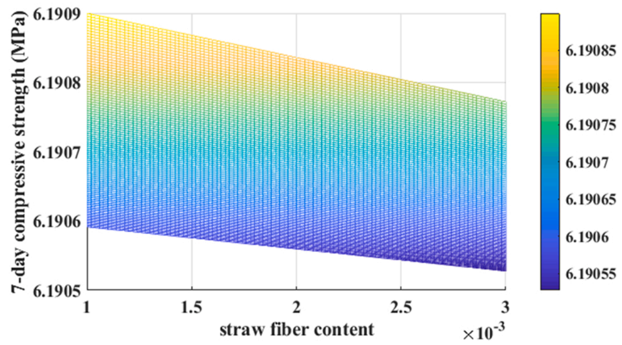
Fig. 10. Mechanical properties of excavated soil-based unfired clay bricks.
Data from Feng et al. [20].

fresh water, and this is because the chloride ion has the function of promoting the solidification of cement-based materials [27–29].

In Yao et al. [21]'s test, Portland cement with 42.5 MPa strength grade and rice straw with crude fiber ranging from 5 mm to 40 mm were used; the fineness of fly ash employed was 18%; fine aggregate with 2.1 fineness modulus and 1.8% silt content was adopted. Based on the uniform test design method, the influence of cement content, sand content, fly ash content and straw fiber content on the mechanical properties of excavated soil-based unfired clay bricks was considered. The specimens were designed as a block with dimensions of 240 mm × 115 mm× 53 mm. It should be pointed out that the briquetting pressure for fabricating bricks was



(a) 7d-compressive strength as a function of cement content



(b) 7d-compressive strength as a function of straw fiber content

Fig. 11. 7d-compressive strength of excavated soil-based unfired clay bricks.

not reported in this test. The mix proportions and the test results of excavated soil-based unfired clay bricks are shown in Appendix A2. It is worth noting that the Chinese Standard JC/T422–2007 [30] was employed to evaluate the properties of excavated soil-based unfired clay bricks based on the test measurement, that is: the bricks with a softening coefficient more than 0.8 and the 28d-compressive strength over 10 MPa can be considered to apply in engineering. It can be seen from Appendix A2 that the test cases of 5, 10 and 15 meet the requirements of the Chinese Standard JC/T422–2007 [30]; and considering the largest contents of excavated soil and straw fiber and the smallest contents of fly ash and sand (i.e., comparison within case 5, case 10 and case 15), the mix proportion of excavated soil-based unfired clay bricks in test case 15 achieves the optimal cost performance ratio.

Based on the experimental results, Yao et al. [21] conducted a second order analysis on the 7d- and 28d-compressive strengths of excavated soil-based unfired clay bricks by taking into account the influence of cement content and straw fiber content. The following equations were obtained using data mining analysis and the relationship of compressive strength-to-cement content and straw fiber content is shown in Figs. 11 and 12.

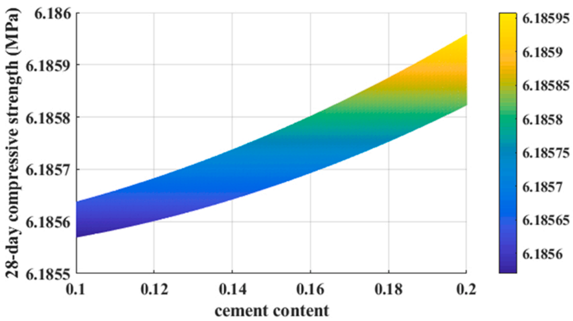
$$f_{c,7d} = 6.191 - 0.319x_1x_4 + 0.011(x_1)^2 \tag{1}$$

$$f_{c,28d} = 6.186 - 0.337x_1x_4 + 0.012(x_1)^2 \tag{2}$$

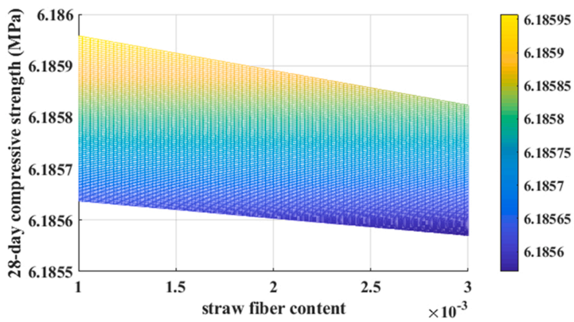
where, x_1 represents the cement content (%); x_4 represents the straw fiber content (%); $f_{c,7d}$ is the 7d-compressive strength; $f_{c,28d}$ is the 28d-compressive strength.

It is worth noting that the effect of sand content and fly ash content on the compressive strength is extremely small and was neglected by Yao et al. [21] in mathematical modeling. It can be seen from Figs. 11–12 that both 7d-compressive strength and 28d-compressive strength of excavated soil-based unfired clay bricks have the same trend under the influence of cement content and straw fiber content, that is: *i*) increasing the cement content leads to improve the compressive strength; and *ii*) increasing the straw fiber content results in decreasing the compressive strength.

Akinyemi et al. [22] used the high plastic excavated soil to manufacture unfired clay bricks. The soil was excavated from a location of termite mound structure with a plastic limit equal to 15.25%, containing 3% sand, 44% silt and 53% clay. Portland cement of 42.5 grade and the chemical admixture Aquaseal 300 (i.e., waterproofing admixture reducing the water transmission through mortar) were employed. Five groups of mix proportions were designed as follows: *i*) in Group A, excavated soil: cement: calcium carbide residue= 100%: 0: 0; *ii*) in Group B, excavated soil: cement: calcium carbide residue= 70%: 30%: 0; *iii*) in Group C, excavated soil: cement: calcium carbide residue= 70%: 20%: 10%; *iv*) in Group D, excavated soil: cement: calcium carbide residue= 70%: 10%: 20%; *v*) in Group E, excavated soil: cement: calcium carbide residue= 70%: 0: 30%. It should be noted that the dosage of chemical admixture in Groups B-E was 0.1 g/m^3. It can be found from the mix proportions that: *i*) the comparison between Group A and Group B is to study the effect of excavated soil replacing cement on properties of unfired clay bricks; *ii*) the comparisons from Group B - Group E is to



(a) 28d-compressive strength as a function of cement content



(b) 28d-compressive strength as a function of straw fiber content

Fig. 12. 28d-compressive strength of excavated soil-based unfired clay bricks.

investigate the effect of calcium carbide residue replacing cement on properties of unfired clay bricks. Water-to-cement ratio was set 0.35 for all mix proportions, and specimens with 50 mm × 50 mm× 50 mm in dimensions were fabricated. The dry compressive strength of excavated soil-based unfired clay bricks is showed in Fig. 13. The largest compressive strength occurred in Group B, and Group C took the second place. Decreasing the cement content but increasing the calcium carbide residue content reduces the compressive strength of excavated soil-based unfired clay bricks. Although the bricks in Group A made of fully excavated soil replacing cement, their dry compressive strength was comparable to that in Group D and Group E, indicating that the termite mound structural soil has a certain characteristic like binding materials. In terms of the cost performance ratio, Group C can reuse the excavated soil to the maximum extent and still receives a relatively high compressive strength.

2.4. Concrete

Wei et al. [25] and Liu et al. [26] were in the same research group and conducted tests on the compressive strength of excavated soil-based concrete characterized with target strength of 30 MPa and 50 MPa (i.e., the normal strength). In each test, the main variable was the excavated soil-binder ratio, that is: in the case of target strength of 30 MPa, the excavated soil-binder ratio contains 0, 5%, 10% and 15%; in the case of target strength of 50 MPa, the excavated soil-binder ratio varies from 0% to 39%. This means that the research goal of the two tests is to check the influence of using excavated soil to replace cement on the compressive strength of normal strength concrete. In addition, the curing age affecting the compressive strength was investigated by Wei et al. [25] and Liu et al. [26]. The raw materials of concrete mixture were the same in two sets of concrete (see Appendix A3), and they are:

Cement: Portland cement with 42.5 MPa strength grade.

Fine aggregate: river sand with 2.9 fineness modulus.

Coarse aggregate: particle size from 5 mm to 25 mm.

Water reducing agent: polycarboxylate-type, 35% water reducing rate.

Excavated soil: generated from shield tunneling in Tianjin metro construction, main components of silicon oxide, alumina and calcium oxide. It is worth noting that the excavated soil after stoving was levigated to the average particle size equal to 11 μm.

Fig. 14 shows the compressive strength of excavated soil-based concrete (normal strength concrete). It can be seen that increasing the curing age helps to improve the compressive strength of concrete, and the larger target strength concrete generally exhibits the higher measured compressive strength when compared to the smaller one at any curing age. These two findings are the regular phenomenon. All of the measured compressive strength of excavated soil-based concrete at 28d reach the target compressive strength. In Wei et al. [25]' test (i.e., target strength of 30 MPa), the compressive strengths of concrete at the excavated soil-binder ratios of 5% and 15% are lower than that of reference concrete (i.e., excavated soil-binder ratio=0), while the compressive strength of concrete at the excavated soil-binder ratio of 10% is a little larger than or comparable to that of reference concrete. The reason (see Fig. 15) is that: the microstructure of concrete without containing excavated soil is composed of a large number of network-shaped C-S-H gel; when the excavated soil-binder ratio is equal to 5%, the microstructure of concrete contains a large number of needle-like AFt crystals and a small amount of spherical material (i.e., excavated soil), which leads to increase the porosity; for the excavated soil-binder ratio increases to 10%, it is found that the microstructure of concrete is dense and appears relatively lots of soil particles, and this may be due to the microaggregate filling effect leading to the microstructure compaction. In Liu et al. [26]' test (i.e., target strength of 50 MPa), the 3d- and 7d-compressive strengths generally decrease with an increase of excavated soil-binder ratio, while the 28d-compressive strengths as a function of excavated soil-binder ratio overall behaves in an opposite fashion. The mechanism of 28d-compressive strength affected by excavated soil-binder ratio explained by Liu et al. [26] is owning to the microstructural pore filled by fine excavated soil.

It should be highlighted that the 28d-strength loss of concrete reported in Wei et al. [25]' test in terms of 10% excavated soil-binder ratio with a reference to the case of zero excavated soil-binder ratio is relatively small; and the 28d-strength growth of concrete presented in Liu et al. [26]' test at the cases of excavated soil-binder ratio ranging from 7.5% to 10% improves a lot with a reference to the case of zero excavated soil-binder ratio. Therefore, the appropriate excavated soil-binder ratio can be adopted as the value of 7.5%– 10%, which can meet the compressive strength requirement of normal strength concrete using excavated soil to replace cement.

3. Conclusions and outlooks

This paper presents a comprehensive literature review on the mechanical properties of cementitious products made with excavated soil replacing fine replacements. A data-driven analysis based on the experimental measurements reported in literature was conducted on the mechanical properties of excavated soil-based cement mortar, geopolymer, unfired clay bricks and concrete at normal condition or after water soaked. Based on the results presented in the review, the following conclusions can be drawn:

(1) Increasing the fine aggregate-to-cement ratio leads to a decrease in the compressive strength of cement mortar regardless of fine aggregate type (i.e., river sand or excavated soil). The compressive strength of cement mortar made of river sand is larger than that of excavated soil-based cement mortar, and the excavated soil with larger plastic nature results in a lower compressive strength of cement mortar.
(2) Employing physical approaches (e.g., thermal treatment, sieving and grinding) acting on or mixing stabilizer into excavated soil can improve the compressive strength of excavated soil-based cement mortar. Compared to the medium plasticity soil, the high plasticity excavated soil drives to more improvement of the compressive strength of cement mortar after thermal treatment.

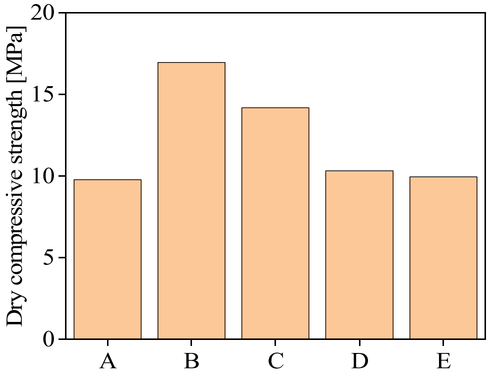


Fig. 13. Dry compressive strength of excavated soil-based unfired clay bricks.
Data from Akinyemi et al. [22].

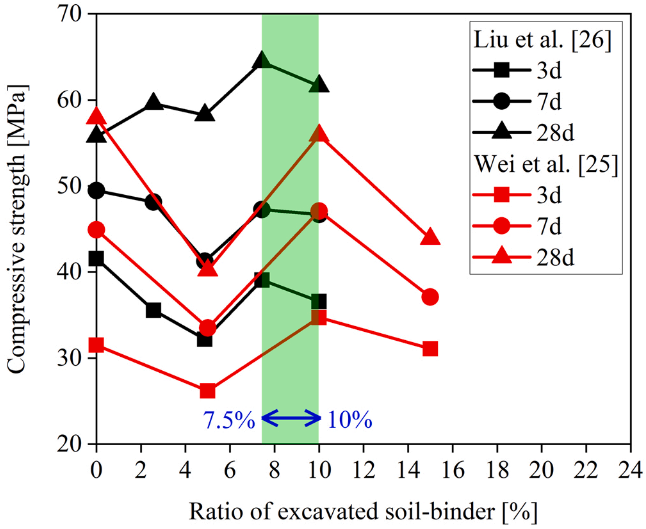
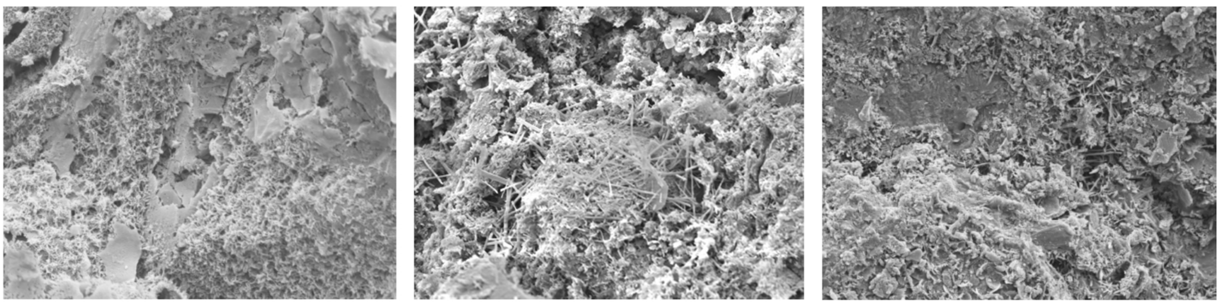


Fig. 14. Compressive strength of excavated soil-based low-strength concrete.



(a) 0 (b) 5% (c) 10%

Fig. 15. SEM microstructures of excavated soil-based low-strength concrete.
Images from Wei et al. [25].

(3) Compared to the cement mortar mixed with granite weathered residual excavated soil, the cement mortar made of alluvial diluvial excavated soil has more stable mechanical properties (i.e., flexural strength, compressive strength and modulus of elasticity) regardless of the ratio of excavated soil-to-total fine aggregate. Increasing the replacement ratio of excavated soil-to-

fly ash leads to a decrease in both compressive strength and flexural strength; and in particular, the excavated soil-based geopolymer has no compressive strength and flexural strength in the case of replacement ratio equal to 100%.

(4) For the normal condition, larger ratio of binding material-excavated soil trends to have higher compressive strength of excavated soil-based unfired clay bricks. For the bricks after soaked, enlarging the ratio of binding material-excavated soil increases the softening coefficient but decreases the water absorption. The softening coefficient at the condition of seawater is larger than that at the condition of fresh water, indicating that the chloride ion has the function of promoting the solidification of cement-based materials.

(5) Larger binding material content and early curing helps to sustain the microstructural stability of excavated soil-based unfired clay bricks. Decreasing the cement content but increasing the calcium carbide residue content reduces the compressive strength of excavated soil-based unfired clay bricks. The appropriate excavated soil-binder ratio can be adopted as the value of 7.5%–10%, which can meet the compressive strength requirement of normal strength concrete using excavated soil to replace cement.

Much remains to be done, and among the aims, this study is that of identifying missing information. Some possible areas for future research are given in the following:

(1) The mix proportion of cementitious products with large content of excavated soil replacing fine aggregate or binding materials should be optimized based on the target mechanical properties for different environmental conditions.
(2) Different sources of excavated soil to fabricate cement-based materials can be investigated.
(3) The mechanism of microstructure of cement-based materials contributing to the strength reduction or increase should be made clearly.
(4) The durability of cementitious products made with excavated soil can be an interesting research topic, such as weathering, dry-wet cycles, acid and alkali corrosion, etc.
(5) The effect of excavated soil content on fire-resistance and dynamic/impact properties of cementitious products needs to be evaluated in detail.
(6) Life cycle assessment on excavated soil-based cementitious products can provide a macro guidance for production and management departments and to promote high-value-added application in civil engineering.

CRediT authorship contribution statement

Daguang Han: Data collection, Formal analysis, Writing – original draft. **Weiwei Xiong:** Formal analysis, Writing – original draft. **Yicun Chen:** Data curation, Funding acquisition, Writing – review & editing. **Jinjun Xu:** Conceptualization, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A1. Dosage of mixture of each specimen (Data from Wang et al. [18])

Specimen code	Fly ash [g]	Excavated soil [g]	Sodium silicate [g]	N_aOH [g]	Water [g]
G1–0	900	0	300	150	300
G2–20	720	180	300	150	300
G3–40	540	360	300	150	300
G4–60	360	540	300	150	300
G5–80	180	720	300	150	300
G6–100	0	900	300	150	300

Appendix A2. Mix proportions and the test results of excavated soil-based unfired clay bricks (Data from Yao et al. [21])

Test case	WES [%]	Cement [%]	Fly ash [%]	Sand [%]	Straw fiber [%]	7d-compressive strength [MPa]	28d-compressive strength [MPa]	Softening coefficient at 28d	Requirements of JC/T422-2007
1	42. 3	10. 0	12. 5	35	0. 20	6. 8	7. 0	0. 69	N
2	44. 7	12. 5	7. 5	35	0. 30	7. 4	7. 5	0. 62	N
3	44. 9	15. 0	5. 0	35	0. 15	7. 6	7. 6	0. 78	N
4	39. 8	17. 5	12. 5	30	0. 25	7.9	7.9	0.86	N
5	**39. 9**	**20. 0**	**10. 0**	**30**	**0. 10**	**10.5**	**10.5**	**0.84**	**Y**
6	54. 8	10. 0	5. 0	30	0. 25	6.5	6.6	0.71	N
7	47. 4	12. 5	15. 0	25	0. 10	7.8	7.9	0.69	N
8	49. 8	15. 0	10. 0	25	0. 20	7.7	7.7	0.74	N
9	52. 2	17. 5	5. 0	25	0. 30	7.6	7.6	0.83	N
10	**44. 9**	**20. 0**	**15. 0**	**20**	**0. 15**	**9.7**	**10**	**0.9**	**Y**
11	59. 7	10. 0	10. 0	20	0. 30	6	5.8	0.55	N
12	59. 9	12. 5	7. 5	20	0. 15	7.4	7.4	0.69	N
13	54. 8	15. 0	15. 0	15	0. 25	8	7.9	0.68	N
14	54. 9	17. 5	12. 5	15	0. 10	8.5	8.5	0.62	N
15	**57. 3**	**20. 0**	**7. 5**	**15**	**0. 20**	**9.9**	**10.2**	**0.8**	**Y**

Note: Y means yes, while N means no.

Appendix A3. Mix proportions of excavated soil-based concrete

Specimen code	Cement [kg/m^3]	Excavated soil [kg/m^3]	Water [kg/m^3]	Fine aggregate [kg/m^3]	Coarse aggregate [kg/m^3]	Water reducing agent [%]	Excavated soil-binder ratio [%]	Water-binder ratio
Wei et al. [25]								
C30–0	380	0	152	747	1101	0.7	0	0.4
C30–5	361	19	152	747	1101	0.7	5	0.4
C30–10	342	38	152	747	1101	0.7	10	0.4
C30–15	323	57	152	747	1101	0.7	15	0.4
Liu et al. [26]								
C50–0	390	0	136	712	1162	0.7	0	0.35
C50–2.5	380	10	136	712	1162	0.7	2.5	0.35
C50–5	371	19	136	712	1162	0.7	5	0.35
C50–7.5	361	29	136	712	1162	0.7	7.5	0.35
C50–10	351	39	136	712	1162	0.7	10	0.35

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