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Application potentials of soda residue as construction materials by chemical stabilisation

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Abstract. Recycling soda residue (SR) as a construction material offers a sustainable and economical method of waste management. This study investigated the performance of various types of stabilisers in improving SR, including ordinary Portland cement (OPC), ground granulated blast-furnace slag (GGBS), fly ash, silica sand, and clay. The fuzzy comprehensive evaluation (FCE) method was employed to identify the suitable stabiliser composition with consideration of strength requirement and cost control. Subsequently, one-dimensional consolidation and field plate load tests were conducted on SR treated with the selected stabiliser composition. The results revealed that GGBS had superior performance in improving the strength of SR. The synergic effect between GGBS and OPC was found to be more beneficial for the improvement of SR than the combination of GGBS with fly ash, silica sand, or clay. Moreover, the SR treated with the selected stabilisation composition exhibited excellent compressibility of SR and satisfactory bearing capacity in the field. This study highlights the technical advantage of recycling SR as a construction material, as well as provides a reference for the sustainable management of bulk solid waste in practice.

Keywords: construction material; fuzzy comprehensive evaluation method; ground granulated blast-furnace slag; ordinary Portland cement; soda residue; waste management

1. Introduction

Soda residue (SR), a by-product generated during the production of soda ash by ammonia soda process, is composed of various calcium components, including $CaCO_3$, $Ca(OH)_2$, $CaCl_2$, and $CaSO_4$ (Zhao *et al.* 2019). Approximately 0.3 tonnes of SR are discharged for every tonne of sodium carbonate produced (Wang *et al.* 2020), leading to an annual production of SR exceeding 5 million tonnes in China (He *et al.* 2020). However, only approximately 3% of SR has been reported to be utilised (Chen *et al*. 2022), while the vast majority of SR is either stockpiled on-site or disposed of in landfills, resulting in land occupation along with water pollution and soil contamination (An *et al.* 2022a, Li *et al*. 2021). As a response to the environmental challenges, researchers have been actively seeking sustainable methods for SR management.

Due to its high content of calcium salts and alkalinity, SR has been recycled in the production of cement clinker (Wang *et al.* 2020; Wang *et al*. 2021), employed in soil amendment (Wei *et al.* 2021, Zha *et al.* 2020a), utilised as adsorbent (Chen *et al*. 2022, Şener 2008), incorporated as alkaline activators in the alkali-activated system (Qi *et al.* 2022). Despite its potential, the consumption of SR in these applications was relatively too low to digest substantial amounts of SR. For instance, Zhao *et al*. (2019) reused SR and fly ash to synthesise geopolymer, with SR accounting for only 20% of the total mix. Wang *et al.* (2020) reported a 5% utilisation of SR in the production of cement. He *et al.* (2019) utilised 30% of SR (by dry soil mass) as a soil stabiliser to improve the cohesion value of soft soil. These studies indicate that there is still significant room for further development in the effective use of SR.

Recycling SR as a sustainable material in civil engineering, such as fill materials, offers a promising and cost-effective solution to manage substantial volumes of SR (Wu *et al.* 2022, Zha *et al.* 2020b). SR itself, however, possesses undesirable geotechnical properties, such as low strength and high compressibility (Zięba *et al.* 2021). To overcome the limitation of SR, Ma *et al.* (2020) incorporated fly ash with SR at a ratio of 1:10, forming a SR-based foundation in the field with a bearing capacity over 210 kPa and a deformation modulus of 34 MPa; Zhao *et al.* (2020) also used fly ash to treat SR at a ratio of 2:3, along with an alkaline activator, creating a SR-based goaf backfill material that exhibited excellent workability and compressive strength. Although these investigations have verified the availability of utilising treated SR as a construction material, more efficient and economical technical references for treating such type of solid waste remain pressing.

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The unconfined compressive strength (UCS) serves as an important parameter to assess the feasibility of recycling waste materials like SR for geotechnical applications (Eker and Bascetin 2022). It also acts as a typical indicator to determine the suitable stabiliser composition required for enhancing the mechanical properties of waste materials. Additionally, economy is another essential factor on construction sites. Balancing the cost of the stabiliser with its effectiveness in improving mechanical properties is essential to maximise the overall benefits of the treatment of SR. Fuzzy comprehensive evaluation (FCE) is a multifactor decision-making method based on fuzzy mathematics (Wei *et al.* 2020). It allows for the simultaneous consideration of all relevant criteria, making the evaluation more comprehensive and objective. By employing FCE, the performance of various stabilisers will be assessed thoroughly, fostering the efficient utilisation of SR and achieving cost-effective solutions in geotechnical applications.

Overall, the literature on the performance of treated SR as a construction material is limited, with most studies focusing on SR as an additive for binders. Additionally, a reasonable method to select suitable stabiliser composition is still scarce. To address these issues, this study introduced various stabilisers into SR to transform it from a weak material into a firmer material. The FCE method was employed to select the suitable stabiliser composition, with consideration of the UCS values of treated SR and the cost of treatment. The compressibility and field performance of treated SR were investigated through one-dimensional consolidation tests and plate load tests to assess the feasibility of the selected stabiliser composition and the suitability of treated SR as a construction material. This treatment will not only contribute to the efficient management of SR but also will provide a valuable reference for similar sustainable management practices.

2. Materials and methodology

2.1 Materials

SR used in this study was obtained from Tianjin Port in China, with a high moisture content of up to 202% and a pH of 11.2. The main composition of SR is 45.8% CaO, 9.2% Cl, and 8.3% SiO_2, with small fractions of Al_2O_3, as detailed in Table 1.

The stabilisers used to improve SR consisted of ordinary Portland cement (OPC), ground granulated blast-furnace slag (GGBS), fly ash, silica sand, and clay. Table 1 lists the chemical compositions of all these materials, and Table 2 lists the basic physical properties of SR and clay. OPC (P.O. 42.5) was provided by Nanjing Conch Cement Co., Ltd. GGBS is a by-product from iron manufacturing industry, with a composition of 36.1% CaO, 34.3% SiO_2, and 17.0% Al_2O_3. Fly ash, an industrial by-product, contains 6.0% CaO, 55.0% SiO_2, and 27.5% Fe_2O_3. Silica sand, with a particle size ranging from 1 mm to 2 mm, comprises over 96% SiO_2 and exhibits less than 4% ignition loss. The clay provided a source of silica and alumina minerals.

Table 1 Chemical compositions of SR, GGBS, OPC, FA, and clay, wt/%

Materials	CaO	SiO_2	MgO	Al_2O_3	Fe_2O_3	SO_3	Cl
SR	45.8	8.3	6.6	3.2	0.7	2.4	9.2
GGBS	36.1	34.3	6.0	17.0	1.4	3.1	-
OPC	63.3	20.0	2.5	5.1	3.3	2.2	-
FA	5.9	55.0	1.3	7.5	27.5	1.1	-
Clay	0.1	53.4	0.4	42.4	0.9	-	-

Table 2 The basic physical properties of SR and clay

Properties	SR	Clay
Moisture content, %	202	19.8
Bulk density, g/cm^3	1.35	1.23
Plastic limit, %	62.1	24.2
Liquid limit, %	80.2	41.0
Plasticity index	18.1	16.8

2.2 Sample preparation

Prior to treating SR, the initial moisture content of SR was naturally reduced from 202 % to 145%. The treated SR specimens for UCS tests were prepared in a cylindrical mould (50 mm in diameter and 100 mm in height). Once specimens were formed, they were demoulded and then placed in a curing chamber with a temperature of 20 ± 2°C and relative humidity of 95 ± 2% until the specified curing time achieved. These samples were prepared in three batches, each stabiliser was mixed with SR at different percentages by the wet weight of SR, as follows:

- 5%, 10%, 15%, and 20% of GGBS-alone (5G, 10G, 15G, and 20G) and OPC-alone (5P, 10P, 15P, and 20P) was mixed with SR, respectively, to comparatively investigate the impact of GGBS and OPC on the strength development of SR. Each specimen was cured for 3, 7, 14, and 28 days, to evaluate the effect of curing times. Through this investigation, a predominant stabiliser can be also determined.
- The effect of replacement of GGBS (G) with OPC (P), fly ash (F), silica sand (S), and clay (C) was comparatively investigated by preparing specimens with a consistent total stabiliser content of 15%, in which 10% was GGBS and the rest of 5% was GGBS, OPC, FA, silica sand, and clay, respectively. These samples were labelled as 15G, 10G5P, 10G5F, 10G5S, and 10G5C.
- The last batch of specimens was prepared for the selection of the suitable stabiliser composition through the FCE method with the consideration of strength and cost. A total of nine proportions, consisting Table 3.

Once the suitable stabiliser composition determined, the SR treated with the selected stabiliser composition was prepared for one-dimensional consolidation and field plate load tests. Specimens for one-dimensional consolidation

Table 3 Proportions of GGBS and OPC

Sample	GGBS (% of wet weight)	OPC (% of wet weight)
4G2P	4	2
6G2P	6	2
8G2P	8	2
4G3P	4	3
6G3P	6	3
8G3P	8	3
4G4P	4	4
6G4P	6	4
8G4P	8	4

tests were prepared in a confining ring with a diameter of 61.8 mm and a height of 20 mm, subsequently cured 7, 14, and 28 days under the same curing conditions. A field test section was prepared for the SR in-situ treated with the suitable stabiliser composition and subjected to a plate load test to assess its deformation characteristics and bearing capacity.

2.3 Test programme

2.3.1 Unconfined compressive strength test

Following the curing time, UCS tests were performed on cured specimens according to JGJ/T233-2011 (2011). The tests were carried out by uniaxial compression apparatus (TKA-WCY-1F) at adisplacement rate of 1 mm/min.

2.3.2 One-dimensional consolidation test

The one-dimensional consolidation test was conducted on the treated SR and untreated SR to evaluate the effectiveness of selected stabiliser composition in the improvement of compressibility. The consolidation test was carried out on the cured specimens following JTGE40-2007 (2007). The test consisted of six incremental loading stages, starting from 50 kPa and increasing to 100 kPa, 200 kPa, 300kPa, 400 kPa, 800 kPa, and 1600 kPa. Each load was maintained constant for 24 h to ensure the primary consolidation ceased.

2.3.3 Field plate load test

To further evaluate the field bearing capacity and settlement performance of treated SR, an on-site SR area at Tianjin Port (20 metres in length, 10 metres in width, and 1.2 metres in depth) was in-situ treated with the selected stabiliser composition, as shown in Fig. 1. After 28 days of field-curing, the plate load test was performed on the treated area to evaluate its bearing capacity in accordance with GB50007-2011 (2011). During the plate load test, a steel circular plate with an area of 0.5 m^2 was placed on top of a coarse sand layer. The sand layer had a thickness of 20 mm and was located at a depth of 15 cm from the ground. The plate was subjected to eight sets of incremental loads, including loading stages of 40 kPa, 60 kPa, 80 kPa, 100 kPa, 120 kPa, 140 kPa, and 160 kPa. Each loading stage

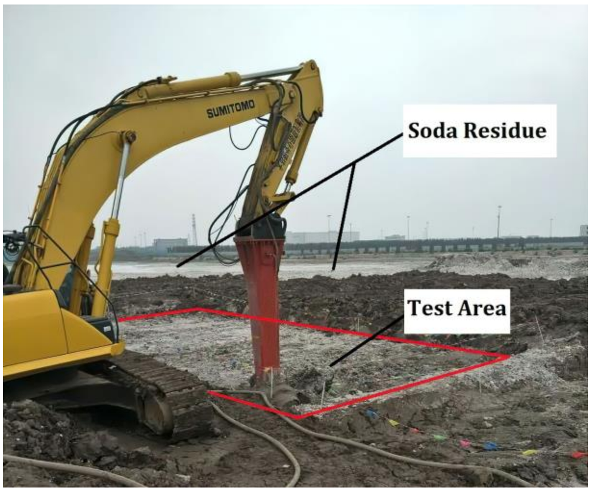


Fig. 1 In-situ stabilisation of soda residue

was sustained until the settlement of the plate was less than 0.1 mm/h for two consecutive hours.

2.4 Fuzzy comprehensive evaluation method

To determine the suitable stabiliser and its content for the treatment of SR, the FCE method was applied to analyse and compare the performance of 4G2P, 6G2P, 8G2P, 4G3P, 6G3P, 8G3P, 4G4P, 6G4P, 8G4P, and 4G6P (Table 3). This comprehensive approach allowed for a thorough assessment based on multiple criteria, including strength requirements and cost considerations. The detailed analysis was as follows.

a) There were three criteria considered to evaluate the performance of various stabilisers, including cost, UCS after 7-day curing, and UCS after 28-day curing. The cost of each stabiliser could be normalised by Eqs. (1) and (2) was employed for the strength results.

$$r_{ij} = \frac{x_i^{\max} - x_{ij}}{x_i^{\max} - x_i^{\min}} \tag{1}$$

$$r_{ij} = \frac{x_{ij} - x_i^{\min}}{x_i^{\max} - x_i^{\min}} \tag{2}$$

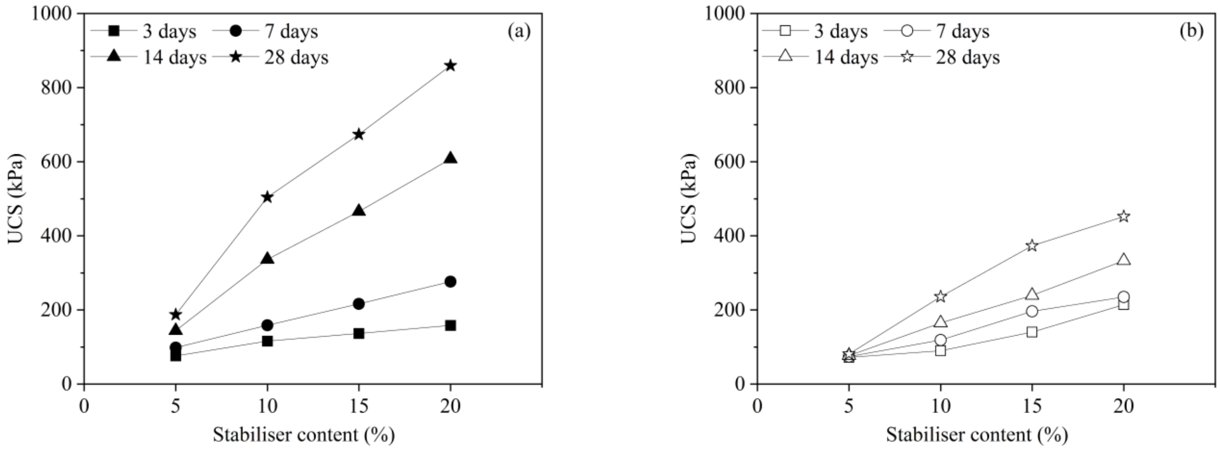
Then, a single-criterion evaluation matrix $\boldsymbol{R}$ was obtained.

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \tag{3}$$

(b) A comprehensive evaluation value $\boldsymbol{B}$ for each stabiliser was calculated by Eq. (4)

$$B = A \times R = (b_1, \dots, b_i) \tag{4}$$

where $\boldsymbol{A}$ is the weight set of cost, 7-day cured UCS, and 28-day cured UCS. Due to the significance of cost control in construction, the weight assigned to cost was 0.4.



(a) GGBS alone (b) OPC alone

Fig. 1 Strength improvement of treated SR

Additionally, both the short-term strength (7 days) and the long-term strength (28 days) were equally important to the construction period. Therefore, the weight of UCS after 7 days and 28 days was both at 0.3. The weight set for evaluation criteria is $A = (0.4, 0.3, 0.3)$.

(c) Thereafter, each stabiliser was assigned with a numerical value, enabling a quantitative and objective comparison. The performance of various stabilisers was ranked through the comprehensive evaluation values b_i (Civanlar and Trussell 1986). The stabiliser with the highest evaluation value b_i was considered as the most suitable stabiliser for the treatment of SR. This method allowed for an efficient selection of the suitable stabiliser, ensuring both cost-effectiveness and strength improvement in treating SR.

3. Results and discussion

3.1 Unconfined compressive strength

3.1.1 SR treated with GGBS and OPC-alone

Fig. 2 depicts the strength improvement of SR treated with GGBS-alone and OPC-alone, demonstrating a consistent increase in strength with curing time and stabiliser content for both treatments. The strength improvement could be attributed to the activation of GGBS by the highly alkalinity of SR, which facilitated the dissolution of silica and alumina from GGBS. These dissolved species then reacted with Ca^{2+} presented in the system to form cementitious products, primarily calcium silicate hydrate (C-S-H) and calcium aluminium silicate hydrate (C-A-S-H) gels (An *et al*. 2022a, He *et al*. 2019). These gels not only filled voids within the matrix but also bonded particles. With the reaction process progressed and the gels hardened, the structure became increasingly dense over time. In addition, the reaction between chloride from SR and reactive alumina can generate Friedel's salt, which also contributes to the improvement of SR (Zhao *et al.* 2019). It is noteworthy that during the initial 7 days, the reaction rate for GGBS-treated SR was relatively low, resulting in a slower strength development compared to the later curing period. This can be expected as the activation from SR on GGBS was most pronounced in the later period, which was similar with the finding obtained in Guo *et al*. (2021).

Furthermore, the strength improvement from 5% to 10% GGBS showed a more significant enhancement compared to the increase from 10% to higher GGBS content. Beyond 10% GGBS, the strength improvement became less pronounced. This decrease in strength improvement can be attributed to the precipitation of free lime caused by the higher GGBS content, which in turn hinders the hydration reaction of GGBS and the formation of hydrate products (Noolu *et al.* 2021). Based on this, it suggests that an effective activation of GGBS and treatment of SR can be achieved by an appropriate amount of GGBS rather than an excessively higher amount.

In the process of treating SR with OPC, the cement hydration reaction generated C-(A)-S-H and $Ca(OH)_2$, which bonded particles together and hardened over time, thus developing the strength of SR over time (Zha *et al.* 2021). Notably, the effect of curing time was negligible for SR treated with 5% OPC after 3 days of curing. This is probably attributed to the completion of major chemical reactions. A linear increase in strength was observed with increasing OPC content, owing to the greater formation of hydrate products, which was consistent with findings from similar studies on OPC treatment (An *et al.* 2022b, Pongsivasathit *et al.* 2019). In the comparison between GGBS and OPC, it was observed that OPC developed comparable or higher strength than GGBS for SR at 3 days of curing. However, beyond 3 days, the OPC-treated SR exhibited significantly lower strength compared to the GGBS-treated SR at all contents. This behaviour can be ascribed to the highly alkaline medium provided by SR. Although the alkaline environment is known to accelerate the cement hydration reaction in the early stage (An *et al.* 2022b), it retards the hydration process at the later stage due to the presence of excessive OH^- (Bentz 2006, Garcia-Lodeiro *et al.* 2013), which disrupts the equilibrium of hydration reaction and subsequently impedes the formation of hydrate products (Martinez-Ramirez and Palomo 2001).

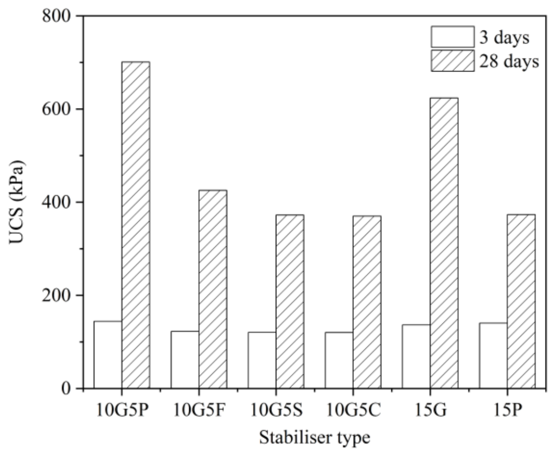


Fig. 2 Strength improvement of SR treated with GGBS-based stabilisers

Overall, the results demonstrated the effectiveness of both GGBS and OPC treatments in enhancing the strength of SR as well as the beneficial impact of extended curing time. Of the results, GGBS-alone exhibited remarkable performance, suggesting its use as a primary stabiliser for further investigation of potential collaboration with other additives to optimise the treatment of SR.

3.1.2 SR treated with GGBS-based stabilisers

In order to further investigate the effect of various type of stabilisers on SR and the collaboration potentials of other additives with GGBS, GGBS was partially replaced by OPC, FA, silica sand, and clay to form GGBS-based stabilisers to treat SR. Fig. 3 presents the UCS of the SR treated with the GGBS-based stabilisers at 3 and 28 curing days. It is observed that all GGBS-based stabilisers contributed similarly to the early strength of SR (3 days). After 28 days of curing, the combination of GGBS and OPC (10G5P) developed the highest enhancement for SR, reaching a strength of 700.8 kPa. The superior performance of 10G5P can be attributed that the activation of GGBS consumed excess $Ca(OH)_2$, which in turn accelerated the hydration process of OPC (Wan et al. 2004), promoting further strength improvement compared to using GGBS and OPC-alone at the same stabiliser content. In contrast, the lower strength observed in the case of 10G5F, 10G5S, and 10G5C compared to 15G implies that the replacement of fly ash, silica sand and clay is not beneficial for the improvement of SR. This was due to the fact that low-calcium FA used as the partial replacement of GGBS reduced the calcium content available for chemical reactions, potentially leading to slower strength development for SR (Sharma and Sivapullaiah 2016); the clay in 10G5C showed no pozzolanic reactivity compared to GGBS (Cheng et al. 2021); and the silica sand acted as an inert aggregate and filled the pore in the matrix without any chemically interactions (Wong et al. 2013), thus limiting its contribution to the strength enhancement.

In conclusion, the replacement of GGBS with OPC offers an effective means of further improving the strength of SR, while the enhancement was compromised by the partial replacements with fly ash, silica sand, or clay. As a result, further investigations were carried out on various proportions of GGBS and OPC to determine the appropriate composition of this blended stabiliser.

3.1.3 Selection of suitable stabiliser composition

The bearing capacity of on-site treated SR area was designed to be above 60 kPa after 28 days of curing, corresponding to a UCS value over 60 kPa according to GB50021-2001 (2001). However, the strength of field-treated materials tends to be lower than that of laboratory-treated materials, and reduction in strength can reach up to approximately 60% (Hebib and Farrell 2003, Horpibulsuk et al. 2006, Miranda et al. 2020). Additionally, the technical specification for in-situ deep mixing technique YBJ255-1991 (1991) suggests the application of a reduction factor of 0.4, which considers the potential decrease in strength under field conditions. Therefore, the UCS of laboratory-treated SR was calculated to be over 150 kPa.

The FCE method was adopted to identify the suitable stabiliser composition with consideration of strength and economy. The evaluated criteria and corresponding comprehensive evaluation values are summarised in Table 1. From the evaluation, the stabiliser, 8G3P obtained the maximum evaluation value of 0.612. Specifically, 8G3P case developed a UCS value of 177.4 kPa after 7 days and 358.4 kPa after 28 days of curing, surpassing the strength requirements of 150 kPa. Overall, 8G3P case was identified as the suitable stabiliser composition for the treatment of SR, providing both desired strength and cost-effectiveness.

3.2 Compressibility of treated SR

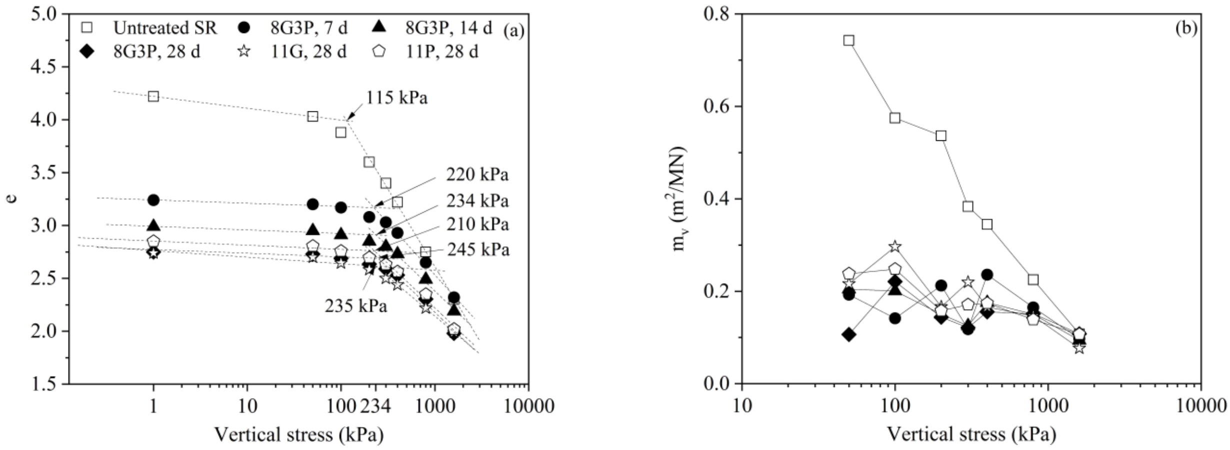
Fig. 4(a) presents the relationship between void ratio and vertical effective stress (σ_v') of untreated SR and treated SR with 8G3P at 7, 14, and 28 curing days, in which the yield stress was determined by the intersection of the recompression and virgin compression lines based on the method proposed by Butterfield (1979). Fig. 4(b) illustrates the variation of coefficient of volume compressibility (m_v) with σ_v'. The coefficient of compression index (Cc) was calculated by the slope of the virgin compression line, corresponding to the linear portion of the e-log σ_v' curve.

The high initial void ratio and initial m_v value observed for untreated SR indicated its inferior engineering properties, characterised by high compressibility and susceptibility to deformation. Upon applying a minor vertical stress of up to 300 kPa, the untreated SR had a considerable reduction in the void ratio and m_v values, suggesting a significant structural collapse. With the addition of 8G3P, the initial void ratio, initial m_v values, and Cc values decreased, and simultaneously, the yield stress of SR increased, which implies a decrease in the compressibility of SR. The improvement in the compressibility can be attributed to the formation of hydrate products (Ding *et al.* 2021). These cementitious gels filled the void spaces within SR and formed a firmer structure, improving the stiffness of SR (Corrêa-Silva *et al.* 2020, Latifi *et al.* 2017). As the curing time increased to 28 days, there was a notable improvement in the compressibility of SR as a result of the progressive filling of voids in SR with

Table 1 Comprehensive evaluation value of different stabilisers in FCE method

Objective set	Cost[a] (CNY/m^3)	UCS (kPa)		Single-criterion evaluation			Comprehensive evaluation value
		7 days	28 days	Cost, R_{1j}	7-day UCS, R_{2j}	28-day UCS, R_{3j}	
4G2P	40.50	91.3	212.2	1.000	0.000	0.000	0.400
6G2P	51.30	114.6	241.5	0.733	0.253	0.159	0.417
8G2P	62.10	148.9	300.8	0.467	0.625	0.480	0.518
4G3P	49.95	109.4	235.7	0.767	0.197	0.127	0.404
6G3P	60.75	132.2	280.2	0.500	0.444	0.369	0.444
8G3P	71.55	177.4	358.4	0.233	0.935	0.793	0.612
4G4P	59.40	121.4	250.3	0.533	0.327	0.207	0.373
6G4P	70.20	140.5	325.4	0.267	0.534	0.614	0.451
8G4P	81.00	183.4	396.6	0.000	1.000	1.000	0.600

[a] The cost of GGBS was 0.4 CNY/kg, and the cost of OPC was 0.7 CNY/kg



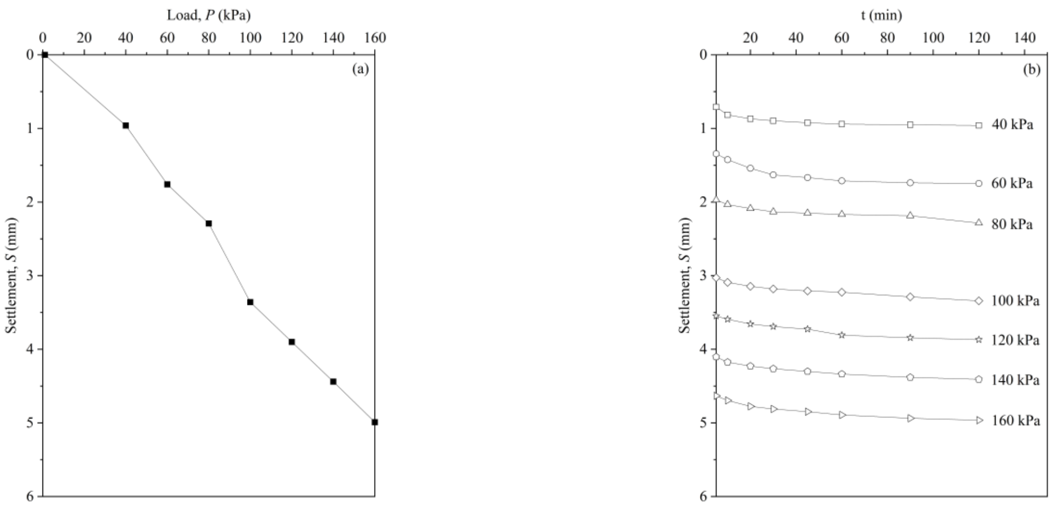
(a) e-log σv' curves (b) e-log σv' curves

Fig. 3 Consolidation characteristics of untreated SR and treated SR

hydrate products (Li *et al.* 2022). For instance, the yield stress of untreated SR increased from 115 kPa to 220 kPa at 7 days, 234 kPa at 14 days, and 245 kPa at 28 days of curing; the Cc value of untreated SR was found to be 1.440, significantly higher than the Cc values for SR treated with 8G3P, which decreased to 0.842 at 7 days, 0.731 at 14 days, and 0.725 at 28 days. Additionally, the high initial m_v value for untreated SR, which was 0.74 m^2/MN, decreased with curing time and ranged between 0.2 and 0.3 m^2/MN, indicating a transformation of the material from high compressibility to medium compressibility (Tomlinson and Boorman 2001). Furthermore, as the vertical stress increased from 50 kPa to 1600 kPa, the reduction in void ratio and m_v values of treated SR decreased over curing time. The variations of initial void ratio, yield stress, Cc values, and m_v values collectively suggest the considerable improvement in the compressibility and stiffness of SR due to the treatment and extended curing time.

Figs. 4(a) and 4(b) also illustrate the cases of 11G and 11P after 28 days of curing, and a comparison with the 8G3P case was made. As shown, SR treated with 11P exhibited the lowest yield stress of 210 kPa, the highest initial mv value of 0.24 m^2/MN, and the highest Cc value of 0.749. The compressibility of 11P was followed by 11G, showing a yield stress of 235 kPa, with similar mv and Cc values. Compared to 11G and 11P, 8G3P case demonstrated the highest yield stress, the lowest Cc value, and the lowest m_v values, highlighting its contribution to a more favourable compressibility and superior resistance to vertical loads. This observation was consistent with strength results, where the combination of GGBS and OPC had a superior performance, while OPC-alone resulted in the lowest strength for SR.

In general, all treated SR cases exhibited significant reduction in voids and progressively similar m_v values as the vertical stress increased and exceeded 800 kPa, eventually converging with untreated SR. The convergence between untreated SR and treated SRs at high vertical stress can be ascribed to the fact that the particles rearranged themselves into a denser state, becoming the main source of resistance to vertical stress (Li and Yi 2022). Consequently, the difference between various stabilisers in improving consolidation characteristics became less pronounced under significant stress. It highlights the importance of carefully



(a) *s* - *P* curve (b) *s*-lg t curve

Fig. 4 Results of plate load test

controlling the loads applied on treated SR during construction to avoid unexpected consequences such as excessive or differential settlement.

In conclusion, the addition of 8% GGBS and 3% OPC proved to be advantageous in reducing the compressibility of SR, developing the highest yield stress, and the lowest m_v and Cc values compared to other treatments. This superiority increased over time, implying the effectiveness of extended curing time in improving the consolidation characteristics of SR. The results highlight the potential of stabilisation technology as an efficient and reliable solution for treating SR, ensuring the formation of a safe and stable foundation material.

3.3 Field bearing capacity of treated SR

After the 28-day curing period for the SR in-situ treated with 8G3P, a plate load test was performed to assess its load-bearing capacity and settlement characteristics. The results depicted in Fig. 5 demonstrated the excellent performance of treated SR under an applied load of 160 kPa, with no evidence of failure. The settlement of treated SR increased smoothly with loading time, indicating its ability to resist the loading without experiencing excessive deformation or instability. The bearing capacity of treated SR was determined to be at least 80 kPa, which was half of the ultimate bearing capacity of 160 kPa, surpassing the design load requirement of 60 kPa. At the bearing capacity of 80 kPa, the corresponding settlement was measured at 2.29 mm, affirming that the foundation area formed by treated SR would be adequate to support the working load without compromising structural stability.

4. Conclusions

The increasing demand for sustainable management of SR has led to the investigation of its feasibility as a construction material. To enhance the mechanical properties of SR, GGBS, OPC, FA, silica sand, and clay were adopted in different combinations to improve SR, and their effectiveness were evaluated through a series of UCS tests. FCE method was employed to identify the suitable stabiliser composition with consideration of strength and economy. The research yielded several valuable findings.

(1) The superiority of GGBS over OPC in enhancing the UCS of treated SR can be attributed to the high alkalinity of SR. The synergic effect between GGBS and OPC further improved the effectiveness of GGBS-alone in improving the strength of SR, which was also more advantageous for strengthening SR compared to the replacement of GGBS with FA, silica sand, or clay.

(2) The FCE method effectively identified the suitable stabiliser composition, a blend of 8% GGBS and 3% OPC, for the treatment of SR, maximising the overall benefits of the treatment method in terms of cost and strength requirements.

(3) The SR treated with 8% GGBS and 3% OPC exhibited the lowest compressibility (highest yield stress, and the lowest m_v and Cc values), followed by GGBS-alone and OPC-alone at equivalent stabiliser content, which was in line with strength results, emphasising the prominent advantage of the combination of GGBS and OPC. Nevertheless, it is noteworthy that the effectiveness of the chemical stabilisation diminished under high vertical effective stresses. As such, attention and control of applied loads on treated SR during construction are essential to maintain its stability and long-term performance.

(4) The in-situ treated SR exhibited a bearing capacity of 80 kPa, accompanied by minimal settlement, fulfilling the engineering requirements. The favourable compressibility and field performance of treated SR demonstrates the viability and efficacy of the employed suitable stabiliser composition.

In summary, the application of stabilisation technology on SR as a construction material offers a sustainable and effective solution for the consumption of a large amount of solid waste. To further promote this management of SR, it will be beneficial to investigate the mechanical behaviours of treated SR under long-term complex environment, which will provide insights to the durability and sustainability of the recycled material in the working environment.

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