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Effects of straw ash–calcium carbide slag curing agent and recycled aggregate on the mechanical properties of sludge soil and their grey correlation analysis

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Graphical abstract



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Abstract: High-water-content sludge soil (SS) requires stabilization before reuse as a pavement fill. This study evaluates a multi-waste system comprising a straw ash–calcium carbide slag binder (SCS; straw ash:calcium carbide slag = 6:4 by mass) fixed at 10% of dry SS and recycled brick–concrete aggregate (RBCM). Heavy compaction, California bearing ratio (CBR), and laboratory unconfined compressive strength (UCS) index tests were used to assess test-specific RBCM contents of 0–70%, brick-to-concrete ratios of 2:1, 1:1, and 1:2, and curing ages of 7–90 d. Grey relational analysis and a GM(1,1) model were applied to the UCS dataset. Maximum dry density, CBR, and the UCS index first increased and then decreased with RBCM content, whereas optimum moisture content decreased. The best overall laboratory response occurred at 30% RBCM and a 1:2 brick-to-concrete ratio. Grey relational analysis ranked RBCM content as the factor most strongly associated with the UCS index, followed by curing age and brick-to-concrete ratio, and the GM(1,1) model reproduced the measured trend. Because the 50 mm UCS specimens were small relative to the 30–40 mm aggregate, those strength values are comparative indices rather than representative field-design parameters. Hydration, interfacial bonding, skeleton, filling, and arching interpretations are proposed hypotheses; direct phase and microstructural verification is still required.

Keywords: sludge soil; straw ash-calcium carbide slag; recycled brick-concrete aggregate; California bearing ratio; unconfined compressive strength; grey prediction model

1. Introduction

Large volumes of high-water-content sludge soil are generated during urban renewal, transport infrastructure construction, underground excavation, and river or lake dredging. Its high void ratio, compressibility, and low shear strength restrict direct reuse and can create instability, settlement, and leachate risks. Stabilization can convert this material into engineering fill: dredged sediments have been evaluated as supplementary cementitious materials [1], activated sediment–fly ash geopolymers [2], glass-powder-modified cemented soils [3], MgO–industrial-residue systems [4], and optimized cement-based mixtures [5]. However, cement-intensive or single-waste approaches do not fully address the combined goals of performance, waste utilization, and lower carbon demand.

Agricultural biomass ashes supply reactive SiO_2 and Al_2O_3 and have been used in soil stabilization and low-carbon binders [6–8]. Calcium carbide slag, whose principal constituent is $\text{Ca}(\text{OH})_2$, can provide calcium and alkalinity to activate silico-aluminous precursors [9–11]. A previous study of straw ash–calcium carbide slag (SCS) stabilized sludge soil used a 6:4 straw-ash-to-calcium-carbide-slag mass ratio and showed that a 10% SCS dosage produced a CBR of 18.7%, while XRD and SEM observations supported pozzolanic-reaction and pore-filling interpretations for that binder-only system [19]. The behavior of SCS when coupled with a coarse recycled-aggregate skeleton, however, has not been established.

Recycled concrete and brick aggregates can improve grading and bearing capacity in pavement layers, although water absorption, crushing resistance, and compositional variability affect performance [12–15]. Their use together with agricultural ash and industrial residues may also reduce demand for Portland cement and virgin aggregate, consistent with broader development of supplementary and alkali-activated materials [16–18]. The coupled response is not straightforward because recycled brick and concrete differ in density, porosity, absorption, and particle strength, while the relative amounts of coarse aggregate, fine SS, and binder govern packing and load transfer.

Accordingly, this study combines SS, SCS, and recycled brick–concrete mixture (RBCM) and examines the effects of RBCM content, brick-to-concrete ratio, and curing age through heavy compaction, CBR, and laboratory UCS index tests. Grey relational analysis is used to compare the associations of the three variables with the UCS index, and a GM(1,1) model is used to describe its time-dependent trend. The study focuses on macroscopic engineering behavior; hydration, interfacial bonding, skeleton, filling, and arching are therefore treated as hypotheses to be tested by future phase and microstructural measurements.

2. Experimental materials and analytical methods

2.1. Experimental materials

2.1.1. Basic properties of raw materials

(1) Sludge soil

The tested material is hereafter uniformly termed sludge soil (SS). It was obtained from waste soil material generated at the construction site of the Wuchang-Lalin River section of the Tiede Expressway. The sampling process was conducted in accordance with the Test Methods of Soils for Highway Engineering (JTG 3430-2020). As shown in Figure 1, the soil sample exhibits a grayish-black appearance overall, with a relatively uniform texture and no visible impurities. To characterize the basic physical properties of the sludge soil used in the experiment and provide a basis for the subsequent design of stabilization mix proportions, its natural water content, Atterberg limits, compaction characteristics, and particle size distribution were determined.



Fig. 1. Undisturbed sludge soil (SS).

The natural water content of the sludge soil was determined to be 50.3%. The Atterberg limits were measured using a photoelectric combined liquid-plastic limit tester. Based on the relationship curve between cone penetration depth and water content, as shown in Figure 2, the liquid limit was obtained as 38.0%, the plastic limit as 21.2%, and the plasticity index as 16.8.

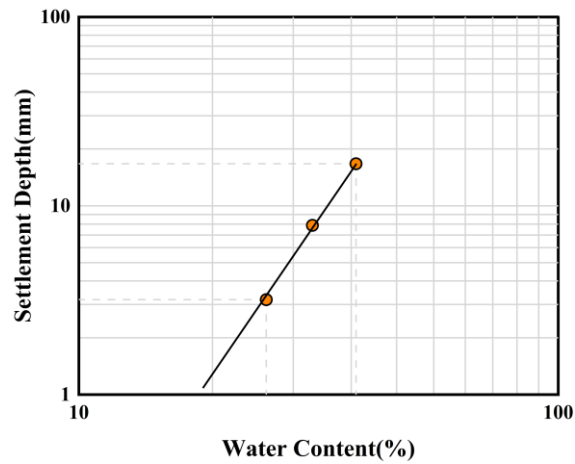


Fig. 2. Relationship between cone penetration depth and water content.

The compaction test was conducted using a multifunctional electric compactor. The compaction curve was plotted from the relationship between water content and dry density, as shown in Figure 3. The maximum dry density was $1.79 \text{ g}\cdot\text{cm}^{-3}$, and the optimum water content was 14.4%.

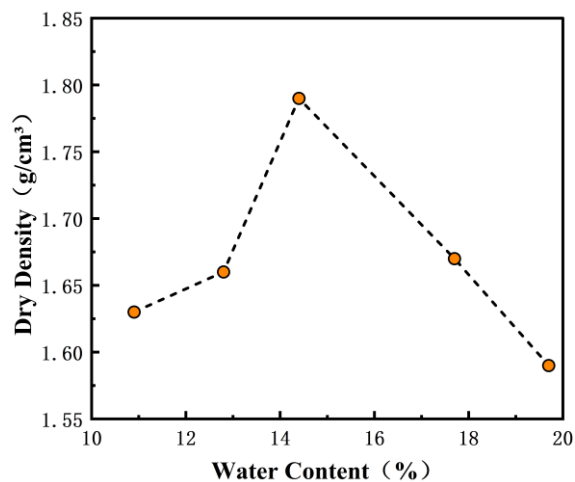


Fig. 3. Relationship between water content and dry density of sludge soil.

The particle size distribution was determined by laser particle size analysis, and the results are presented in Figure 4. The sludge soil is predominantly composed of clay and silt particles, and can be classified as fine-grained soil according to the Standard for Engineering Classification of Soil (GB/T 50145-2007).

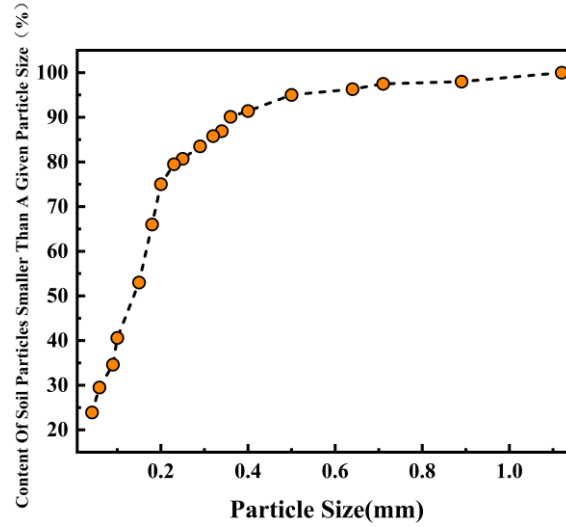


Fig. 4. Particle size distribution of sludge soil.

For ease of overall comparison, the main physical property parameters of the sludge soil used in the experiment are summarized in Table 1.

Table 1. Basic physical properties of sludge soil.

Index	Value
Natural water content/%	50.3
Liquid limit/%	38.0
Plastic limit/%	21.2
Plasticity index	16.8
Maximum dry density/(g·cm ⁻³)	1.79
Optimum moisture content/%	14.4

As shown in Table 1, the sludge soil used in the experiment exhibits a relatively high natural water content and is predominantly composed of clay and silt particles, with characteristics including a high fine particle content, stringent compaction control requirements, and poor engineering stability. Consequently, when used directly for subgrade filling, it is difficult to meet the strength and stability requirements, thus necessitating stabilization/solidification treatment.

(2) Straw ash

The straw ash used in this experiment was sourced from a biomass power plant in Heilongjiang Province. Because the raw ash had a loss on ignition of approximately 15.0%, it was subjected to secondary calcination at 400 °C for 2 h. This preparation condition follows the previously reported protocol for straw ash used in an SCS soil stabilization system [19] and was adopted to reduce residual unburned matter without using a substantially higher calcination temperature.

The particle size distribution of the straw ash is shown in Figure 5. Over 99% of the straw ash consists of fine particles, with a mean particle size of 7.35 μm , a D50 (median particle size) of 7.23 μm , a D90 of 32.3 μm , and a specific surface area of 7160 cm^2/g .

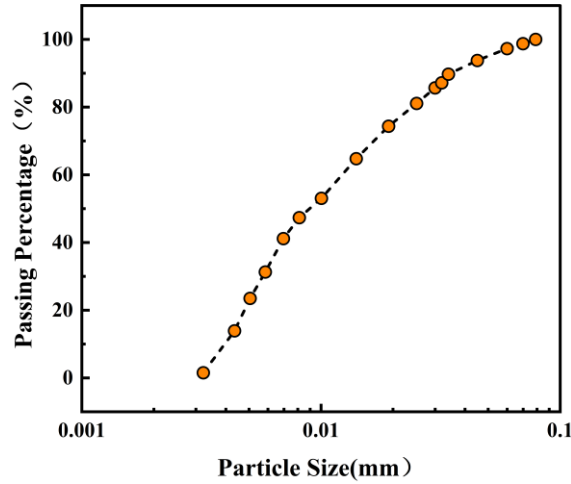


Fig. 5. Particle size distribution of straw ash.

The chemical composition of the straw ash was determined using X-ray fluorescence spectroscopy, as presented in Table 2. It is evident from the table that the predominant oxide in the straw ash is SiO_2 , with a content of 60.05%, followed by Al_2O_3 , with a content of 12.36%. According to the standard Pozzolanic Materials Used for Cement, the combined content of SiO_2 and Al_2O_3 in pozzolanic materials should be no less than 50%. It can thus be seen that the chemical composition of the straw ash meets the requirements specified in the standard.

Table 2. Contents of major oxide components in straw ash (%).

Oxide	SiO ₂	Al ₂ O ₃	K ₂ O	CaO	Fe ₂ O ₃	MgO	Na ₂ O
Content	60.05	12.36	3.97	8.36	3.93	2.8	1.49

(3) Calcium carbide slag

The calcium carbide slag used in the experiment was obtained from a chemical enterprise in Zhengzhou, Henan Province. It is an acetylene-production by-product whose principal constituent is Ca(OH)_2 and whose initial water content was approximately 20%. The slag was oven-dried at $105 \pm$

5 °C to constant mass, cooled in a desiccator, and sealed before use. This temperature is suitable for removing free moisture and is far below the dehydroxylation temperature of Ca(OH)_2 .



Fig. 6. Carbide slag.

The particle size distribution of the pretreated calcium carbide slag is shown in Figure 7. It can be observed that the calcium carbide slag consists predominantly of fine particles, accounting for over 99% of the total. Additionally, the mean particle size of the calcium carbide slag is 3.75 μm , with a D50 (median particle size) of 6.31 μm , a D90 of 28.56 μm , and a specific surface area of 9183 cm^2/g .

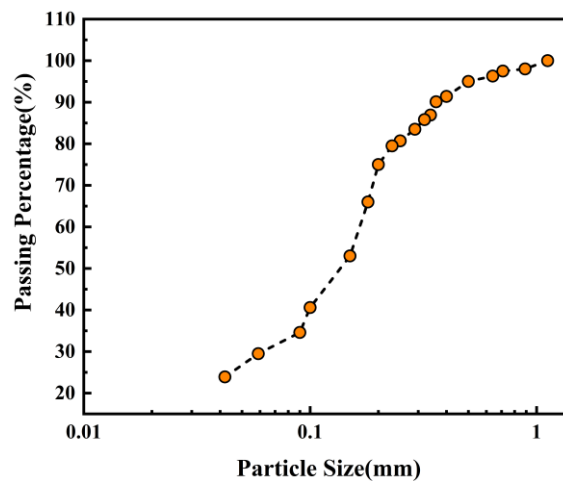


Fig. 7. Particle size distribution of carbide slag.

(4) Recycled aggregates from construction waste

The preparation process of the recycled aggregates is illustrated in Figure 8. To ensure the purity of the recycled aggregates, the raw construction waste was subjected to a combined manual and mechanical sorting prior to crushing to remove impurities such as metals, wood, and plastics, thereby ensuring that the feedstock consisted primarily of hard constituents such as concrete and bricks. Subsequently, the bulk materials were preliminarily crushed using a hydraulic breaker, followed by secondary crushing via a jaw crusher to produce the recycled concrete aggregate, recycled brick aggregate, and recycled mortar aggregate required for the experiment. Finally, the physical and mechanical properties of the resulting recycled aggregates were tested and analyzed in accordance with the Test Methods of Aggregate for Highway Engineering (JTG 3432-2024).

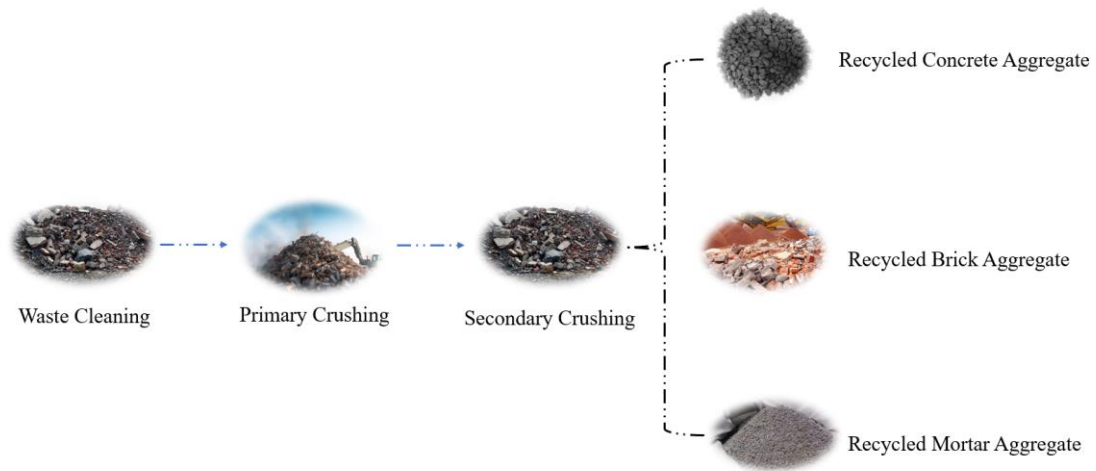


Fig. 8. Crushing scheme for construction waste.

The apparent morphology of the recycled aggregates from construction waste is shown in Figure 9. As shown in the figure, the recycled aggregates exhibit irregular shapes, abundant angularity, and a loose, porous structure. Due to the influence of crushing and weathering, noticeable microcracks are present on aggregate surfaces, resulting in significantly lower intrinsic strength than that of natural aggregates. The particle gradation curve for recycled aggregates is shown in Figure 10. As indicated by the gradation curve, the recycled aggregates are predominantly composed of coarse aggregates (particle size greater than 4.75 mm), accounting for over 70% of the total, while the content of fine aggregates (particle size less than 4.75 mm) is below 30%. This aggregate gradation and porous nature will directly influence the stabilization effect on the sludge soil and the macroscopic mechanical properties of the stabilized soil.



Fig. 9. Apparent morphology of construction waste.

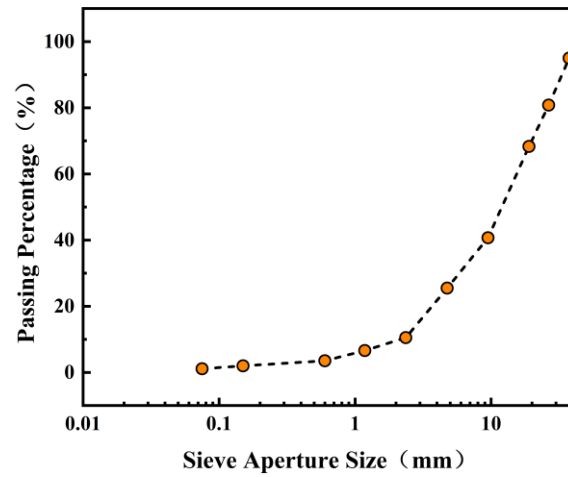


Fig. 10. Gradation curve of recycled aggregate.

As shown in Figure 11, among the three recycled aggregate types, the clay and clay-lump contents are highest for recycled brick, followed by recycled concrete, and lowest for recycled mortar. Specifically, the clay content of recycled brick is approximately 2.2%, and the clay lump content is approximately 1.4%, indicating that bricks possess more pores and their surfaces are more prone to adhering to argillaceous impurities. The clay content of recycled concrete is approximately 1.1%, and the clay lump content is approximately 1.2%, representing an intermediate level. The clay content of recycled mortar is approximately 0.7%, and the clay lump content is approximately 0.9%, reflecting a relatively higher degree of cleanliness.

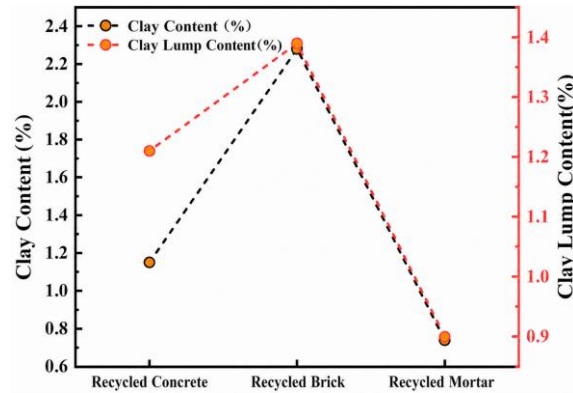


Fig. 11. Clay and clay-lump contents of recycled concrete, recycled brick, and recycled mortar aggregates.

The density and water absorption test results for recycled aggregates from construction waste are presented in Figure 12. Specifically, the apparent density, saturated surface-dry density, bulk density, and water absorption of recycled concrete are $2.63 \text{ g}\cdot\text{cm}^{-3}$, $2.41 \text{ g}\cdot\text{cm}^{-3}$, $2.32 \text{ g}\cdot\text{cm}^{-3}$, and 3.33%, respectively. For recycled brick, the corresponding values are $2.49 \text{ g}\cdot\text{cm}^{-3}$, $2.19 \text{ g}\cdot\text{cm}^{-3}$, $1.80 \text{ g}\cdot\text{cm}^{-3}$, and 16.2%, respectively. For recycled mortar, the values are $2.44 \text{ g}\cdot\text{cm}^{-3}$, $2.25 \text{ g}\cdot\text{cm}^{-3}$, $1.99 \text{ g}\cdot\text{cm}^{-3}$, and 4.9%, respectively.

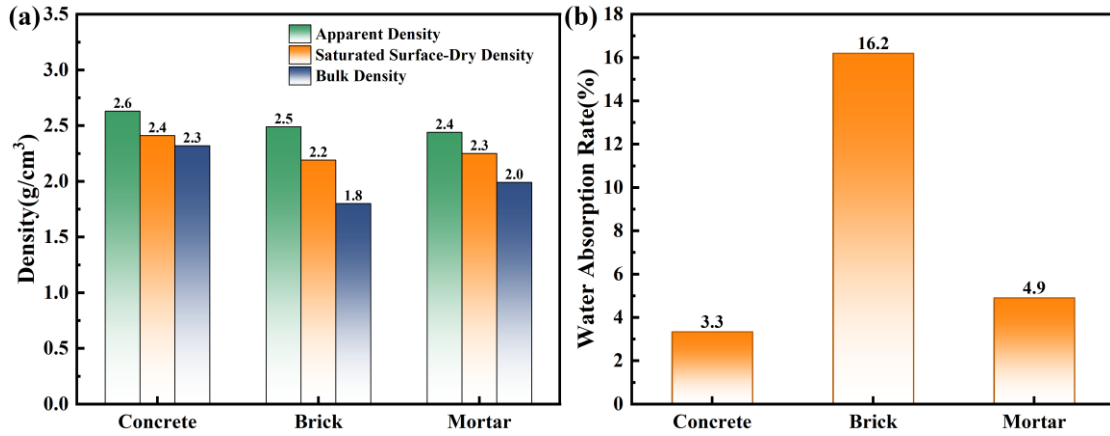


Fig. 12. Physical properties of recycled aggregates: (a) density; (b) water absorption.

The test results of the elongated and flaky particle content of the recycled aggregates from construction waste are shown in Figure 13. In the 5-10 mm particle size range, the elongated and flaky particle contents of recycled concrete, recycled brick, and recycled mortar are 7.9%, 6.5%, and 5.8%, respectively. In the particle size ranges of 10-20 mm and 20-30 mm, the elongated and flaky particle contents of recycled brick are 27.9% and 21.6%, respectively.

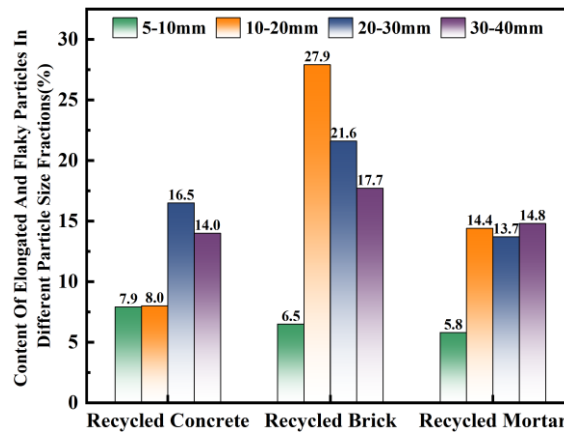


Fig. 13. Content of elongated and flaky particles in recycled aggregate.

(5) Recycled aggregate-stabilized sludge soil

In the present RBCM experiment, the internal SCS proportion was not treated as an independent variable. Preliminary binder screening reported previously [19] identified a straw-ash-to-calcium-carbide-slag mass ratio of 6:4. That study also showed that 10% SCS produced a CBR of 18.7%, exceeding the cited upper-roadbed threshold, although 20% was selected there as the optimum binder-only dosage when strength and economy were considered together. The present study therefore fixed SCS at 10% as a moderate baseline to limit binder consumption and keep the effect of RBCM distinguishable; 10% is not claimed here as the globally optimum SCS dosage for the SCS–RBCM system.

2.1.2. Brick-to-concrete ratio and recycled aggregate content

All contents were calculated relative to the oven-dry mass of SS: SCS content = $m_{SCS}/m_{SS} \times 100\%$, and RBCM content = $m_{RBCM}/m_{SS} \times 100\%$. The brick-to-concrete ratios were 2:1, 1:1, and 1:2 by mass. The recycled aggregate used in the experimental program included the reported 30–40 mm fraction. The test-specific factor levels are summarized in Table 3. Compaction used RBCM contents of 0, 10, 20, 30, 50, and 70%; the 70% group was retained as a high-coarse-fraction endpoint. CBR and UCS used 0, 10, 30, 40, and 50% RBCM; the 40% group resolved the descending branch after the 30% peak. Thus, the original blanket statement of “10–50% RBCM” has been replaced by the actual matrix for each test.

Table 3. Complete experimental mix design and test matrix.

Series	SCS (% dry SS)	SA:CS	RBCM (% dry SS)	Brick:concrete	Conditioning/age	Response
Untreated control	0	—	0	—	Test-specific	Baseline SS
SCS-only control	10	6:4	0	—	UCS: 7/14/28/90 d	Compaction; CBR; UCS index
RBCM compaction	10	6:4	10, 20, 30, 50, 70	2:1, 1:1, 1:2	Conditioned $\geq$ 12 h	MDD; OMC
RBCM CBR	10	6:4	10, 30, 40, 50	2:1, 1:1, 1:2	Immersed 4 d	CBR
RBCM UCS	10	6:4	10, 30, 40, 50	2:1, 1:1, 1:2	7/14/28/90 d	Comparative UCS index

Note: SCS and RBCM contents are expressed as percentages of oven-dry SS mass. The SCS ratio and brick-to-concrete ratio are mass ratios. The 50 mm $\times$ 50 mm UCS geometry is discussed as a limitation in Section 3.2.4. MDD = maximum dry density; OMC = optimum moisture content.

2.2. Analytical methods

2.2.1. Compaction characteristics

All component masses were determined on an oven-dry basis. After removal of impurities, SS was oven-dried at no more than 100 °C to constant mass, pulverized, and passed through a 2 mm sieve in accordance with JTG 3430-2020. Straw ash and calcium carbide slag were first dry-mixed at

6:4, the resulting SCS was blended with SS at 10%, and RBCM was then added at the level and brick-to-concrete ratio listed in Table 3. Water was added to the target content, and the mixture was sealed for at least 12 h for moisture equilibration. Heavy compaction tests were then performed according to JTG 3430-2020 and JTG E51-2009 to determine the mixture-specific maximum dry density and optimum moisture content.

2.2.2. California bearing ratio

Each CBR mixture was prepared at its own optimum moisture content and maximum dry density obtained from the corresponding compaction group, rather than at one common set of water contents. After standard compaction in the CBR mold, a surcharge plate was placed on the specimen and the specimen was immersed for four days. Penetration loading was then applied at 1 mm/min in accordance with JTG E51-2009.

2.2.3. Unconfined compressive strength

The UCS program evaluated the effects of RBCM content, brick-to-concrete ratio, and curing age while SCS was fixed at 10% with a straw-ash-to-calcium-carbide-slag ratio of 6:4. Because the specimen size was small relative to the aggregate size, the measured values are reported as comparative laboratory UCS indices and are not used as representative field-design strengths.

Cylindrical specimens, 50 mm in diameter and 50 mm in height, were molded at the mixture-specific optimum moisture content and target dry density. After demolding, each specimen was wrapped in plastic film, sealed in a bag, and cured at 20 ± 1 °C and $\geq 95\%$ relative humidity for 7, 14, 28, or 90 d. Axial loading was applied at 1 mm/min. Three parallel specimens were prepared for each group; the mean was accepted when within-group dispersion did not exceed 15%, otherwise the group was checked for an outlier and retested when necessary. The specimen-to-particle-size limitation is evaluated in Section 3.2.4.

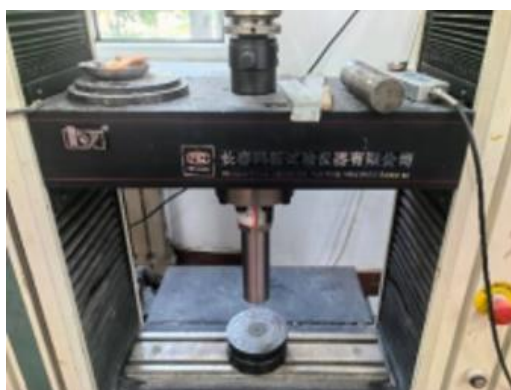


Fig. 14. Electronic universal testing machine.

3. Analysis of test results

3.1. Influence of brick-to-concrete ratio on the mechanical properties of stabilized sludge soil

3.1.1. Influence of brick-to-concrete ratio on the compaction characteristics of stabilized sludge soil

The compaction test procedure followed that described in Section 2.2.1. Plain sludge soil and stabilized soil with only SCS binder (RBCM content of 0%) were designed as control groups. Based on the experimental data, the compaction test results for stabilized sludge soil with different brick-to-concrete ratios and RBCM contents are presented in Figure 15.

As shown in Figure 15(a), when the RBCM content was 0%, no recycled brick-concrete aggregate was incorporated into the specimen; therefore, the compaction parameters of the stabilized sludge soil under different brick-to-concrete ratios were essentially identical, and this condition can serve as the baseline group for subsequent comparative analysis. Under this condition, the optimum water content of the stabilized sludge soil was 16.9%, and the maximum dry density was $1.67 \text{ g}\cdot\text{cm}^{-3}$.

As shown in Figure 15(b), when the RBCM content was 10%, as the brick-to-concrete ratio changed from 2:1 to 1:1 and 1:2, i.e., with the proportion of waste concrete gradually increasing, the maximum dry density of the stabilized sludge soil exhibited an overall increase, while the optimum water content decreased progressively, indicating that increasing the proportion of waste concrete is conducive to improving the compaction performance of the blended soil. Specifically, the maximum dry density increased from $1.75 \text{ g}\cdot\text{cm}^{-3}$ to $1.91 \text{ g}\cdot\text{cm}^{-3}$ and $1.92 \text{ g}\cdot\text{cm}^{-3}$, while the optimum water content decreased from 13.3% to 12.4% and 12.3%.

As shown in Figure 15(c), when the RBCM content was 20%, the stabilized soil under different brick-to-concrete ratios still exhibited a trend in which the maximum dry density increased, and the optimum water content decreased with increasing waste concrete proportion. Specifically, at brick-to-concrete ratios of 2:1, 1:1, and 1:2, the maximum dry densities were $1.76 \text{ g}\cdot\text{cm}^{-3}$, $1.93 \text{ g}\cdot\text{cm}^{-3}$, and $1.95 \text{ g}\cdot\text{cm}^{-3}$, with corresponding optimum water contents of 12.5%, 11.7%, and 10.4%, respectively. This indicates that at this content level, the skeletal support effect of the waste concrete particles was further enhanced, contributing to improved compactness after compaction.

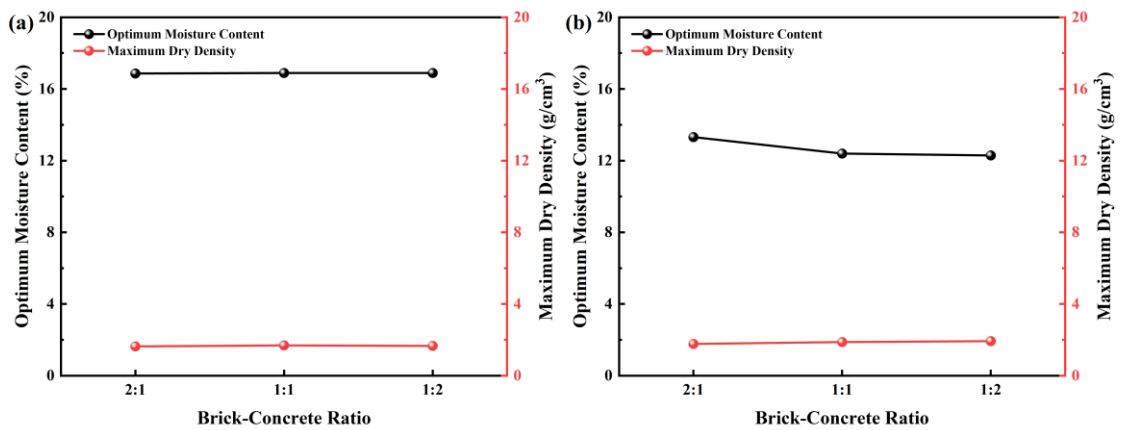
As shown in Figure 15(d), when the RBCM content was 30%, the stabilized sludge soil's maximum dry density reached a relatively high level and continued to increase with increasing waste concrete proportion, while the optimum water content decreased continuously. Specifically, as the brick-to-concrete ratio changed from 2:1 to 1:1 and 1:2, the maximum dry density increased from $1.81 \text{ g}\cdot\text{cm}^{-3}$ to $1.96 \text{ g}\cdot\text{cm}^{-3}$ and $1.99 \text{ g}\cdot\text{cm}^{-3}$, while the optimum water content decreased from 11.6% to 10.4% and 9.9%. Among these, the maximum dry density at a brick-to-concrete ratio of 1:2 was the highest across all test groups, indicating that when the RBCM content was 30% and the proportion of

waste concrete was relatively high, the particle composition of the blended soil was well balanced, yielding the best compaction result.

As shown in Figure 15(e), when RBCM content increased to 50%, maximum dry density remained higher at larger concrete fractions but declined relative to the 30% RBCM groups. At brick-to-concrete ratios of 2:1, 1:1, and 1:2, the maximum dry densities were $1.73 \text{ g}\cdot\text{cm}^{-3}$, $1.89 \text{ g}\cdot\text{cm}^{-3}$, and $1.96 \text{ g}\cdot\text{cm}^{-3}$, and the optimum moisture contents were 11.0%, 10.1%, and 9.5%, respectively. The decline after 30% is consistent with, but does not directly demonstrate, reduced packing efficiency at higher coarse fractions.

As shown in Figure 15(f), when the RBCM content was 70%, the maximum dry density of the stabilized sludge soil decreased further compared with that at the 50% content level, yet the trend of higher maximum dry density with a higher proportion of waste concrete was still maintained across different brick-to-concrete ratios. Specifically, at brick-to-concrete ratios of 2:1, 1:1, and 1:2, the maximum dry densities were $1.68 \text{ g}\cdot\text{cm}^{-3}$, $1.87 \text{ g}\cdot\text{cm}^{-3}$, and $1.90 \text{ g}\cdot\text{cm}^{-3}$, with optimum water contents of 10.7%, 9.8%, and 9.3%, respectively. This indicates that an excessive amount of RBCM reduces the overall compatibility of the blended soil and diminishes the compaction effectiveness.

Overall, at the same RBCM content, as the brick-to-concrete ratio changed from 2:1 to 1:2, the maximum dry density of the stabilized sludge soil increased overall, while the optimum water content decreased overall. This is primarily attributable to the material differences between waste bricks and waste concrete: waste bricks possess higher porosity and water absorption, and relatively lower particle strength and density, which tend to increase the water demand of the blended soil; whereas waste concrete particles exhibit higher density and strength, with a more pronounced skeletal support effect, which is conducive to improving the compactness after compaction. Meanwhile, across all brick-to-concrete ratios, the maximum dry density first increased and then decreased with increasing RBCM content, reaching a relatively high level at 30%; the optimum water content, in contrast, decreased with increasing RBCM content. In summary, at a brick-to-concrete ratio of 1:2 and an RBCM content of 30%, the stabilized sludge soil achieved the highest maximum dry density, a relatively low optimum water content, and optimal compaction.



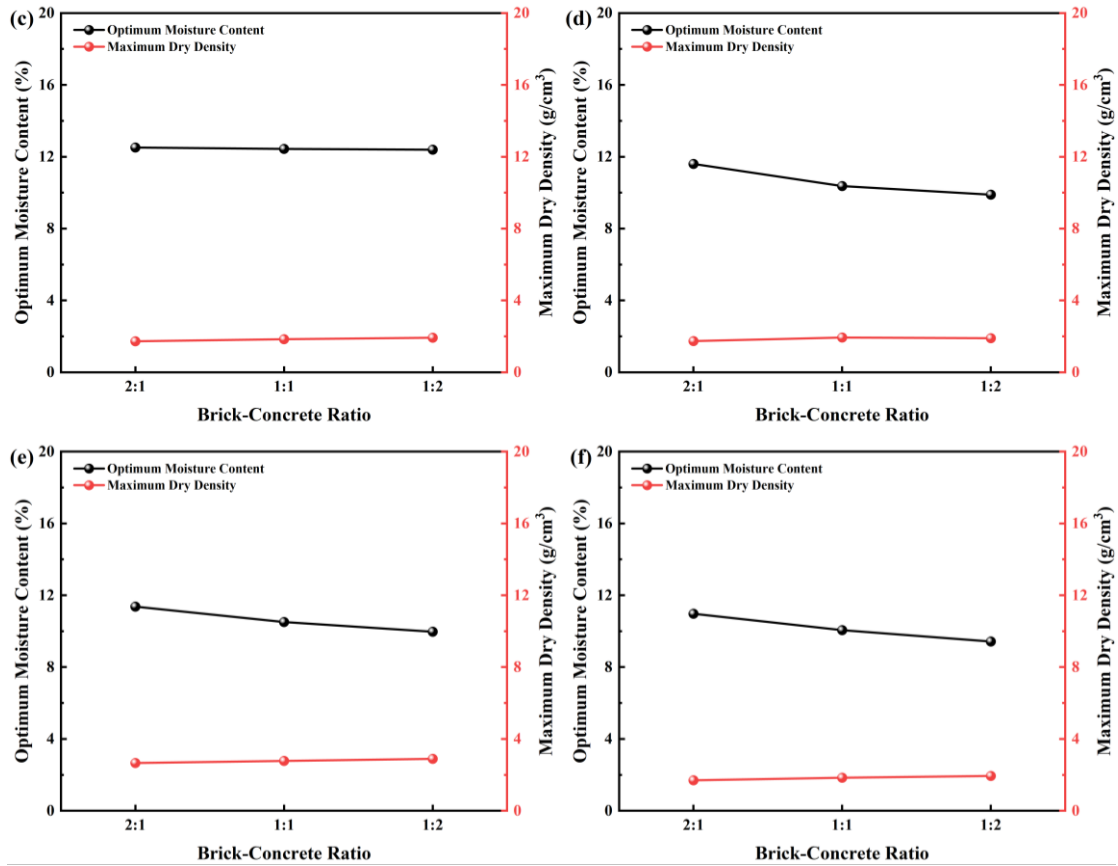


Fig. 15. Effect of brick-to-concrete ratio on the optimum moisture content and maximum dry density of stabilized sludge soil at different RBCM contents (a) RBCM 0%, (b) RBCM 10%, (c) RBCM 20%, (d) RBCM 30%, (e) RBCM 50%, (f) RBCM 70%.

3.1.2. Influence of brick-to-concrete ratio on the California bearing ratio of stabilized sludge soil

The California bearing ratio (CBR) test procedure followed that described in Section 2.2.2. Plain sludge soil and stabilized soil with only 10% SCS and 0% RBCM were used as control groups. Based on the experimental data, the CBR test results for stabilized sludge soil with different brick-to-concrete ratios and RBCM contents are plotted in Figure 16.

As shown in Figure 16(a), at a 2:1 brick-to-concrete ratio, CBR increased from 32.1% at 10% RBCM to 37.6% at 30% and then decreased to 33.4% and 32.6% at 40% and 50%. Relative to plain SS and the 10% SCS-only control, RBCM incorporation produced a large measured increase in bearing response. The test does not directly identify the internal structural cause of the descending branch.

As shown in Figure 16(b), at a 1:1 ratio, CBR increased from 33.8% at 10% RBCM to 39.8% at 30% and then decreased to 35.9% and 34.4% at 40% and 50%. Values remained higher than those of the corresponding 2:1 groups.

As shown in Figure 16(c), at a brick-to-concrete ratio of 1:2, CBR increased from 36.4% at 10%

RBCM to 43.5% at 30% RBCM and then decreased to 40.3% and 37.1% at 40% and 50%, respectively. The higher values at the greater concrete fraction are empirically consistent with improved load transfer, but the internal skeleton was not directly observed.

At the same RBCM content, CBR generally increased as the concrete fraction increased. The higher measured density, strength, and lower absorption of recycled concrete provide a plausible explanation, but formation of a more stable internal skeleton was not directly observed.

In summary, the brick-to-concrete ratio significantly influences the California bearing ratio of stabilized sludge soil. Under the experimental conditions of this study, the CBR value of the stabilized sludge soil reached its maximum at a brick-to-concrete ratio of 1:2, indicating that appropriately increasing the proportion of waste concrete in the RBCM is conducive to enhancing the bearing capacity of the stabilized sludge soil.

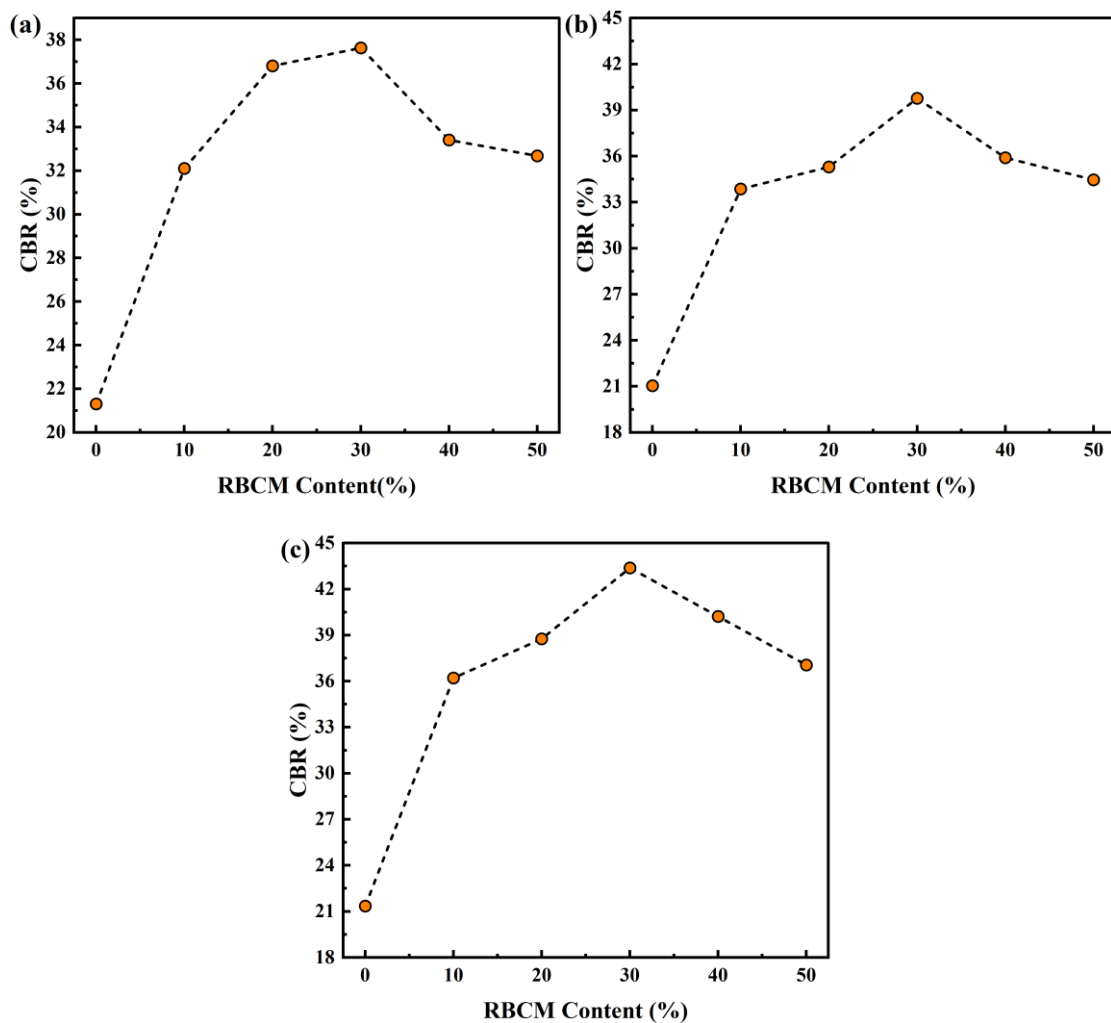


Fig. 16. Relationship between CBR and RBCM content (a) Brick-concrete ratio 2:1, (b) Brick-concrete ratio 1:1, (c) Brick-concrete ratio 1:2.

3.1.3. Influence of brick-to-concrete ratio on the comparative UCS index

The UCS-index procedure followed Section 2.2.3, with curing ages of 7, 14, 28, and 90 d. Figure

17 shows the comparative UCS index under the three brick-to-concrete ratios.

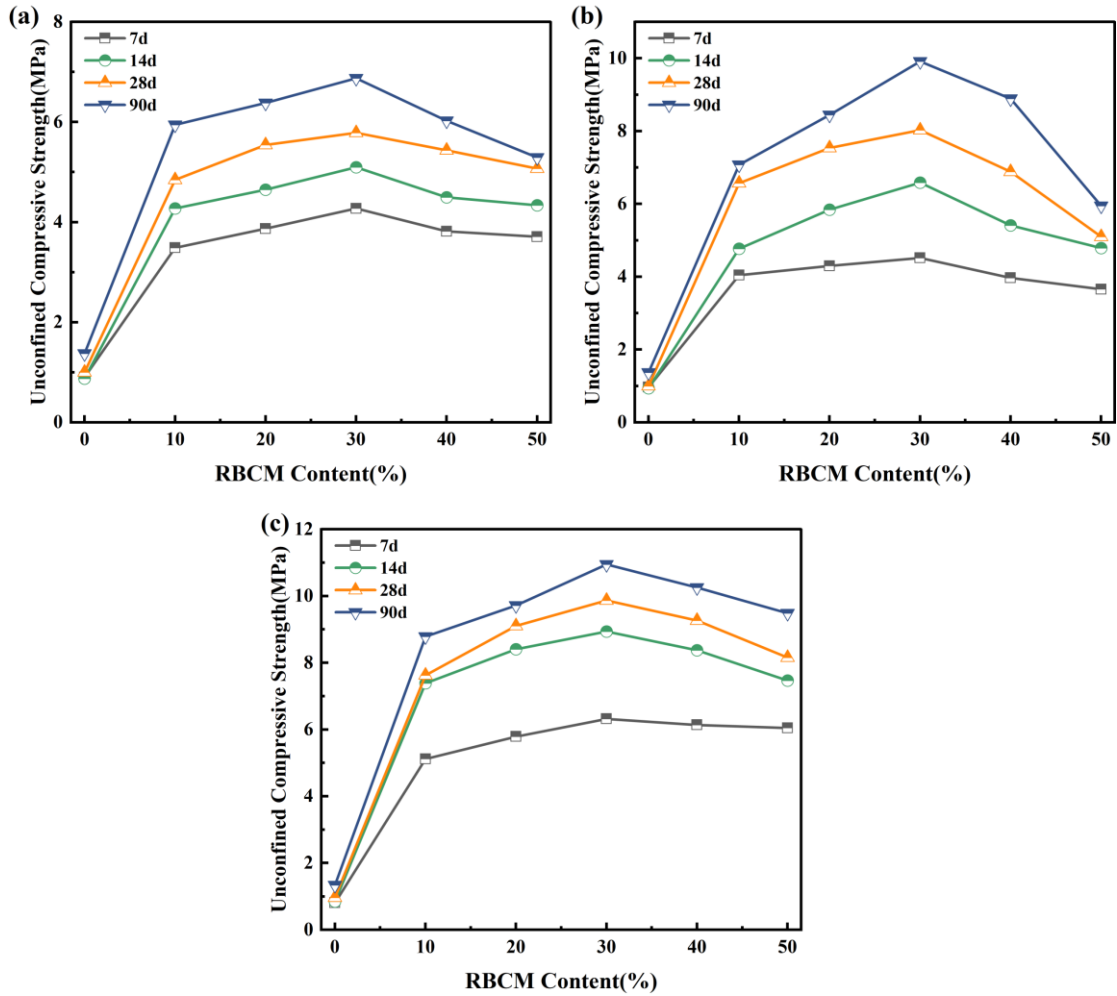


Fig. 17. Relationship between RBCM content and the comparative UCS index: (a) brick-to-concrete ratio 2:1, (b) 1:1, and (c) 1:2.

As shown in Figure 17(a), at a 2:1 ratio, the 7, 14, 28, and 90 d UCS indices increased from 3.51, 4.25, 4.87, and 5.94 MPa at 10% RBCM to 4.25, 5.07, 5.79, and 6.88 MPa at 30% and then decreased at 40% and 50%. These values describe a measured content trend without identifying its internal structural cause.

As shown in Figure 17(b), at a 1:1 ratio, the 7, 14, 28, and 90 d UCS indices increased from 4.03, 4.73, 6.54, and 7.09 MPa at 10% RBCM to 4.48, 6.58, 8.02, and 9.98 MPa at 30% and then decreased at 40% and 50%. Values were generally higher than in the corresponding 2:1 groups.

As shown in Figure 17(c), the 1:2 brick-to-concrete groups produced the highest UCS indices. The 7, 14, 28, and 90 d values increased from 5.12, 7.39, 7.63, and 8.79 MPa at 10% RBCM to 6.32, 8.94, 9.87, and 10.95 MPa at 30% RBCM and then decreased at higher contents. The trend is consistent with more effective bulk load transfer at an intermediate RBCM content, but it does not directly identify an aggregate skeleton or interfacial reaction product.

At a given RBCM content and curing age, the UCS-index ranking was 1:2 > 1:1 > 2:1. Waste concrete had higher measured density and lower water absorption than waste brick, which provides

a plausible bulk-scale explanation for this ordering. Formation of a continuous skeleton, interfacial cementation, and void filling were not directly measured.

Across brick-to-concrete ratios, maximum dry density, CBR, and the UCS index first increased and then decreased with RBCM content, whereas optimum moisture content decreased. These repeatable bulk trends identify 30% RBCM as the best tested content; packing and skeleton explanations remain interpretations rather than direct observations.

At the same RBCM content, increasing the concrete fraction generally increased maximum dry density, CBR, and the UCS index and decreased optimum moisture content. The 1:2 ratio gave the best overall laboratory response, followed by 1:1 and 2:1. This empirical ordering is consistent with measured aggregate-property differences; detailed skeleton and interfacial mechanisms require direct verification.

3.2. Influence of recycled aggregate content on the mechanical properties of stabilized sludge soil

3.2.1. Influence of recycled aggregate content on the compaction characteristics of stabilized sludge soil

The compaction procedure followed Section 2.2.1. Plain SS and the 10% SCS-only mixture were controls. Figure 18 shows that maximum dry density first increased and then decreased with RBCM content, whereas optimum moisture content decreased over the tested range. These statements describe the measured bulk response; the internal packing state was not directly observed.

At 0% RBCM, maximum dry density was $1.67 \text{ g}\cdot\text{cm}^{-3}$ and optimum moisture content was 16.9%. At 10% RBCM, maximum dry densities for brick-to-concrete ratios of 2:1, 1:1, and 1:2 were 1.75, 1.91, and $1.92 \text{ g}\cdot\text{cm}^{-3}$, while optimum moisture contents were 13.3%, 12.4%, and 12.3%. These are measured compaction differences; the underlying particle arrangement was not directly imaged.

At 20% RBCM, maximum dry densities for brick-to-concrete ratios of 2:1, 1:1, and 1:2 were 1.76, 1.93, and $1.95 \text{ g}\cdot\text{cm}^{-3}$, and optimum moisture contents were 12.5%, 11.7%, and 10.4%. At 30% RBCM, maximum dry densities reached 1.81, 1.96, and $1.99 \text{ g}\cdot\text{cm}^{-3}$, respectively—the highest values for the corresponding ratios—while optimum moisture contents decreased to 11.6%, 10.4%, and 9.9%. A favorable packing state is one possible explanation for the 30% peak, not a direct observation.

At 50% RBCM, maximum dry densities for the 2:1, 1:1, and 1:2 ratios were 1.73, 1.89, and $1.96 \text{ g}\cdot\text{cm}^{-3}$, with optimum moisture contents of 11.0%, 10.1%, and 9.5%. At 70%, maximum dry densities decreased to 1.68, 1.87, and $1.90 \text{ g}\cdot\text{cm}^{-3}$, while optimum moisture contents were 10.7%, 9.8%, and 9.3%. The density decrease is consistent with reduced packing efficiency at high coarse fractions, but voids and arching were not directly measured.

A possible packing-based interpretation is that low RBCM contents are fine-matrix dominated,

intermediate contents promote coarse-particle contacts with SS occupying intervening spaces, and excessive RBCM promotes unfilled voids or local arching. This interpretation is consistent with the 30% peak but was not directly imaged or measured.

In summary, the RBCM content significantly affects the compaction characteristics of the stabilized sludge soil. Under the experimental conditions of this study, at an RBCM content of 30%, the proportion of coarse and fine particles was relatively optimal, and the stabilized sludge soil exhibited relatively high compactness and favorable compaction effectiveness.

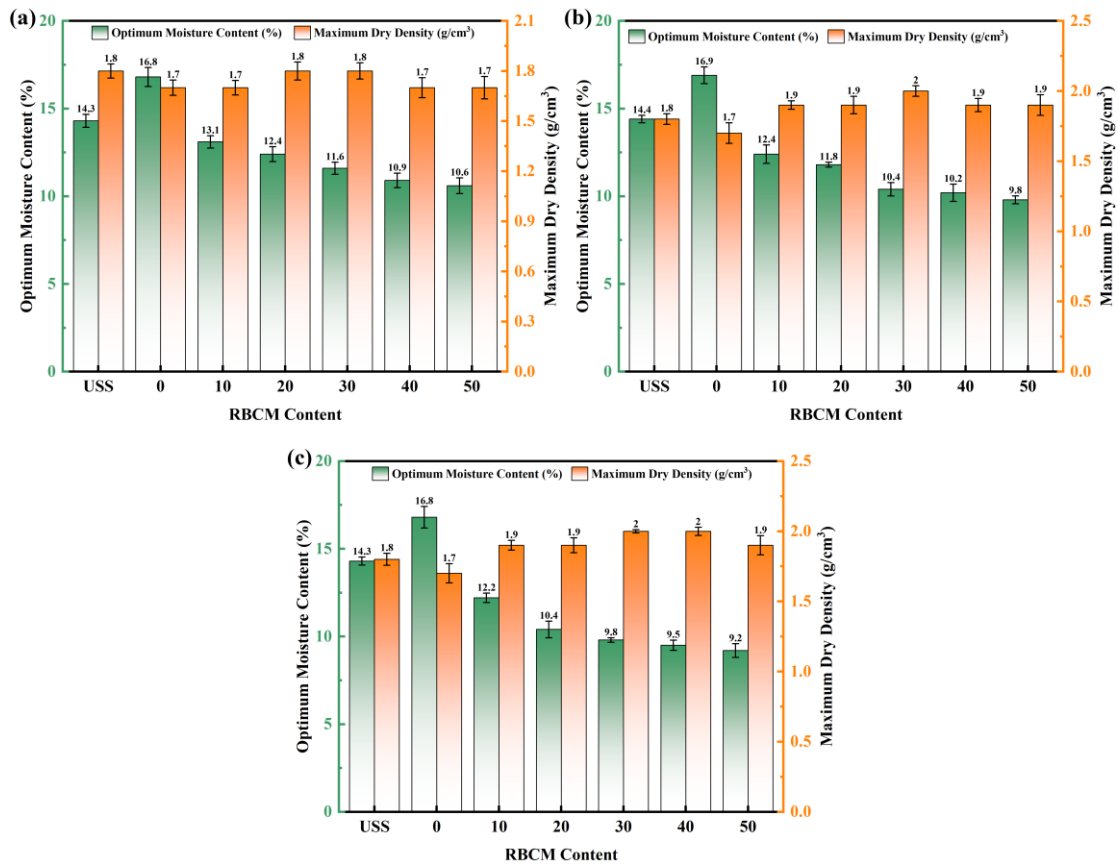


Fig. 18. Relationships between RBCM content and the compaction parameters: (a) Brick-concrete ratio 2:1, (b) Brick-concrete ratio 1:1, (c) Brick-concrete ratio 1:2.

3.2.2. Influence of recycled aggregate content on the California bearing ratio of stabilized sludge soil

The California bearing ratio test procedure followed that described in Section 2.2.2, with plain sludge soil and stabilized soil incorporating only 10% SCS at an RBCM content of 0% set as the control groups. The CBR test results of the stabilized sludge soil under different RBCM contents are presented in Figure 19.

Across the three brick-to-concrete ratios, CBR first increased and then decreased with RBCM content. This measured trend identifies an intermediate optimum; explanations based on skeleton development, void filling, or loss of compatibility remain hypotheses.

At 10% RBCM, CBR values were 32.1%, 33.8%, and 36.4% for brick-to-concrete ratios of 2:1, 1:1, and 1:2. At 30% RBCM they reached 37.6%, 39.8%, and 43.5%, corresponding to increases of 5.5, 6.0, and 7.1 percentage points. The data show the peak directly; the proposed skeleton and void-filling explanation was not measured.

At 40% RBCM, CBR values for the 2:1, 1:1, and 1:2 ratios were 33.4%, 35.9%, and 40.3%; at 50% they were 32.6%, 34.4%, and 37.1%. These values confirm a descending branch after the 30% peak. Reduced packing efficiency is a possible, unverified explanation.

In summary, CBR depended on RBCM content and was highest at 30% for all three brick-to-concrete ratios. This conclusion is based on measured bearing response and does not itself establish skeleton support or void-filling mechanisms.

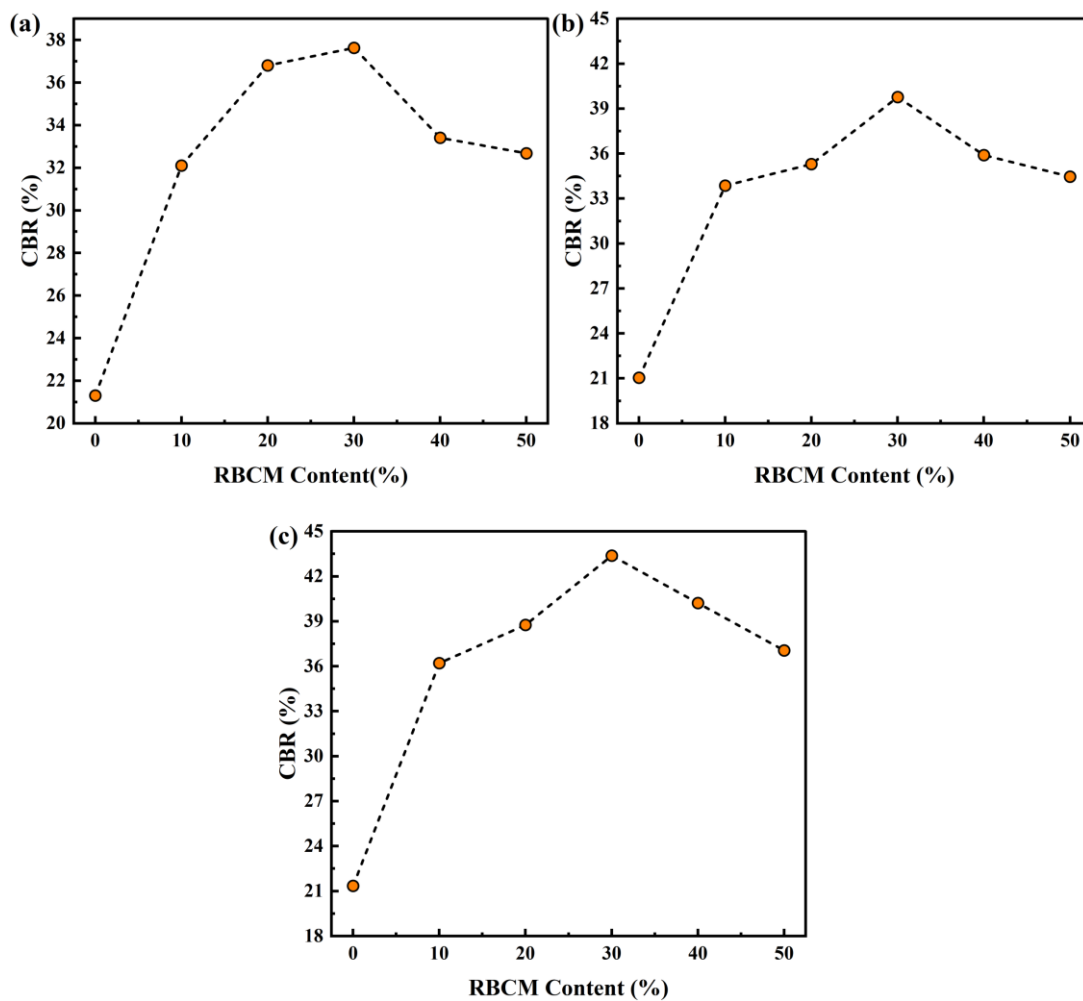


Fig. 19. Relationships between RBCM content and CBR: (a) Brick-concrete ratio 2:1, (b) Brick-concrete ratio 1:1, (c) Brick-concrete ratio 1:2.

3.2.3. Influence of recycled aggregate content on the comparative UCS index

The laboratory UCS-index procedure followed Section 2.2.3, with curing ages of 7, 14, 28, and 90 d. Figure 20 summarizes the measured relationships with RBCM content.

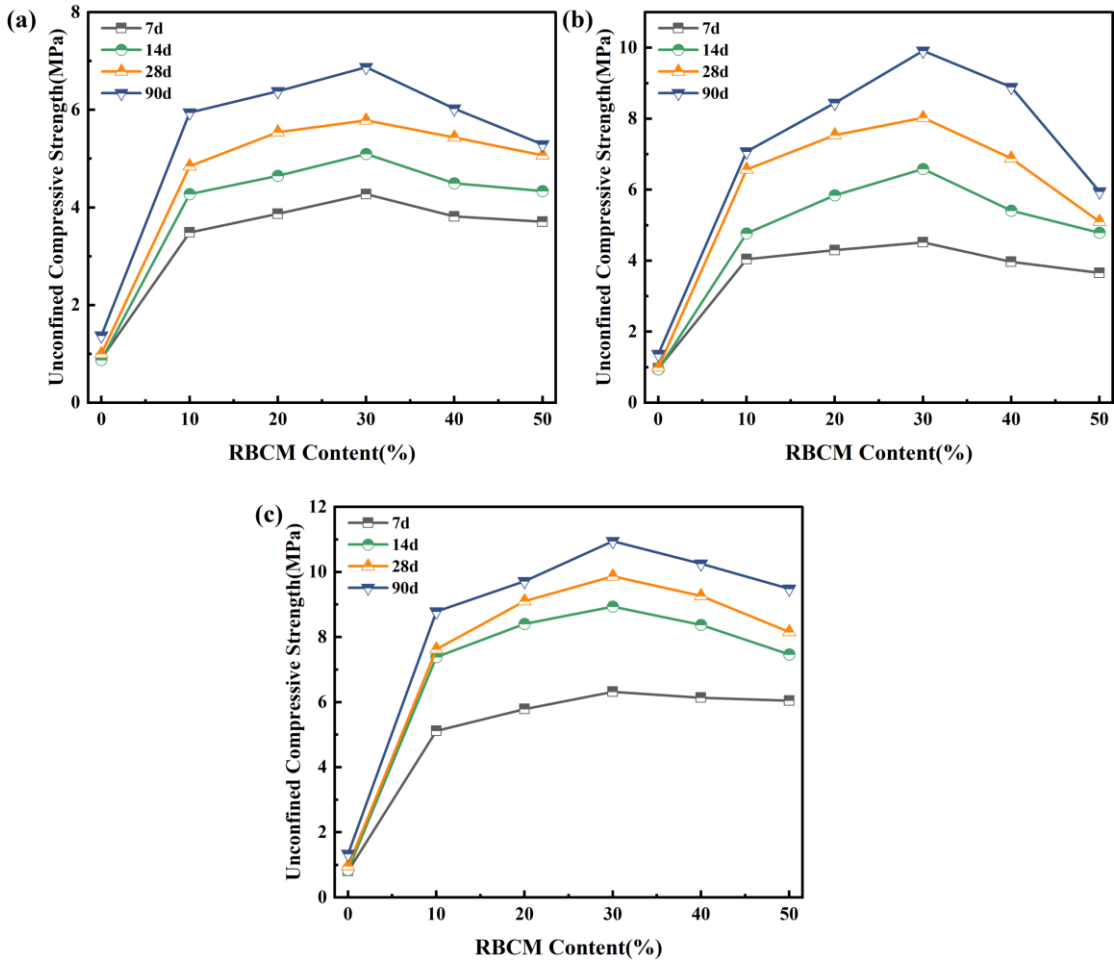


Fig. 20. Relationships between RBCM content and the comparative UCS index: (a) brick-to-concrete ratio 2:1, (b) 1:1, and (c) 1:2.

As shown in Figure 20, the comparative UCS index first increased and then decreased with RBCM content and reached a relatively high level at 30% across the tested ratios and ages. The trend is consistent with improved bulk load transfer at an intermediate coarse fraction, although the structural explanation was not directly verified.

For the SCS-only group (0% RBCM), the 7, 14, 28, and 90 d UCS indices were 0.81, 0.85, 0.97, and 1.34 MPa. At 10% RBCM, the corresponding values were 3.51, 4.25, 4.87, and 5.94 MPa for the 2:1 ratio; 4.03, 4.73, 6.54, and 7.09 MPa for 1:1; and 5.12, 7.39, 7.63, and 8.79 MPa for 1:2. These are measured group differences; the specific contributions of skeleton support and cementation were not separated.

At 30% RBCM, the 7, 14, 28, and 90 d UCS indices were 4.25, 5.07, 5.79, and 6.88 MPa for the 2:1 ratio; 4.48, 6.58, 8.02, and 9.98 MPa for 1:1; and 6.32, 8.94, 9.87, and 10.95 MPa for 1:2. These were the highest values in the respective content series. A favorable skeleton–matrix configuration is a hypothesis consistent with the peak, not a directly measured structure.

At 40% and 50% RBCM, the UCS index declined but remained above the SCS-only group. The increase with curing age is consistent with progressive binder reaction and particle bonding; however,

neither reaction products nor interfacial pore filling were directly measured in the present SCS–RBCM specimens.

At the recycled-aggregate/SS interface, $\text{Ca}(\text{OH})_2$ supplied by calcium carbide slag activates the reactive SiO_2 and Al_2O_3 in straw ash, promoting the formation of C-S-H and C-A-S-H gels. These gels nucleate on the rough recycled-aggregate surfaces, bridge the aggregate–soil contact zone, and fill interfacial pores; therefore, the well-graded mixture at 30% RBCM develops a denser interfacial transition zone, whereas excessive RBCM leaves voids that cannot be completely filled by the available fines and hydration products.

In summary, the comparative UCS index depended on RBCM content, brick-to-concrete ratio, and curing age. Within the tested matrix, 30% RBCM and a 1:2 ratio gave the highest values. These trends do not remove the specimen-size and evidentiary limitations below.

3.2.4. Limitations of the UCS geometry and mechanism interpretation

The recycled aggregate included particles of 30–40 mm, whereas the UCS cylinders were 50 mm in diameter and height, corresponding to a diameter-to-maximum-particle-size ratio of only 1.25–1.67. This geometry is insufficient to provide a representative elementary volume for the field gradation. The reported UCS values should therefore be interpreted only as comparative indices within this laboratory matrix and should not be transferred directly to field design. Verification requires larger specimens with a diameter of at least approximately five times the maximum particle size, or a separately validated scaled-gradation protocol. In addition, the proposed hydration, cementation, void-filling, skeleton, and arching mechanisms are inferences from raw-material chemistry, bulk engineering trends, and prior evidence for a related binder-only system [19]. The current study contains no direct XRD, TGA, SEM–EDS, or pore-structure evidence for the SCS–RBCM specimens; such measurements are required to test these hypotheses.

3.3. Grey relational analysis and prediction of the comparative UCS index

3.3.1. Grey relational analysis

RBCM content, curing age, and brick-to-concrete ratio were used as comparison sequences, and the comparative UCS index was used as the characteristic sequence.

The comparative UCS index was designated as the parent sequence Y . RBCM content, curing age, and brick-to-concrete ratio were denoted X_1 , X_2 , and X_3 , respectively.

(1) Determination of the grey relational analysis sequences

The analysis sequence formula is as follows. Let X be the grey relational factor set, $Y_0(k) \in Y_i$ be the parent sequence, and $x_i(k) \in x_i$ be the characteristic sequence. $Y_0(k)$ and $x_i(k) \in x_i$ are the k -th data points of Y_0 and x_i , respectively.

$$X = \{x_i | i \in N, N = (0, 1, 2, \dots, m, m \geq 2)\} \quad (1)$$

$$x_i = \{x_i(1), x_i(2), x_i(n)\}$$

$$x_i(k) \in x_i, k \in K, K = (1, 2, \dots, n), n \geq 3$$

Denote Y as the grey relational factor set, then,

$$Y = \{y_i | i \in N, N = (0, 1, 2, \dots, m, m \geq 2)\}$$

$$y_i = \{y_i(1), y_i(2), y_i(n)\}$$

$$y_i(k) \in y_i, k \in K, K = (1, 2, \dots, n), n \geq 3$$

(2) Dimensionless treatment of the indicators

Prior to the subsequent evaluation, each factor set sequence needs to be standardized and converted into dimensionless data. Different standardization functions are adopted for different types of sequences, as specified below:

Cost-type standardization function:

$$x_i = \frac{(\max x_j - x_j)}{(\max x_j - \min x_j)}$$

Benefit-type standardization function:

$$x_i = \frac{(x_j - \min x_j)}{(\max x_j - \min x_j)}$$

Moderate-type standardization function:

$$x_i = \frac{x_j^*}{|x_j - x_j^*| + x_j^*}$$

In this study, the benefit-type standardization function was adopted to preprocess the data.

(3) Calculation of the grey relational coefficient

The first step is to calculate the absolute difference sequence between the parent sequence and the subsequences. Subsequently, the maximum and minimum values are extracted from the absolute difference sequence to compute the relational coefficient. Let ρ be the distinguishing coefficient, which lies within the interval (0, 1). A smaller value of ρ leads to a greater difference among the relational coefficients and a stronger distinguishing capability. In this paper, ρ is set to 0.5. The relational coefficient is calculated as follows:

$$\Delta_0 = |Y_0(k) - x_i(k)|$$

Determination of the extrema:

$$\Delta_{\min} = \min_{i=1}^n \min_{k=1}^m |Y_0(k) - x_i(k)|$$

$$\Delta_{\max} = \max_{i=1}^n \max_{k=1}^m |Y_0(k) - x_i(k)|$$

Calculation of the relational coefficient:

$$\gamma\{Y_0(k)\} = \frac{\Delta_{\min} + \rho\Delta_{\max}}{\Delta_0 + \rho\Delta_{\max}}$$

Based on the formula, the grey relational coefficients between each indicator and the unconfined compressive strength were calculated.

Table 4. Grey relational coefficient.

X ₁	X ₂	X ₃
1	1	1
0.9892	0.855	0.9922
0.9581	0.6664	0.9694
0.8734	0.3333	0.9054
0.6156	0.5272	0.5405
0.4454	0.4563	0.4352
0.4327	0.5304	0.4264
0.3805	0.6899	0.3885
0.7541	0.5988	0.9694
0.6589	0.6106	0.9037
0.4968	0.6029	0.6833
0.4622	0.5545	0.6361
0.8447	0.6402	0.4053
0.7213	0.6502	0.4308
0.6427	0.7628	0.4547
0.5409	0.4896	0.5030
0.7982	0.4911	0.5045
0.5077	0.4160	0.4002
0.4627	0.4559	0.3792

0.4295	0.7962	0.3627
0.8639	0.5800	0.9807
0.7879	0.5345	0.7533
0.5784	0.5363	0.6029
0.5042	0.6587	0.5428
0.7825	0.6125	0.4166
0.9393	0.6184	0.4451
0.8408	0.6875	0.4847
0.7098	0.5114	0.5248
0.8643	0.4658	0.4792
0.6411	0.3978	0.3841
0.5512	0.4252	0.3588
0.4740	1	0.3333
0.6022	0.567	0.9459
0.9209	0.4944	0.6796
0.7645	0.5085	0.5697
0.5422	0.832	0.4669
0.5803	0.5828	0.4308
0.6671	0.5853	0.4630
0.7680	0.6656	0.4956
0.9962	0.5414	0.5547
0.5678	0.4741	0.4875
0.8709	0.4171	0.4011
0.9131	0.4491	0.3747
0.7320	0.8744	0.3492
0.4227	0.6063	0.9512
0.5143	0.5581	0.7984
0.6427	0.5776	0.6525

0.9967	0.7020	0.5179
0.4164	0.6164	0.4149
0.4508	0.6314	0.4390
0.5121	0.6995	0.4792
0.5583	0.4941	0.5075
0.4272	0.4783	0.4918
0.5123	0.4529	0.4322
0.5671	0.5011	0.4082
0.7146	0.7670	0.3687
0.3333	0.6293	0.9021
0.3724	0.6059	0.8942
0.3862	0.7314	0.8422
0.5492	0.6156	0.5742
0.3349	0.6252	0.4112
0.3554	0.6441	0.4333
0.3837	0.7382	0.4634
0.3924	0.4591	0.4725

(4) Ranking of the relational degrees

Relational degree was ranked by r_i . Within this dataset, RBCM content X_1 had the largest relational degree with the comparative UCS index. This ranking describes association within the tested matrix and does not by itself establish causation.

Table 5. Grey relational degree.

X_1	X_2	X_3
0.6300	0.5981	0.5667

3.3.2. Construction of the grey prediction model

3.3.2.1. Construction of the grey prediction GM(1,1) model

The grey prediction model is a mathematical modeling approach designed for trend forecasting in systems with small sample sizes and incomplete information, and is applicable to short-term trend

analysis of nonlinear and non-stationary systems. Among these models, the grey GM(1,1) model is the most widely used, with the specific construction steps as follows:

(1) Assume that the original data sequence has n observations: $X^{(0)} = \{X^{(0)}(1), X^{(0)}(2), L, X^{(0)}(n)\}$

(2) A new sequence is generated by performing a first-order accumulation on the original data sequence: $X^{(1)} = \{X^{(1)}(1), X^{(1)}(2), L, X^{(1)}(n)\}$, 其中 $X^{(1)}(n) = \sum_{i=1}^n X^{(0)}(i)$

Here, $X^{(0)} = \{x^{(0)}(1), x^{(0)}(2), \dots, x^{(0)}(n)\}$ is the original non-negative data sequence; $x^{(0)}(k)$ is the observed UCS at the k th curing age; n is the number of observations; and $k = 1, 2, \dots, n$ is the observation index. $X^{(1)} = \{x^{(1)}(1), x^{(1)}(2), \dots, x^{(1)}(n)\}$ is the first-order accumulated generating operation (1-AGO) sequence, where $x^{(1)}(k) = \sum_{i=1}^k x^{(0)}(i)$.

(3) The newly generated data sequence is modeled, yielding the first-order grey differential equation dynamic model as follows:

In the grey differential equation, $z^{(1)}(k) = 0.5x^{(1)}(k) + 0.5x^{(1)}(k-1)$ is the background value; a is the development coefficient, which describes the growth trend of the sequence; and b is the grey input (endogenous control) coefficient.

$$\frac{dX^{(1)}}{dt} + \alpha X^{(1)} = \mu$$

where α and μ are undetermined coefficients, with α being the development coefficient and μ the endogenous control coefficient.

(4) Let $\hat{a} = \begin{bmatrix} \alpha \\ \mu \end{bmatrix}$, and estimate the parameters $\hat{a}$ using the least squares method, yielding

$$\hat{a} = (B^T B)^{-1} B^T Y_n$$

$$\text{where, } Y_n = [x^{(0)}(2), x^{(0)}(3), L, x^{(0)}(m)] \quad B = \begin{bmatrix} -[X^{(1)}(2) + X^{(1)}(1)]/2 & 1 \\ -[X^{(1)}(3) + X^{(1)}(2)]/2 & 1 \\ L & L \\ -[X^{(1)}(m) + X^{(1)}(m-1)]/2 & 1 \end{bmatrix}$$

The parameter vector is $\hat{u} = [a, b]^T$; B is the $(n-1) \times 2$ data matrix constructed from $-z^{(1)}(k)$ and a unit column; $Y_n = [x^{(0)}(2), x^{(0)}(3), \dots, x^{(0)}(n)]^T$ is the response vector; and T denotes matrix transposition.

$$Y_n = [x^{(0)}(2), x^{(0)}(3), L, x^{(0)}(m)] \quad (2)$$

(5) The discrete-time response function of the grey prediction model is derived as:

$$\hat{X}^{(1)}(k+1) = [X^{(0)}(1) - \frac{\mu}{\alpha}]e^{-\alpha k} + \frac{\mu}{\alpha}, k=1,2,L,m \quad (3)$$

(6) The predicted values can be restored as:

$$\hat{X}^{(0)}(k+1) = \hat{X}^{(1)}(k+1) - \hat{X}^{(1)}(k) = (1 - e^\alpha)[X^0(1) - \frac{\mu}{\alpha}]e^{-\alpha k} \quad (4)$$

(7) Model verification

For the GM(1,1) model to be meaningful, the development coefficient *a* should lie within the interval (-2, 2). If the model is meaningful, a relative error test can be conducted to determine the

mean relative error $D = \frac{1}{n} \sum_{i=1}^n \left| \frac{X^{(0)}(i) - \hat{X}^{(0)}(i)}{X^{(0)}(i)} \times 100\% \right|$, where $i = 1, 2, L, n$.

For verification, $\hat{x}^{(0)}(k)$ denotes the predicted value, $\varepsilon(k) = |x^{(0)}(k) - \hat{x}^{(0)}(k)|/x^{(0)}(k) \times 100\%$ is the relative error at observation k, and $\bar{\varepsilon} = (1/n) \sum_{k=1}^n \varepsilon(k)$ is the mean relative error.

The model accuracy is expressed as follows: $u = (1 - D) \times 100\%$ when $\mu > 80\%$, the model prediction results meet the requirements. When $u > 90\%$, the model prediction accuracy is relatively high.

3.3.2.2. Prediction and verification

Since the predicted function comprised a total of 16 groups, and according to Section 3.1, the unconfined compressive strength and California bearing ratio of the stabilized soil at an RBCM content of 30% were higher than those at other contents, the 30% content level under three different brick-to-concrete ratio conditions was selected for the prediction of unconfined compressive strength. The prediction process using the grey prediction model was as follows:

(1) Taking the brick-to-concrete ratio of 1:2 as an example, let the original sequence be:

$$X^{(0)} = \{X^{(0)}(1), X^{(0)}(2), L, X^{(0)}(n)\} = \{0.81 \ 0.85 \ 0.97 \ 1.34\}$$

(2) A new sequence was formed after first-order accumulation of the original sequence:

$$X^{(1)} = \{X^{(1)}(1), X^{(1)}(2), L, X^{(1)}(n)\} = \{0.81 \ 1.66 \ 2.63 \ 3.97\}$$

(3) Determination of the data matrix B and Y_n :

$$B = \begin{bmatrix} -1.235 & 1 \\ -2.145 & 1 \\ -3.3 & 1 \end{bmatrix} Y_n = [0.85 \cdot 0.97 \cdot 1.34]$$

(4) Determination of the parameters $\hat{a} = (B^T B)^{-1} B^T Y_n = \begin{bmatrix} 0.37519 \\ 6180.667 \end{bmatrix}$, since $\hat{a} = \begin{bmatrix} \alpha \\ \mu \end{bmatrix}$, it follows that

$$\alpha = 0.23887, \quad \mu = 0.93411.$$

The discrete-time response function of the grey prediction model is:

$$\hat{X}^{(8)}(k+1) = -87.42588939e^{-0.10035k} + 93.74588939$$

The mean relative error was 0.1417%, and the model accuracy was 99.8583%.

For the brick-to-concrete ratio of 1:1, the function is:

$$\hat{X}^{(9)}(k+1) = -31.82649787e^{-0.20222k} + 36.30649787$$

The mean relative error was 0.6281%, and the model accuracy was 99.3719%.

For the brick-to-concrete ratio of 2:1, the function is:

$$\hat{X}^{(10)}(k+1) = -31.46073136e^{-0.15273k} + 35.71073136e$$

The mean relative error was 0.97091%, and the model accuracy was 99.02909%. The development coefficients of the above three models, $|a| < 0.3$, all lie within the interval $(-2, 2)$, indicating that the trend of system variation is relatively moderate, the fluctuation of the data sequence is small, and the prediction accuracy of the models is relatively high, rendering them suitable for prediction. The measured and predicted curves of the unconfined compressive strength are presented in Figure 3-7.

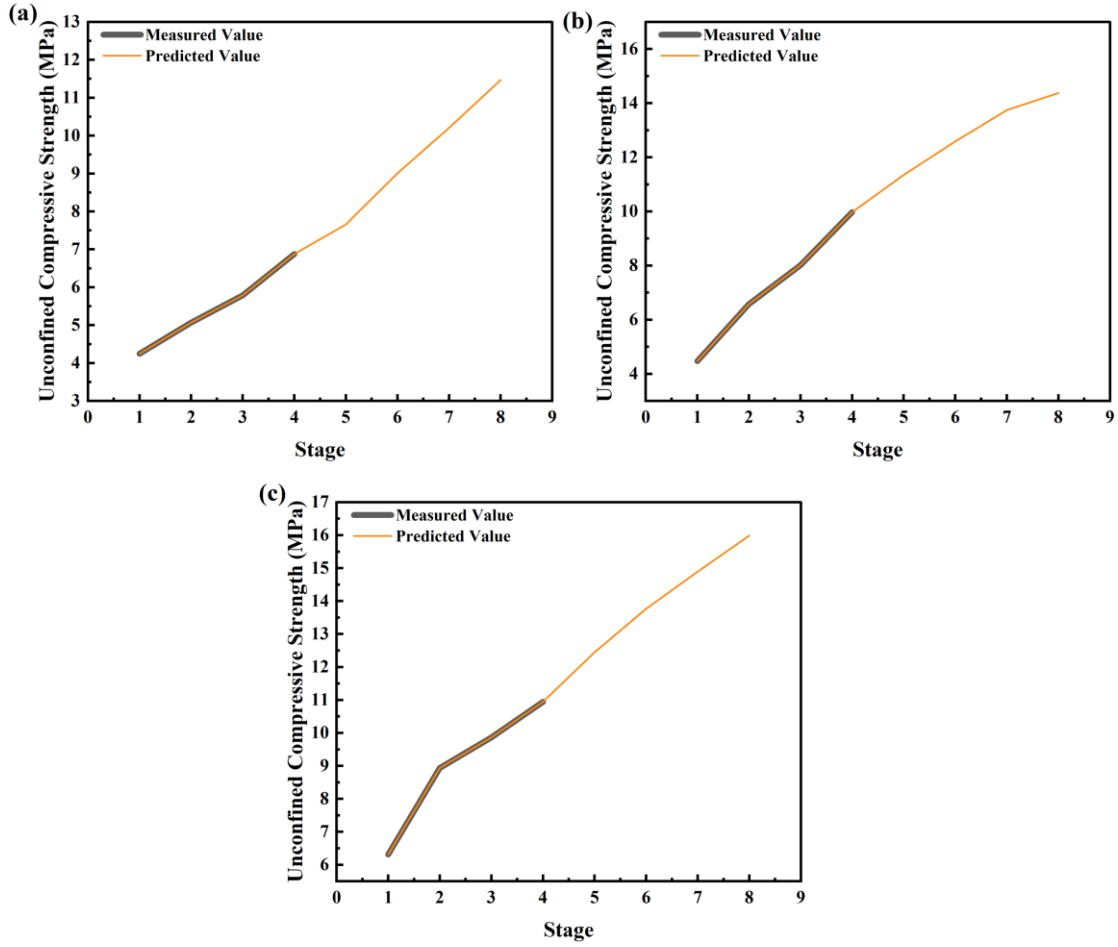


Fig. 21. Measured and GM(1,1)-predicted comparative UCS indices: (a) brick-to-concrete ratio 1:2, (b) 1:1, and (c) 2:1.

4. Conclusions

This study used heavy compaction, CBR, comparative laboratory UCS-index tests, grey relational analysis, and a GM(1,1) model to evaluate SCS–RBCM-stabilized sludge soil. The main conclusions are as follows.

(1) RBCM content markedly affected compaction. Maximum dry density first increased and then decreased, whereas optimum moisture content decreased over the tested range. The 30% RBCM group produced the highest maximum dry density. A packing/skeleton explanation is consistent with this trend but was not directly verified by internal-structure imaging.

(2) CBR first increased and then decreased with RBCM content and reached its highest value at 30% for each brick-to-concrete ratio. Increasing the concrete fraction increased CBR, with the 1:2 group performing best under the tested conditions.

(3) Mechanistically, C–S–H and C–A–S–H gels generated by activation of straw ash adhere to the rough recycled-aggregate surfaces, bridge the aggregate–SS interface, and fill interfacial pores, thereby strengthening the skeleton–matrix bond.

(4) For a given RBCM content and curing age, the 1:2 brick-to-concrete ratio generally produced the highest maximum dry density, CBR, and UCS index, followed by 1:1 and 2:1. This ordering is associated empirically with the higher proportion of denser, stronger recycled concrete; the detailed load-transfer mechanism remains to be measured.

(5) Grey relational analysis ranked RBCM content, curing age, and brick-to-concrete ratio in descending order of association with the UCS index. The GM(1,1) model reproduced the measured time-development trend for this dataset, but extrapolation beyond the tested matrix requires independent validation.

Under the experimental conditions, 30% RBCM and a 1:2 brick-to-concrete ratio gave the best overall laboratory response. Two limitations constrain engineering interpretation: the 50 mm UCS specimens were not geometrically representative of the 30–40 mm aggregate, and no direct phase or microstructural measurements were performed on the SCS–RBCM mixtures. Accordingly, the UCS values are comparative indices, and the proposed hydration–bonding–skeleton mechanism remains a testable hypothesis. Larger-specimen mechanical tests and XRD/TGA/SEM–EDS/pore-structure analyses are needed before field-design application.

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Data availability

The authors confirm that the data supporting the findings of this study are available within the article.

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.

Author contribution statement

Yuxuan Wu: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Software, Visualization, Writing – original draft, Writing – review & editing. **Zixiong Chen:** Investigation, Data curation, Validation, Visualization, Writing – review & editing. **Yongcheng Ji:**

Conceptualization, Methodology, Resources, Supervision, Project administration, Funding acquisition, Writing – review & editing. **Xu Wang**: Investigation, Formal analysis, Validation, Writing – review & editing. **Jun Wang**: Methodology, Validation, Writing – review & editing. All authors have read and approved the final manuscript and agree to be accountable for all aspects of the work.

Use of AI statement

None

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