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Tri-axial shear performance of urban dredged silt stabilized with a biochar-modified alkali-activated slag binder

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Urban dredged silt has a weak structure and poor water stability, which limit its direct infrastructure reuse. In this study, we evaluate a biochar-modified alkali-activated slag (BAS) binder comprising corn-straw biochar, ground granulated blast-furnace slag (GGBS), and carbide slag. Response surface methodology was used to assess the effects of binder composition on unconfined compressive strength (UCS). The numerical optimization module recommended 13.26% GGBS, 8.25% carbide slag, and 4.30% biochar by total specimen mass. The measured 28 days UCS of this combination was 6.25 MPa, compared with the software-reported prediction of 6.32 MPa. For the combined analysis, the normalized internal dry-mass ratio was adopted as the BAS formulation for the consolidated un-drained tri-axial program at different binder dosages, water contents, and curing ages. At 28 days and 18% water content, cohesion and friction angle were 169.4 kPa and 38.5° at 5% BAS and 195.2 kPa and 42.5° at 15% BAS, respectively. Among the tested water contents, both parameters were the highest at 18%. Their increments became small after 60 days of curing. At 15% dosage, 18% water content, and 28 days, BAS gave $c = 195.2$ kPa and $\phi = 42.5^\circ$, whereas the cement comparison group gave $c = 191.7$ kPa and $\phi = 42.1^\circ$. Relative to alkali-activated slag without biochar and the lime comparison group, BAS cohesion was 16.40% and 23.62% higher, respectively. The corresponding friction-angle values were 12.73% and 17.40% higher, respectively. Taken together, these findings position BAS as a promising clinker-free strategy for valorizing industrial and agricultural by-products through the sustainable stabilization and infrastructure reuse of urban dredged silt.

KEYWORDS

alkali-activated slag, biochar, dredged silt, infrastructure reuse, tri-axial shear strength

1 Introduction

Urban dredged silt is generated during river-channel maintenance, municipal excavation, underground-space development, and infrastructure renewal. In its untreated state, it commonly has a high water content, weak particle bonding, and poor resistance to disturbance. These features limit its direct use in subgrades, embankments, and shallow ground improvement. Infrastructure reuse requires conversion of the dredged

material into a compactable geomaterial with reproducible strength parameters under relevant stress states. Binder treatment can improve the strength and workability of dredged sediment, although the resulting performance depends on the water content, binder chemistry, curing conditions, and the test path used to evaluate the treated soil (Hu et al., 2024). Cement- and ground-granulated-blast-furnace-slag (GGBS)-treated dredged sediments have been investigated for construction reuse (Zhang et al., 2020). Studies of calcium-hydroxide-activated slag further show that activator dilution and pore structure can limit reaction efficiency in high-water-content dredged sediment (Ma et al., 2025).

Portland cement and lime remain common stabilizers because hydration, flocculation, cation exchange, and cemented-aggregate formation can improve the bonded and frictional components of soil strength. Cement-treated clay develops strength as a function of curing and water content (Horpibulsuk et al., 2010). Cement manufacture, however, has a substantial embodied-carbon burden associated with limestone calcination and fuel combustion (Andrew, 2018). Reducing clinker demand is, therefore, a central strategy for lowering the environmental burden of cementitious materials (Scrivener et al., 2018). This issue is relevant to dredged silt because the treatment volumes can be large and the target product is generally a stabilized earthwork material rather than a high-value structural component. A clinker-free alternative is useful only if it provides engineering-relevant shear parameters while incorporating industrial by-products or biomass-derived constituents.

Alkali-activated materials offer a pathway for reducing clinker dependence in soil stabilization. In calcium-rich precursors such as GGBS, alkaline activation dissolves reactive glassy phases and promotes precipitation of calcium-silicate-hydrate and calcium-aluminosilicate-hydrate gels. These products can coat mineral particles, bridge particle contacts, and refine pores, which may increase cohesion and mobilized frictional resistance (Provis, 2018). This concept has been extended to dredged silt and high-liquid-limit soils. Response surface methodology (RSM) has been used to proportion an alkali-activated slag treatment for dredged silt (Hu et al., 2024), while fly-ash- and GGBS-derived geopolymers have improved the strength, California bearing ratio (CBR), and resilient modulus of a high-liquid-limit soil (Li et al., 2025). Solid-waste geopolymer subgrade materials have also been evaluated for mechanical and durability performance (Li et al., 2026). These studies support alkali activation as a stabilization route, but they also show that the component dosage and water state must be controlled.

Carbide slag is relevant because its calcium-hydroxide-rich composition can provide both alkalinity and calcium for slag activation. As a solid by-product activator, it may be more convenient for large-volume earthwork treatment than concentrated sodium-hydroxide or sodium-silicate solutions. Calcium carbide residue has been examined in geopolymer binders (Mohammed et al., 2025), and calcium carbide slag combined with high-reactivity fly ash has been used to stabilize expansive soil (Qiu et al., 2025). Carbide slag can also act as an activator in composite cementitious binders (Yang et al., 2024). In dredged sediments, calcium-hydroxide-activated GGBS systems are sensitive to activator chemistry and pore structure

(Ma et al., 2025). Lime- and carbide-slag-activated GGBS has been used to stabilize dredged sludge (Lang et al., 2021b), while carbide sludge- and GGBS-treated clay slurries have shown confinement-dependent tri-axial behavior (Li et al., 2022). The appropriate carbide-sludge content in GGBS-treated slurry has further been linked to the initial pH, indicating that calcium supply and alkalinity must be balanced (Li and Yi, 2023). These findings indicate that carbide slag can be a useful activator, but they do not establish whether a porous biomass-derived modifier changes the tri-axial shear envelope of stabilized urban silt.

Biochar is a candidate modifier because its porous structure, surface functional groups, and water-retention capacity can influence particle packing and hydration conditions. Biochar-amended cementitious composites show changes in hydration, pore structure, and internal curing, although the mechanical response depends on the particle size, dosage, and dispersion (Rashid et al., 2024). A meta-analysis of Portland-cement composites likewise found that the effect of biochar depends on the mixture and curing variables (Zhao et al., 2024). Related pavement-material studies also report sensitivity to particle size and additive dosage (Jia et al., 2025; Wei et al., 2026). Biochar has been investigated in carbon-dioxide-cured clay stabilization (Hanafi et al., 2024) and with industrial by-products in soft clay, quick clay, and peat (Hov et al., 2023). Biochar feedstock can influence the mechanical behavior and carbon-dioxide mineralization in cemented soft clay (Hanafi et al., 2025). A biochar-slag binder has also been shown to affect the compressibility, structure, and leaching behavior of stabilized alluvium (Sargent et al., 2023). Sewage-treatment-sludge biochar-activated slag has been reported as a binder for soft-soil stabilization (Gonzalez et al., 2021), and reactive-magnesia systems amended with biochar or GGBS have been evaluated for dredged marine soil (Onyekwena et al., 2024). Collectively, these results indicate that biochar may modify water distribution and particle packing, whereas excessive biochar may dilute the cementitious phase or introduce weak porous inclusions. Fine-grained wood biochar has also been shown to affect the geotechnical and microstructural behavior of pavement-subgrade clay (Saberian et al., 2025).

Alkali-activated slag, carbide slag, and biochar have each been examined largely in isolation. Binders combining them are usually proportioned and reported through unconfined compressive strength (UCS), which is suitable for screening mixtures but does not describe the resistance of a stabilized soil sample to shear under confinement. Few studies have carried an optimized composition of this type through to the cohesion and friction angle required for geotechnical assessment. The present study addresses this gap for urban dredged silt stabilized with a biochar-modified alkali-activated slag (BAS) binder. RSM selects a component combination from UCS results, and the normalized ratio of that combination is carried into a consolidated un-drained (CU) tri-axial program. The objectives are to quantify the effect of binder dosage, water content, and curing age on the total-stress shear parameters of BAS-stabilized silt and benchmark those parameters against ordinary Portland cement (OPC), alkali-activated slag without biochar (AS), and lime (OL) tested under the same conditions.

TABLE 1 Basic physical and engineering properties of the processed dredged silt.

Property	Value	Unit
Soil type	Low-liquid-limit clay	–
Natural water content	48.5	%
Liquid limit	40.5	%
Plastic limit	29.6	%
Plasticity index	10.9	–
Maximum dry density of processed untreated silt	1.70	g cm ⁻³
California bearing ratio (CBR)	18	%
Organic matter content	3.2	%
pH	6.8	–

2 Materials and methods

2.1 Urban dredged silt

The urban dredged silt was obtained from a river-channel construction site in Jinan, China. Before testing, it was initially dewatered, air-dried for 7 days, oven-dried at 55 °C for 10 h, cleaned to remove stones and debris, crushed, passed through a 2-mm round-hole sieve, and homogenized. Table 1 summarizes its physical properties. Based on the measured Atterberg limits, the silt was classified as a low-liquid-limit clay. Its natural water content was 48.5%, and its organic matter content and pH were 3.2% and 6.8, respectively. Figure 1 presents the compaction curve and particle-size distribution of the processed untreated silt. Specifically, Figure 1a shows the relationship between the water content and dry density, while Figure 1b presents the particle-size distribution.

2.2 Binder constituents

The BAS binder contained corn-straw biochar, GGBS, and carbide slag. The biochar was produced by drying corn straw at 60 °C for 8 h, crushing it to 2 mm–4 mm particles, and pyrolyzing it at 500 °C for 2 h at a heating rate of 10 °C min⁻¹. GGBS served as the main latent hydraulic precursor. Carbide slag, a light-gray industrial by-product dominated by portlandite and calcite, served as the solid alkaline activator and calcium source. Table 2 shows the measured physical indices and oxide compositions.

2.3 Preliminary RSM screening of component dosages

A preliminary RSM stage screened the component dosages before the tri-axial program. A 17-run Box–Behnken design (BBD) was used to represent non-linear and interacting effects with fewer runs than a three-factor full factorial design (Ferreira et al., 2007). The independent variables were the GGBS dosage (X_1), carbide-slag dosage (X_2), and biochar dosage (X_3). Their coded levels were 5%, 10%, and 15% for GGBS; 4%, 7%, and 10% for carbide

slag; and 0%, 5%, and 10% for biochar. All percentages in this stage were component additions expressed relative to the total specimen mass. Although the sums of the factor-wise lower and upper bounds are 9% and 35%, respectively, the total component dosages of the 17 mixtures included in the BBD ranged from 12% to 32% because the design did not include the simultaneous all-low or all-high corner combinations. The BBD, therefore, screened component–dose combinations; it was not a mixture design conducted at a constant total binder content. The responses were 7 and 28 days UCS. For the RSM center-point stabilized mixture containing 10% GGBS, 7% carbide slag, and 5% biochar, a separate compaction test gave an optimum water content of 18.1% and a corresponding maximum dry density of 1.62 g cm⁻³. These compaction-test values characterize only the RSM center-point mixture. All RSM specimens were prepared at this water content. Three parallel specimens were tested for each design run, and their mean UCS was used as the response. This stage is treated as a preliminary within-program screen.

The coded variables were defined so that $X_1 = (\text{GGBS dosage} - 10)/5$, $X_2 = (\text{carbide slag dosage} - 7)/3$, and $X_3 = (\text{biochar dosage} - 5)/5$, where each dosage is expressed as a percentage by the total specimen mass. The second-order RSM model was expressed as Equation 1.

$$Y = \beta_0 + \sum_{i=1}^3 \beta_i X_i + \sum_{i=1}^3 \beta_{ii} X_i^2 + \sum_{i < j} \beta_{ij} X_i X_j + \varepsilon \quad (1)$$

where Y is UCS, the β terms are regression coefficients, and ε is the residual error. Model fitting, analysis of variance (ANOVA), and numerical optimization were conducted in Design-Expert. Terms with $p < 0.05$ were interpreted as statistically significant within the fitted RSM model (Bezerra et al., 2008).

2.4 BAS formulation for the combined analysis

The component combination recommended by the RSM analysis was normalized to an internal dry-mass ratio among GGBS, carbide slag, and biochar. The combined analysis treats this ratio as the formulation linking the RSM and the tri-axial stages. The normalized internal ratio was shown in Equation 2.

$$m_{\text{GGBS}}:m_{\text{carbide slag}}:m_{\text{biochar}} = 51.38:31.96:16.66 \quad (2)$$

In the tri-axial program, total BAS dosage was expressed relative to the dry mass of silt, as shown in Equation 3.

$$D_{\text{BAS}} = \frac{m_{\text{GGBS}} + m_{\text{carbide slag}} + m_{\text{biochar}}}{m_{\text{dry silt}}} \times 100\% \quad (3)$$

The internal GGBS: carbide slag: biochar ratio was held constant at 51.38:31.96:16.66. For 100 g of dry silt, total BAS dosages of 5%, 10%, and 15% correspond to GGBS/carbide slag/biochar masses of 2.57/1.60/0.83 g, 5.14/3.20/1.67 g, and 7.71/4.79/2.50 g, respectively. The molding water content was defined as $w = m_{\text{water}}/m_{\text{dry silt}} \times 100\%$. Thus, the 5%–15% series evaluates the dosage response of this fixed UCS-selected formulation rather than re-optimizing its internal ratio for confined shear strength.

Four stabilized systems were considered. BAS denotes the biochar, GGBS, and carbide-slag system. OPC denotes the ordinary

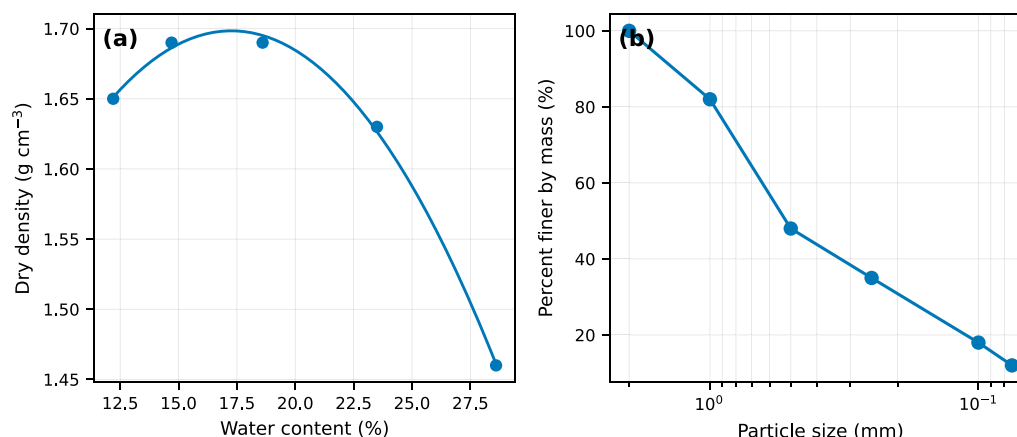


FIGURE 1
Characterization of the processed untreated dredged silt. (a) Compaction curve. (b) Particle-size distribution.

TABLE 2 Binder constituent data.

Constituent	Function in BAS	Key measured data
Biochar	Porous modifier and water-regulating component	Density 0.46 g cm ⁻³ ; specific surface area 46.08 m ² g ⁻¹ ; pH 9.46; ash 7.23%
GGBS	Main reactive precursor	Density 2.93 g cm ⁻³ ; specific surface area 628 m ² kg ⁻¹ ; CaO 35.30%; SiO ₂ 34.50%; Al ₂ O ₃ 16.70%; MgO 5.01%; Fe ₂ O ₃ 1.50%; SO ₃ 1.24%; Na ₂ O 0.52%; K ₂ O 0.33%
Carbide slag	Alkaline activator and calcium source	Light gray by-product dominated by portlandite and calcite; CaO 67.87%; SiO ₂ 1.55%; Al ₂ O ₃ 1.96%; MgO 0.33%; SO ₃ 0.31%; Fe ₂ O ₃ 0.26%; Na ₂ 0.03%

Portland cement comparison system, AS denotes a GGBS–carbide-slag comparison system without biochar, and OL denotes the lime comparison system. AS is treated as an alkali-activated slag binder-system comparison rather than a compositionally matched control isolating the effect of biochar. Untreated silt was not included as a tri-axial control because it disintegrated during immersion and could not provide a stable specimen for CU testing. Its absence limits direct quantification of improvement relative to untreated silt.

2.5 Specimen preparation, curing, and tri-axial testing

Tri-axial specimens were prepared following the general procedures of GB/T 50123–2019. Cylindrical specimens were 39.1 mm in diameter and 80 mm high. The processed dry silt and binder were weighed according to the target dosage and water content, mechanically mixed for 10 min, and compacted in layers in a cylindrical mold using the same procedure. Dry density and compaction degree were not treated as independent control variables, so the water-content series reflects the combined influence of molding water content, compaction state, and binder reaction.

After de-molding, specimens were cured at 20±2 °C and at least 95% relative humidity until the target age. Before tri-axial testing, they were vacuum-saturated, immersed in clean water

for 12 h, and tested immediately. Specimens were accepted when the degree of saturation calculated in accordance with GB/T 50123–2019 exceeded 95%; the recorded value was approximately 96%. Pore-water pressures were not measured, so effective stresses were not calculated. The reported cohesion and internal friction angle are, therefore, interpreted as total-stress CU parameters rather than effective-stress parameters. They are intended for comparative engineering interpretation under the tested procedure and confining-pressure range rather than as general design parameters.

The tri-axial program examined the binder dosage, water content, and curing age. The BAS dosage series used 5%, 10%, and 15% BAS at 18% water content and 28 days. The water-content series used 15%, 18%, and 21% water at 15% binder dosage and 28 days. The curing-age series used 7, 28, 60, and 120 days at 15% binder dosage and 18% water content. OPC, AS, and OL were included as comparison systems. The program analyzed here is summarized in Table 3 and is not fully factorial.

The procedure was a CU tri-axial test performed on an MCU automatic hydraulic tri-axial apparatus (Figure 2). Confining pressures were 50, 100, and 150 kPa. For each mix proportion and confining-pressure condition, at least three replicate specimens were tested, and the reported strength parameters represent the mean of the replicates. The drainage line remained open while each specimen

TABLE 3 Reported and analyzed subset of the consolidated un-drained tri-axial program.

Purpose	Binder	Dosage	Water content	Curing age
Binder dosage effect	BAS	5%, 10%, and 15%	18%	28 days
Comparison with cement	OPC	10% and 15%	18%	28 days
Binder-system comparison	AS and OL	15%	18%	28 days
Water content effect	BAS and OPC	15%	15%, 18%, and 21%	28 days
Curing age effect	BAS and OPC	15%	18%	7, 28, 60, 120 days



FIGURE 2
CU tri-axial loading system (MCU automatic hydraulic tri-axial apparatus).

was isotropically consolidated at the target confining pressure, and consolidation was terminated when the axial deformation rate decreased below 0.01 mm h^{-1} . After consolidation, the drainage line was closed and the specimen was sheared under un-drained conditions at a displacement rate of 0.5 mm min^{-1} . Failure was defined by the peak deviator stress $q = \sigma_1 - \sigma_3$; when no distinct peak occurred, the deviator stress at an axial strain of 15% was adopted in accordance with GB/T 50123–2019.

During data reduction, the consolidated cross-sectional area and the area during un-drained shearing were calculated, respectively, as

$$A_c = A_0(1 - \Delta V/V_0)^{2/3}, \quad A = A_c / (1 - 0.01\epsilon_a).$$

Here, A_0 is the initial cross-sectional area, $\Delta V/V_0$ is the volumetric strain during consolidation, and ϵ_a is the axial strain expressed as a percentage.

The tri-axial results were interpreted using the Mohr–Coulomb shear strength equation, as shown in Equation 4.

$$\tau_f = c + \sigma \tan \phi \quad (4)$$

where τ_f is shear strength at failure, σ is normal stress, c is cohesion, and ϕ is the internal friction angle. The Mohr circles shown in this article were reconstructed from the reported c and ϕ values at the three test confining pressures. For a tri-axial compression state, the major principal stress at failure can be expressed as shown in Equation 5.

$$\sigma_1 = \sigma_3 \frac{1 + \sin \phi}{1 - \sin \phi} + \frac{2c \cos \phi}{1 - \sin \phi} \quad (5)$$

where σ_3 is the confining pressure. Each circle was drawn with center $(\sigma_1 + \sigma_3)/2$ and radius $(\sigma_1 - \sigma_3)/2$. This reconstruction is

a visualization of the fitted parameters, not an independent set of experimental failure points. In addition to c and ϕ , curing-age development was summarized using the shear strength at the tangency point between the envelope and the circle,

$$\tau_{f,100} = c + \left(\frac{\sigma_1 + \sigma_3}{2} - \frac{\sigma_1 - \sigma_3}{2} \sin \phi \right) \tan \phi. \quad (6)$$

This quantity was evaluated at the intermediate confining pressure of $\sigma_3 = 100 \text{ kPa}$ and is denoted $\tau_{f,100}$. It is a derived envelope index rather than an independent measurement. The percentage difference in a parameter P was calculated as shown in Equation 7.

$$I_p = \frac{P_{\text{BAS}} - P_{\text{reference}}}{P_{\text{reference}}} \times 100\% \quad (7)$$

where the reference parameter was obtained from OPC, AS, or OL under the same dosage, water content, and curing age. All differences are descriptive and do not establish statistical significance.

3 Results and discussion

3.1 Preliminary RSM screening

Figure 3 compares the measured and fitted UCS values for the 17 BBD runs. At 7 days, UCS ranged from 3.39 to 4.81 MPa; at 28 days, it ranged from 4.73 to 6.28 MPa. These ranges show that UCS varied across the investigated component–dose combinations. As established in Section 2.3, the total component addition was not constant, so these responses cannot be attributed only to changes in the internal binder proportions.

Table 4 shows the term-by-term ANOVA results for the full quadratic models. For the 7-day response, the X_2X_3 interaction was not significant within the model ($F = 2.59$, $p = 0.1517$) and was excluded from the final equation. All displayed terms were retained for the 28 days response. The final fitted equations in coded variables were shown in Equations 8, 9.

$$Y_7 = 4.75 + 0.34X_1 + 0.19X_2 + 0.1375X_3 - 0.095X_1X_2 - 0.305X_1X_3 - 0.2275X_1^2 - 0.5025X_2^2 - 0.3825X_3^2 \quad (8)$$

$$Y_{28} = 6.22 + 0.3963X_1 + 0.3213X_2 + 0.165X_3 - 0.11X_1X_2 - 0.1125X_1X_3 - 0.0875X_2X_3 - 0.317X_1^2 - 0.377X_2^2 - 0.3845X_3^2 \quad (9)$$

The positive first-order coefficients and negative quadratic coefficients describe a curved response within the studied factor

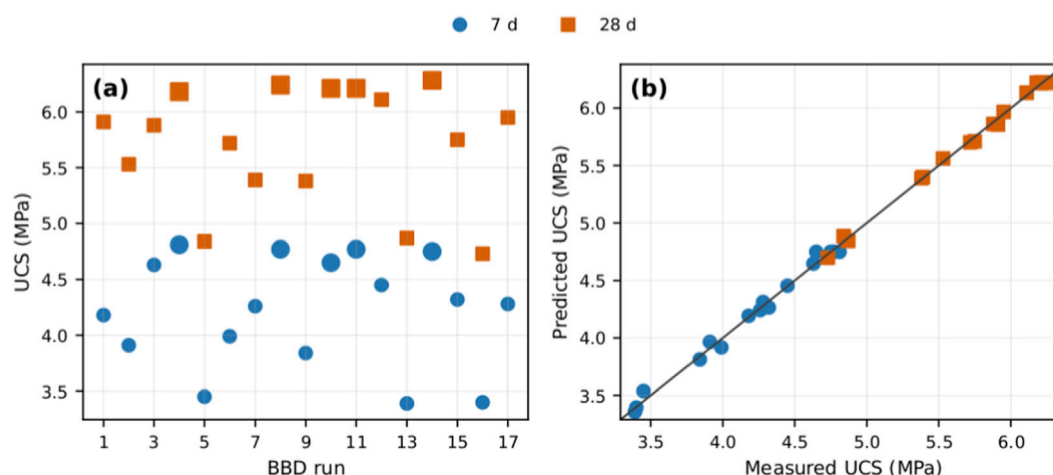


FIGURE 3
BAS component-dose screening. (a) Measured UCS for the 17 BBD runs. (b) In-sample measured and fitted UCS.

TABLE 4 Analysis of variance of the full quadratic models for 7 days and 28 days UCS.

Source	Df	7 days UCS			28 days UCS		
		Sum of squares	F	p	Sum of squares	F	p
Model	9	3.8765	111.46	<0.0001	4.2647	206.09	<0.0001
X_1 (GGBS)	1	0.9248	239.32	<0.0001	1.2561	546.31	<0.0001
X_2 (carbide slag)	1	0.2888	74.74	<0.0001	0.8256	359.07	<0.0001
X_3 (biochar)	1	0.1513	39.14	0.0004	0.2178	94.73	<0.0001
X_1X_2	1	0.0361	9.34	0.0184	0.0484	21.05	0.0025
X_1X_3	1	0.3721	96.29	<0.0001	0.0506	22.02	0.0022
X_2X_3	1	0.0100	2.59	0.1517	0.0306	13.32	0.0082
X_1^2	1	0.2179	56.39	0.0001	0.4231	184.02	<0.0001
X_2^2	1	1.0632	275.13	<0.0001	0.5984	260.27	<0.0001
X_3^2	1	0.6160	159.42	<0.0001	0.6225	270.73	<0.0001

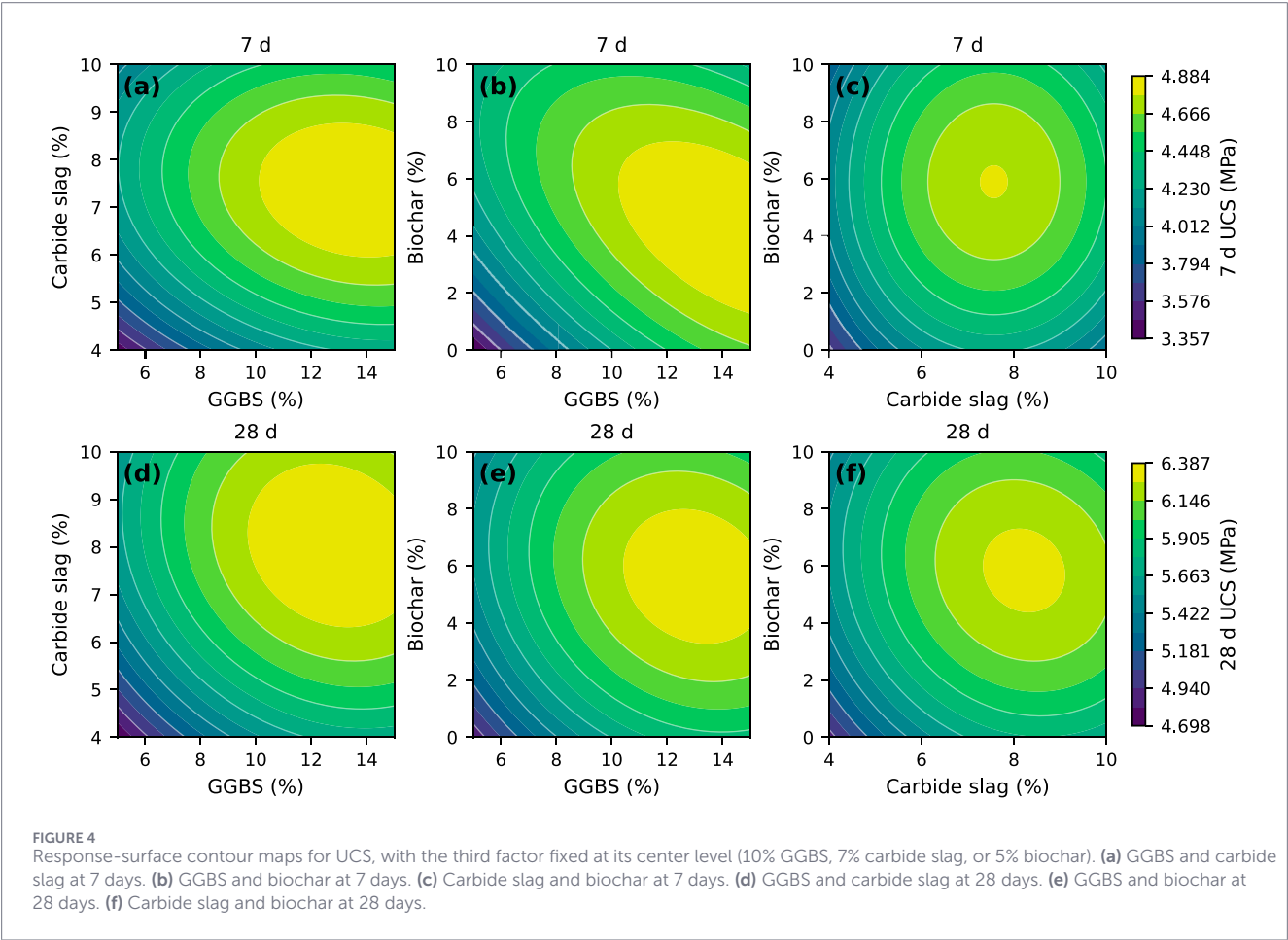
space; they do not, by themselves, identify a unique optimum under unspecified numerical constraints. The full quadratic models had $F = 111.46$ for 7 days UCS and $F = 206.09$ for 28 days UCS (Table 4). Table 5 summarizes the fit statistics and the separate confirmation test. For the 7 days response, the statistics refer to the reduced model without X_2X_3 . The adjusted and predicted R^2 values were similar, the coefficients of variation were below 2%, and adequate precision exceeded four for both ages. Recalculation using the five repeated center-point run means as the pure-error estimate gave non-significant lack of fit for the reduced 7 days model ($F = 1.57$, $p = 0.336$) and the full 28 days model ($F = 2.42$, $p = 0.207$). The linear-term F values followed the order GGBS > carbide slag > biochar. At 28 days, for example, the respective values were 546.31, 359.07, and 94.73. This ordering applies to the linear terms within this fitted design and should not be interpreted as a general ranking of the total constituent effects.

Figure 4 shows pairwise response-surface slices with the third factor fixed at its center level. For the GGBS–carbide-slag pair, fitted UCS increased from the low-dose region toward higher GGBS and intermediate-to-high carbide-slag dosages, then flattened or decreased near the upper boundary. This curvature is consistent with a balance between precursor supply and activation, although no reaction products were measured. For the GGBS–biochar pair, the fitted high-UCS region occurred at higher GGBS and moderate biochar dosages. The carbide-slag–biochar contours were more rounded, particularly at 7 days, consistent with the smaller fitted interaction relative to the GGBS-related pairs.

When maximization of 28 days UCS was specified as the response objective, the Design-Expert numerical module recommended 13.26% GGBS, 8.25% carbide slag, and 4.30% biochar by the total specimen mass, with a predicted UCS of 6.32 MPa. A separate confirmation test gave 6.25 MPa, corresponding to a relative difference of 1.12% when normalized by the measured value. This

TABLE 5 Fit statistics of the final response surface models and confirmation of the selected BAS component combination.

Model	CV (%)	R^2	Adj. R^2	Pred. R^2	Adequate precision
7 days UCS	1.61	0.9905	0.9810	0.9439	28.1222
28 days UCS	0.84	0.9962	0.9914	0.9591	41.3714
Selected component dosages (GGBS/carbide slag/biochar)		Normalized BAS ratio (GGBS: carbide slag: biochar)		Predicted/measured 28 days UCS (MPa)	
13.26/8.25/4.30		51.38:31.96:16.66		6.32/6.25	
				Relative error (%)	
				1.12	



combination is treated as the software-recommended combination in the present analysis. Normalization of the three dosages gave a GGBS: carbide slag: biochar ratio of 51.38:31.96:16.66, which was adopted as the fixed UCS-selected BAS formulation for the tri-axial analysis.

3.2 Overview of the tri-axial shear parameters

Table 6 summarizes the tri-axial parameters analyzed here; conditions shared by more than one analysis series appear in more than one row. Three descriptive patterns are evident. Increasing BAS dosage coincided with increases in both cohesion and internal

friction angle. Water content produced a non-monotonic response, with the highest values at 18% for both BAS and OPC among the three tested contents. Curing age coincided with progressively smaller increments, particularly after 60 days.

The following sections examine the reported parameter trends with binder dosage, water content, and curing age. The fixed UCS-selected BAS formulation is used throughout this analysis.

3.3 Effect of BAS dosage

Figure 5 shows the parameter-reconstructed Mohr–Coulomb envelopes for the dosage and comparison series at 18% water content and 28 days. Cohesion increased from 169.4 kPa at 5% BAS to

TABLE 6 Tri-axial shear strength parameters.

Analysis group	Binder condition	Binder dosage	Water content	Curing age	c (kPa)	ϕ (°)
Dosage	BAS	5%	18%	28 days	169.4	38.5
Dosage	BAS	10%	18%	28 days	181.9	42.3
Dosage	BAS	15%	18%	28 days	195.2	42.5
Comparison	OPC	10%	18%	28 days	177.3	41.1
Comparison	OPC	15%	18%	28 days	191.7	42.1
Comparison	AS	15%	18%	28 days	167.7	37.7
Comparison	OL	15%	18%	28 days	157.9	36.2
Water content	BAS	15%	15%	28 days	176.7	39.6
Water content	BAS	15%	18%	28 days	195.2	42.5
Water content	BAS	15%	21%	28 days	187.6	41.2
Water content	OPC	15%	15%	28 days	169.3	39.3
Water content	OPC	15%	18%	28 days	191.7	42.1
Water content	OPC	15%	21%	28 days	176.4	41.5
Curing age	BAS	15%	18%	7 days	190.2	41.5
Curing age	BAS	15%	18%	28 days	195.2	42.5
Curing age	BAS	15%	18%	60 days	196.4	43.1
Curing age	BAS	15%	18%	120 days	196.8	43.3
Curing age	OPC	15%	18%	7 days	185.7	41.2
Curing age	OPC	15%	18%	28 days	191.7	42.1
Curing age	OPC	15%	18%	60 days	195.9	42.6
Curing age	OPC	15%	18%	120 days	196.2	43.0

181.9 kPa at 10% BAS and 195.2 kPa at 15% BAS. Relative to the 5% condition, the numerical increases at 10% and 15% BAS were 7.38% and 15.23%, respectively. The internal friction angle increased from 38.5° to 42.3° between 5% and 10% BAS, followed by a smaller change to 42.5° at 15%. Within the three tested levels, the friction-angle increment, therefore, diminished earlier than the cohesion increment.

The dosage trend is consistent with, but does not directly demonstrate, increased cementitious bonding and changes in particle packing. At the fixed component ratio, a larger BAS addition provides more reactive slag and activator, potentially increasing hydrate formation and the bonded component represented by the cohesion intercept. Cemented aggregates could also alter interlocking and mobilized friction. The increase in ϕ between 5% and 10% BAS followed by little change between 10% and 15% is evidence of diminishing numerical returns over the tested range, not proof of a microstructural threshold. Microstructural and density measurements would be needed to test this interpretation.

At 10% dosage, BAS gave $c = 181.9$ kPa and $\phi = 42.3^\circ$, compared with 177.3 kPa and 41.1° for OPC. At 15%, the respective values were 195.2 kPa and 42.5° for BAS and 191.7 kPa and 42.1° for OPC. The numerical BAS–OPC differences were 2.59% in cohesion and 2.92% in friction angle at 10%, and 1.83%, and 0.95% at 15%. These

small differences are reported as descriptive arithmetic comparisons under the tested conditions.

The numerical separation from AS and OL was larger. At 15% dosage, 18% water content, and 28 days, AS gave $c = 167.7$ kPa and $\phi = 37.7^\circ$, whereas OL gave $c = 157.9$ kPa and $\phi = 36.2^\circ$. Relative to AS and OL, the BAS cohesion values were 16.40% and 23.62% higher, respectively, and the friction angles were 12.73% and 17.40% higher. Figure 6 summarizes the dosage trends and the binder-type comparison at 15% dosage. These are descriptive differences under one test condition. The comparison does not isolate the effect of biochar.

3.4 Effect of water content

Figure 7 shows the parameter-reconstructed envelopes for BAS and OPC at 15% binder dosage, 28 days, and water contents of 15%, 18%, and 21%. For BAS, cohesion increased from 176.7 to 195.2 kPa as the water content increased from 15% to 18% and then decreased to 187.6 kPa at 21%. The corresponding friction angles were 39.6°, 42.5°, and 41.2°. Thus, 18% gave the highest BAS parameters among the three tested water contents. This condition is close to the 18.1% compaction optimum measured for the RSM center-point mixture, but the sparse three-level series does not define a precise tri-axial optimum.

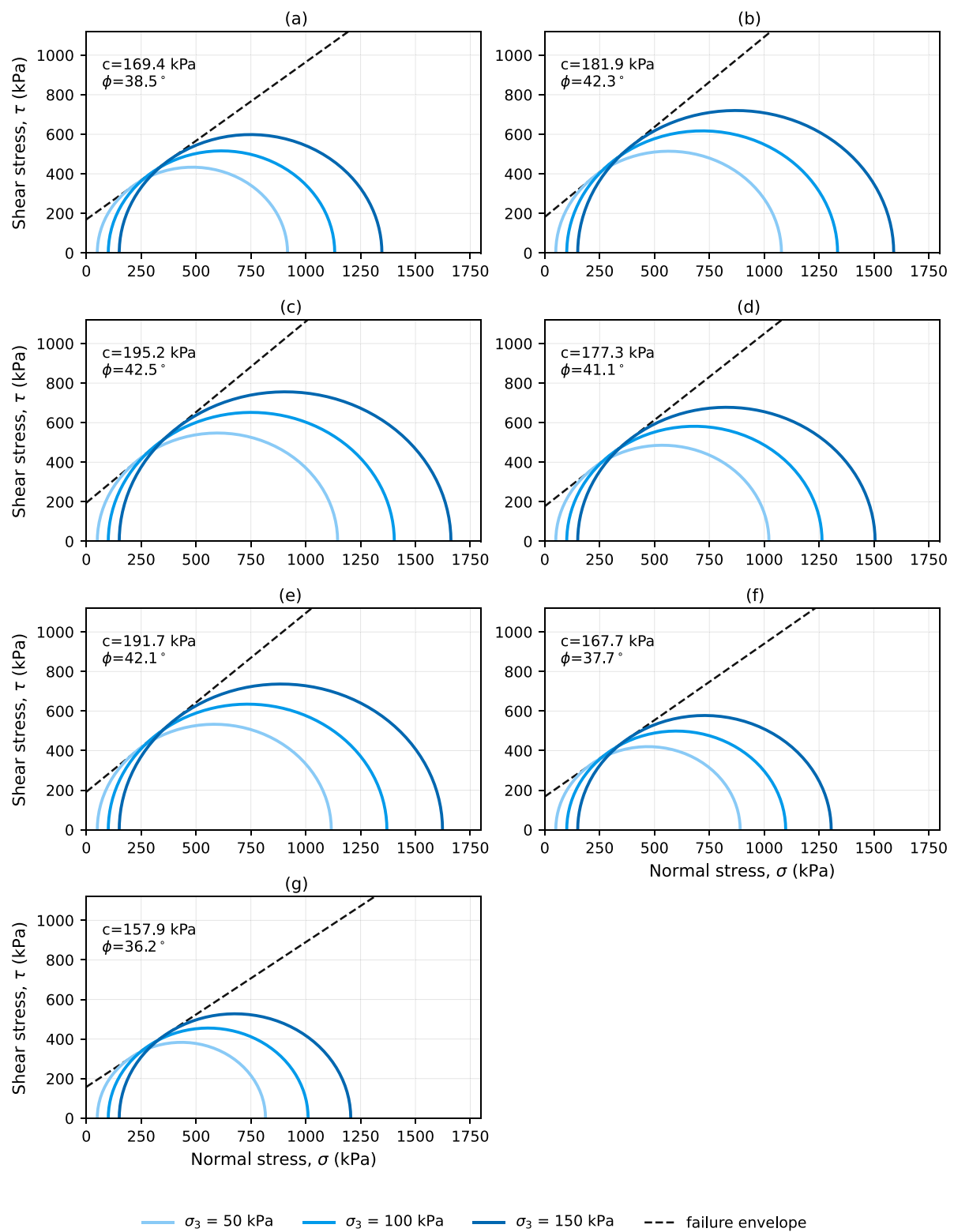


FIGURE 5 Parameter-reconstructed Mohr-Coulomb diagrams for dosage and binder type. (a) 5% BAS. (b) 10% BAS. (c) 15% BAS. (d) 10% OPC. (e) 15% OPC. (f) 15% AS. (g) 15% OL. Envelopes and circles are reconstructed from the reported c and ϕ .

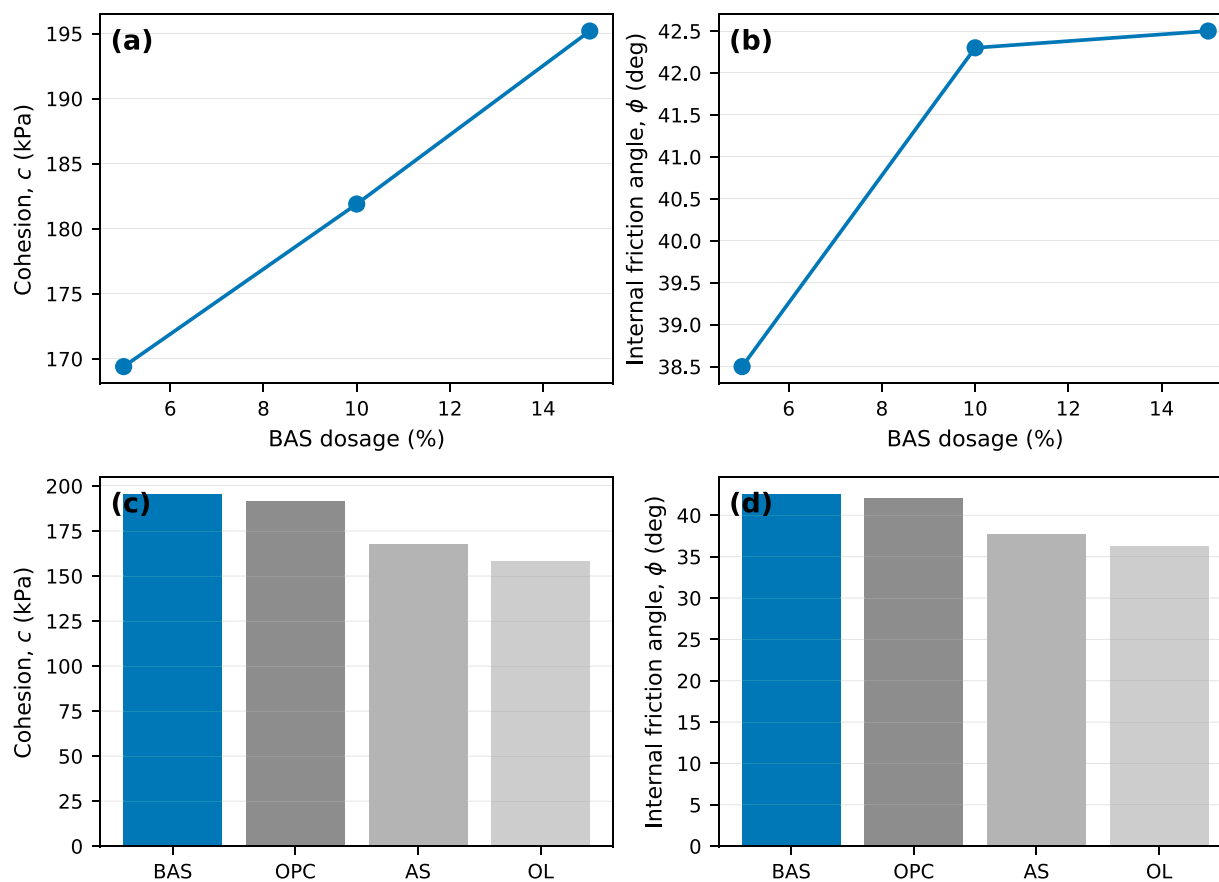


FIGURE 6 Dosage and binder-type effects. (a) Cohesion. (b) Internal friction angle. (c) Cohesion comparison at 15% dosage. (d) Internal friction angle comparison at 15% dosage.

OPC followed the same inverted-U pattern. Cohesion increased from 169.3 kPa at 15% water content to 191.7 kPa at 18% and then decreased to 176.4 kPa at 21%. The friction angle increased from 39.3° to 42.1° and then decreased to 41.5°. Similar water-content sensitivity has been reported for dredged sludge stabilized with alkali-activated GGBS (Lang et al., 2021a). The observed pattern may reflect competing effects of wetting, ion mobility, compaction, pore volume, and pore-solution dilution. These mechanisms were not measured and are not quantified separately here.

The decrease at 21% water content is practically relevant even though the binder dosage was unchanged. Relative to 18%, the BAS cohesion and friction angle at 21% were lower by 7.6 kPa and 1.3°, respectively. The corresponding OPC differences were 15.3 kPa and 0.6°. The results indicate that a field specification would need to control moisture and compacted density in addition to the binder dosage; the present data do not define acceptable field-control limits.

3.5 Effect of curing age

Figure 8 shows the parameter-reconstructed diagrams for BAS and OPC at 15% binder dosage, 18% water content, and curing ages of 7, 28, 60, and 120 days. BAS cohesion increased from

190.2 kPa at 7 days to 195.2, 196.4, and 196.8 kPa at 28, 60, and 120 days, respectively. The corresponding friction angles were 41.5°, 42.5°, 43.1°, and 43.3°. The increments decreased with curing age.

OPC exhibited a similar time-dependent pattern. Its cohesion increased from 185.7 kPa at 7 days to 191.7, 195.9, and 196.2 kPa at 28, 60, and 120 days, respectively. Its friction angle increased from 41.2° to 42.1°, 42.6°, and 43.0°. The reported mean BAS cohesion and internal friction angle values were slightly higher than the corresponding OPC values at all four curing ages. The cohesion difference narrowed from 4.5 kPa at 7 days to 0.5 and 0.6 kPa at 60 and 120 days, respectively, while the differences in internal friction angle remained within 0.3–0.5°. Without replicate uncertainty, these values describe trajectories rather than statistically distinct curing responses.

Figure 9 summarizes the four tested ages without imposing a kinetic model. For BAS, $\tau_{f,100}$ increased from 463.3 kPa at 7 days to 490.6 kPa at 120 days, with successive relative increments of 3.73%, 1.56%, and 0.52%. For OPC, it increased from 453.5 to 487.1 kPa, with corresponding increments of 3.96%, 2.45%, and 0.86%. For BAS, the successive cohesion increments were 2.63%, 0.61%, and 0.20%, while the friction-angle increments were 2.41%, 1.41%, and 0.46%. Most of the observed change through 120 days had,

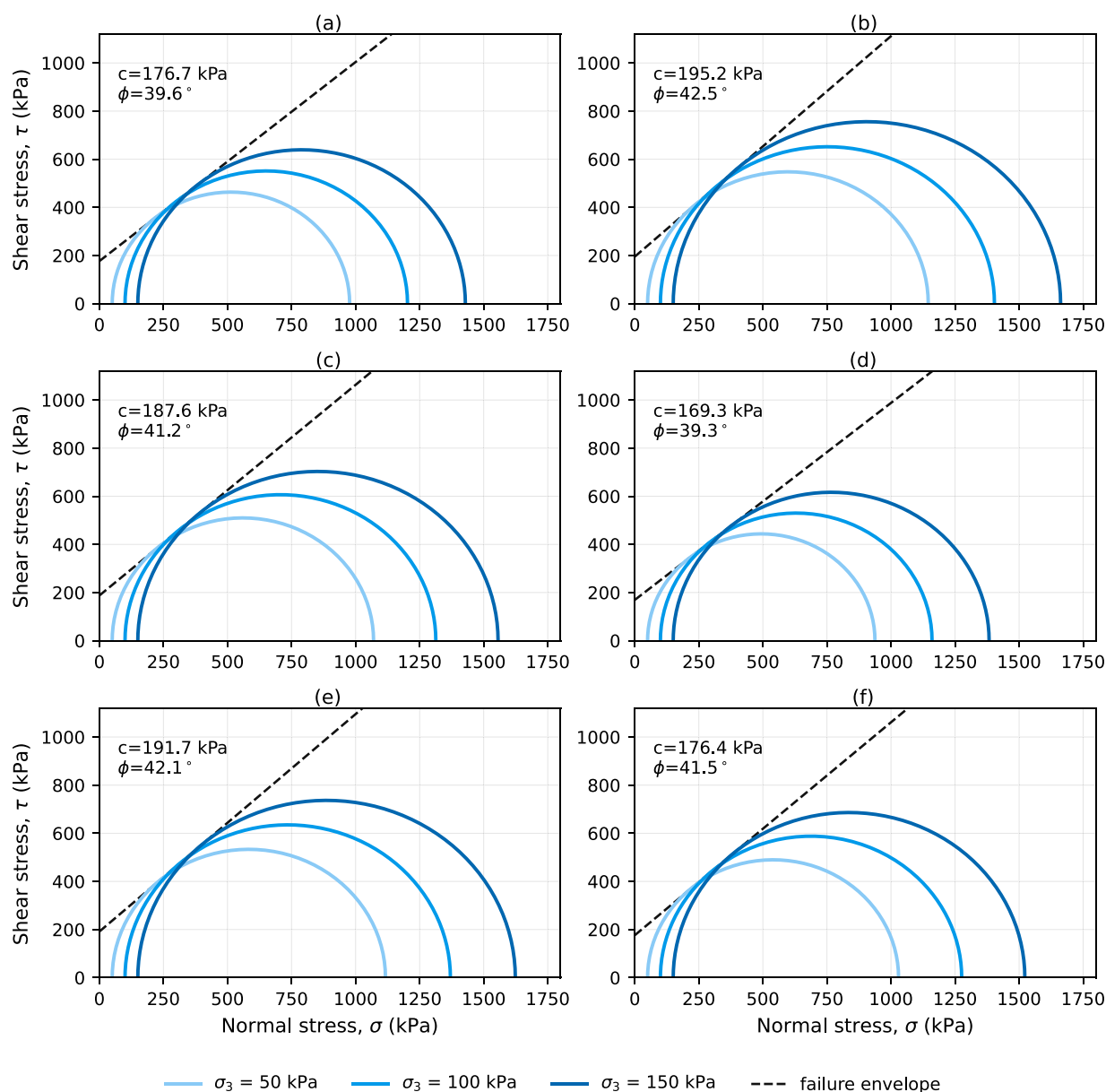


FIGURE 7

Parameter-reconstructed Mohr–Coulomb diagrams for water content. (a) BAS at 15%. (b) BAS at 18%. (c) BAS at 21%. (d) OPC at 15%. (e) OPC at 18%. (f) OPC at 21%. Envelopes and circles are reconstructed from the reported c and ϕ .

therefore, occurred by 60 days. Continued activated-slag reaction and pore filling are plausible explanations (Yi et al., 2015), but the present data do not provide direct chemical or microstructural evidence.

The curing-age change in the tri-axial parameters was smaller than the approximately 31% increase in center-point UCS between 7 and 28 days in the RSM stage. The two responses should not be compared as equivalent measures because the programs used different binder contents, specimen conditioning, confinement, and loading paths. The difference is, therefore, not assigned to a single mechanism. The curing series should be read as the evolution of the total-stress parameters after vacuum saturation and immersion.

3.6 Integrated interpretation of tri-axial responses

The RSM and tri-axial trends are consistent with coupled cementitious bonding and fabric effects, but the contribution of each BAS component is not separated here. The increase in cohesion with BAS dosage is compatible with additional cementitious bonding. The BAS–AS difference is interpreted as a difference between the two binder systems under the tested conditions and does not isolate the contribution of biochar.

Among the three water contents, 18% produced the highest parameters, and the curing increments became small after 60 days. BAS and OPC values were numerically close, whereas the separation

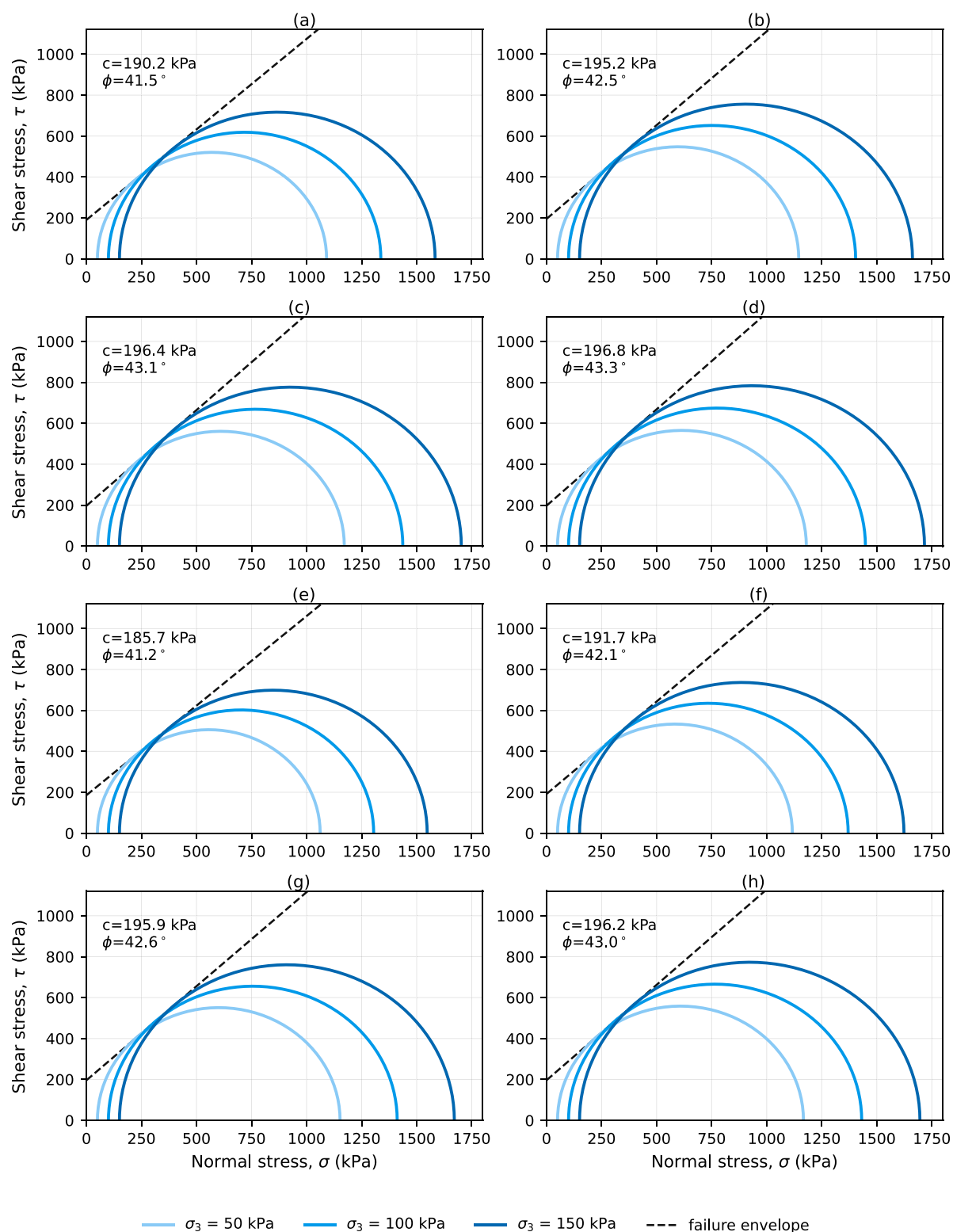


FIGURE 8

Parameter-reconstructed Mohr-Coulomb diagrams for curing age. (a) BAS at 7 days. (b) BAS at 28 days. (c) BAS at 60 days. (d) BAS at 120 days. (e) OPC at 7 days. (f) OPC at 28 days. (g) OPC at 60 days. (h) OPC at 120 days. Envelopes and circles are reconstructed from the reported c and ϕ .

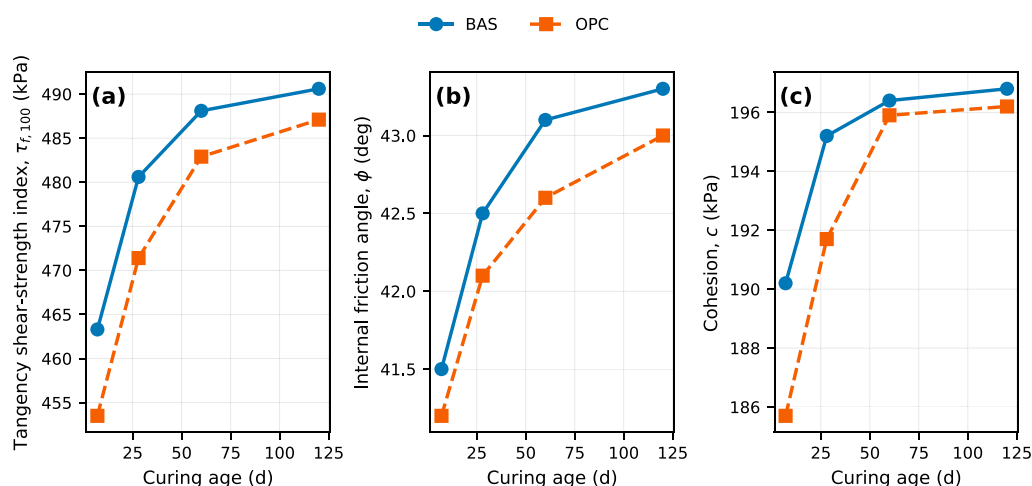


FIGURE 9

Curing-age series of the shear parameters. (a) Derived tangency shear-strength index $\tau_{f,100}$ (Equation 6, $\sigma_3 = 100$ kPa). (b) Total-stress internal friction angle, ϕ . (c) Total-stress Mohr–Coulomb cohesion intercept, c .

from AS and OL was larger. These comparisons describe observed parameter trends and do not establish statistical significance, equivalence, or component-specific causation.

3.7 Engineering significance and sustainability boundary

The main engineering contribution is the comparison of total-stress Mohr–Coulomb parameters for a clinker-free BAS formulation. The RSM and UCS tests provided a preliminary component–dose screen, whereas the tri-axial program examined confinement-dependent parameters at 50 kPa–150 kPa. The results identify the binder dosage, water content, and curing age as relevant variables. They do not provide design parameters outside the tested materials, conditioning procedure, and stress range.

The sustainability inference is limited to material substitution. BAS combines GGBS, carbide slag, and corn-straw biochar without Portland cement, consistent with research on waste-derived infrastructure materials (Li et al., 2026; Shaqour, 2024; Wei et al., 2022a,b). This study did not include life-cycle assessment, carbon accounting, leaching, durability, effective-stress characterization, or microstructural measurements. No net carbon or environmental benefit can, therefore, be quantified from the present results.

3.8 Applicability and limitations

The reported total-stress parameters are most applicable to the tested silt, specimen preparation, saturation, curing and loading conditions, and the confining-pressure range of 50 kPa–150 kPa.

The available records include the reported fitted c and ϕ values but are insufficient to reproduce the complete stress–strain response, failure stresses, and failure strains. Figures 5, 7, 8 are parameter-reconstructed representations rather than independent experimental evidence. The linear Mohr–Coulomb criterion is used as an engineering representation within the tested pressure range;

possible non-linearity would require tests over a wider range. The tri-axial program evaluated a fixed UCS-selected BAS formulation rather than an internal ratio optimized for confined shear, and the related mechanistic interpretations remain qualitative and require microstructural verification.

Future work should extend testing to other silt sources and stress conditions and further assess mixture optimization and long-term performance.

4 Conclusion

This study evaluated a clinker-free biochar-modified alkali-activated slag binder for the infrastructure reuse of urban dredged silt, focusing on the shear-strength parameters that govern its geotechnical use. The conclusions are as follows:

1. Response surface screening resolved the three constituents into a workable composition: 13.26% GGBS, 8.25% carbide slag, and 4.30% biochar by the total specimen mass, equivalent to an internal dry-mass ratio of 51.38:31.96:16.66. A confirmation test returned 28 days UCS of 6.25 MPa against a predicted 6.32 MPa, and the linear-term ranking placed GGBS ahead of carbide slag and biochar.
2. Increasing BAS dosage from 5% to 15% increased cohesion from 169.4 to 195.2 kPa and the internal friction angle from 38.5° to 42.5°. Cohesion increased more continuously with dosage, whereas the internal friction angle increased mainly between 5% and 10% BAS.
3. Among the three tested water contents, the highest reported tri-axial shear parameters for both BAS and OPC occurred at 18%. This level was close to the 18.1% compaction optimum measured for the RSM center-point mixture.
4. Strength development was front-loaded in time. Between 7 and 120 days, BAS cohesion rose from 190.2 to 196.8 kPa and the friction angle increased from 41.5° to 43.3°, with roughly

nine-tenths of the total change complete by 60 days. Curing beyond 60 days added little to the saturated shear envelope.

1. The reported mean BAS parameters were numerically close to those of OPC under the tested conditions, with arithmetic differences of 0.95%–2.92% under matched dosage conditions. The corresponding numerical differences from AS and OL were larger. The BAS–AS difference represents a comparison between binder systems and does not isolate the contribution of biochar.

Taken together, these results demonstrate the potential of BAS as a clinker-free, resource-efficient solution for sustainable soil stabilization. Its performance depends on the coordinated control of binder dosage, moisture conditions, and curing regime. With further validation of the long-term durability, environmental safety, and life-cycle benefits, BAS could provide a promising pathway for converting industrial and agricultural by-products into lower-carbon geomaterials for infrastructure applications.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

Author contributions

KW: Writing – original draft, Writing – review and editing. YhZ: Writing – original draft, Writing – review and editing. QF: Writing – original draft, Writing – review and editing. MW: Writing – original draft, Writing – review and editing. ZT: Writing – original draft. ZiW: Writing – original draft, Writing – review and editing. YuZ: Writing – original draft, Writing – review and editing.

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Conflict of interest

Author KW was employed by Shandong Public Transport Group Co., Ltd. Authors QF and ZT were employed by Shandong Pengcheng Road and Bridge Group Co., Ltd.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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