frontiers | Frontiers in Earth Science

TYPE Original Research
PUBLISHED 28 December 2023
DOI 10.3389/feart.2023.1276159

Check for updates

OPEN ACCESS

EDITED BY
Yi Xue,
Xi'an University of Technology, China

REVIEWED BY
Arif Ali Baig Moghal,
National Institute of Technology Warangal, India
Dominic E. L. Ong,
Griffith University, Australia

*CORRESPONDENCE
Lei Liu,
liulei830413@sohu.com
Yan Ma,
yma641111@163.com

RECEIVED 11 August 2023
ACCEPTED 30 October 2023
PUBLISHED 28 December 2023

CITATION
Yan J, Liu L, Ma Y, Wang Z and Ren T (2023), Strength properties of soils treated with calcium-based flocculants and their impact on vacuum preloading. *Front. Earth Sci.* 11:1276159.
doi: 10.3389/feart.2023.1276159

Strength properties of soils treated with calcium-based flocculants and their impact on vacuum preloading

Jinkai Yan[1], Lei Liu[2]*, Yan Ma[1]*, Zhihui Wang[1] and Tianxiang Ren[1]

[1]Chinese Academy of Geological Sciences, Beijing, China, [2]Urban Construction School, Beijing City University, Beijing, China

In this study, a series of unconfined compressive strength tests were conducted to investigate the effect of calcium-based flocculants on the strength and deformation properties of slurry. The test results indicated that the presence of calcium-based flocculants [$Ca(OH)_2$ or $CaCl_2$] significantly enhanced the unconfined compressive strength (q_u) of soil. A non-linear relationship was observed between q_u and $CaCl_2$ content, revealing that the maximum value of q_u is obtained at a $CaCl_2$ concentration of 24.8%. q_u exhibited a high increase rate at early curing time in the presence of $Ca(OH)_2$, with a lower increase rate after a longer curing time and high $Ca(OH)_2$ content. The deformation modulus E_{50} showed an increasing trend with increasing $CaCl_2$ content at 3 and 7 d, followed by a decreasing trend with increasing $CaCl_2$ content at 14 and 28 d. However, the failure strain ε_f for $CaCl_2$-treated soil ranges from 2.4% to 4.8%, showing no relation with q_u. A significant increase in E_{50} for $Ca(OH)_2$-treated soil in the early curing stages (3 and 7 d) was observed because of the increase in q_u. After 14 d of curing, E_{50} tended to decrease with increasing $Ca(OH)_2$ content. A positive relationship between the degree of vacuum and q_u in the presence of calcium-based flocculants was proposed, indicating that a higher q_u of treated soil leads to a lower water content after vacuum treatment for the same preloading period, emphasizing that the vacuum treatment efficiency increases with an increase in the q_u of calcium-based flocculant-treated soil.

KEYWORDS

dredged slurry, calcium-based flocculants, strength, vacuum efficiency, soil treatment

1 Introduction

Flooding is a natural disaster that causes massive economic losses and human casualties annually, particularly in recent decades, owing to global climate change. Therefore, to prevent flood disasters and keep river channels unobstructed, dredging projects have been implemented in most urban cities around the Yangtze and Yellow River regions, generating thousands of dredged soils with high initial water contents annually in China (Zeng et al., 2015, 2021; Bian et al., 2016, 2022a; Liu et al., 2018). These large dredged soils are placed inside a slurry pond and left for several years because of their low permeability and engineering properties (Wang et al., 2019; Min et al., 2020; Xu et al., 2020). Owing to its low cost, large treatment area, and high efficiency, the vacuum-preloading method is often regarded as a suitable technique for accelerating the aforementioned process and reusing dredged materials (Chai et al., 2010; Indraratna et al., 2012; Cai et al., 2019).

TABLE 1 Basic properties of flocculants [after Yan et al. (2020)].

Flocculants	Molecular weight	Purity	Impurity content	Insoluble matter content	Heavy metal content
$CaCl_2$	110.99	≥96%	≤0.6%	≤0.015%	≤0.6%
$Ca(OH)_2$	74.09	≥95%	≤1.2%	≤0.3%	≤0.002.4.8%

Generally, the vacuum-preloading method requires a drainage channel, such as prefabricated vertical drains (PVDs), to allow for vacuum pressure transmission through the PVDs and for water flow out of the slurry. However, fine-grained particles may cause clogging of the PVDs, thereby reducing the transmission rate of the vacuum pressure (Chu et al., 2006; Wang et al., 2016; Cao et al., 2019). Recently, a combination of chemical treatment and vacuum preloading has been introduced to increase the treatment efficiency (Wu et al., 2015; Wang et al., 2017). When additional flocculants were added to the slurry, the flocculation effect triggered a large net-frame structure in the soil, resulting in an increase in the permeability and settlement rate of the slurry, which in turn led to a significant increase in the dewatering capacity of the slurry and enhancement of the effectiveness of vacuum preloading (Mallela et al., 2017; Wang et al., 2019; Moghal et al., 2020). In light of this mechanism, numerous researchers have proposed different chemical agents, such as lignite, polyacrylamide (PAM) $FeCl_3$, or CaO, as flocculants to improve the vacuum preloading efficiency (Mallela et al., 2017; Gao et al., 2019; Wang et al., 2019; He et al., 2020). The change in microstructure due to these chemical agents led to the formation of a flocculated fabric and increased soil strength, which benefited slurry movement during vacuum preloading. However, some lime-based (CaO) agents may induce highly brittle sandy slurry structures, leading to unfavorable engineering properties (Wang et al., 2019). Therefore, investigating the effect of flocculants on slurry strength and vacuum preloading efficiency is important.

In this study, to achieve more optimized results than the vacuum preloading method, two calcium-based flocculants, including $Ca(OH)_2$ and $CaCl_2$, were introduced to improve the slurry strength. Subsequently, the effect of the strength increase on the vacuum-preloading efficiency was analyzed and compared with that reported in previous studies (Yan et al., 2020).

2 Materials and experimental methods

2.1 Materials

BB slurry was collected from a dredging project in the Huaihe River, Eastern China. The liquid and plastic limits in BB slurry were 58% and 26%, respectively. This slurry is classified as high-plasticity clay (CH) according to the Unified Soil Classification System (ASTM D2487). The specific gravity of the soil particles was 2.70 Mg/m^3.

Calcium hydroxide ($Ca(OH)_2$) and calcium chloride ($CaCl_2$), manufactured by the Damao Chemical Reagent Factory, Tianjin, China, were used as calcium-based flocculants. Their basic properties have been outlined by Yan et al. (2020) and their basic compositions are summarized in Table 1.

2.2 Experimental methods

The test programs for the two calcium-based flocculant-treated soils are listed in Table 2. To obtain a homogeneous slurry, a soil slurry with an initial water content that was double the liquid limit was prepared by mixing raw soil with a predetermined amount of water. Then the calcium chloride (0.3%, 0.6%, 1.2%, 2.4%, 4.8% by dry soil weight) and calcium hydroxide (0.3%, 0.6%, 1.2%, 2.4%, 4.8% by dry soil weight) powders were poured into a blender and mixed for approximately 5–10 min to achieve uniformity. The mixture was then transferred to a plastic cylindrical mold with a diameter of 39.1 mm and a height of 80 mm. The cylindrical samples were removed after 24 h. The cylindrical specimens were wrapped separately in plastic bags under 95% relative humidity and at 20 ± 2°C and then cured.

Unconfined compression tests (UCT) were performed on the specimens at different curing times (3, 7, 14, and 28 d) following ASTM D4219. The vertical displacement rate of the UCTs was 1 mm/min. Triplicate measurements of the unconfined compressive strength (q_u) were conducted, and the average value was used. The experimental setup is plotted in Figure 1.

3 Results and discussion

3.1 Stress-strain relationship curve

Figure 2 shows the stress–strain relationship curves of the treated soil at different flocculant contents and curing times. This indicates that the stress of the cured soil increased with strain towards the peak stress, followed by a decrease in stress with strain, showing a typical strain-softening type for all specimens.

With an increase in curing time, the stress-strain curves tended to move towards the left of the axis, with an increase in the peak stress with curing time. However, the strain at the peak stress decreased with increasing curing time, except for the case of 2.4% $CaCl_2$ with little change in the strain at the peak stress at different curing times. At the same curing times, an increase in the peak stress with increasing flocculant content was observed as the strain of the peak stress increased. This indicates that the addition of flocculants and curing times lead to increased soil brittleness.

3.2 Unconfined compressive strength

Figure 3 shows the variation in the unconfined compressive strength q_u with $CaCl_2$ content at different curing times. For a given $CaCl_2$ concentration, the longer the curing time, the greater the value of q_u. This behavior indicates a chemical reaction between $CaCl_2$, clay particles, and water that lasts approximately 28 d. As expected, the addition of $CaCl_2$ significantly increased the q_u value

TABLE 2 Test programme.

Flocculants	Slurry initial water content: %	Flocculants content: %	Curing time: days
$CaCl_2$	116	0.0	3, 7, 14, 28
		0.3	
		0.6	
		1.2	
		2.4	
		4.8	
$Ca(OH)_2$	116	0.0	
		0.3	
		0.6	
		1.2	
		2.4	
		4.8	

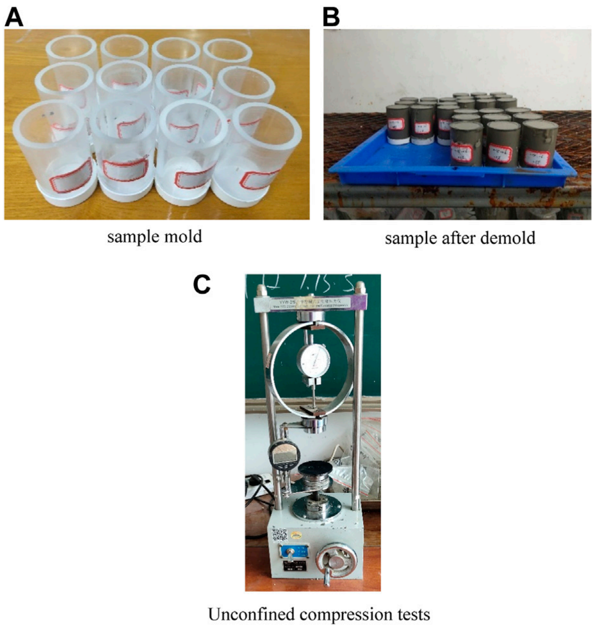

FIGURE 1
Experimental setup. **(A)** Sample mold. **(B)** Sample after demold. **(C)** Unconfined compression tests.

compared with that of the soil without $CaCl_2$ under the same curing time. q_u for soil treated with $CaCl_2$ is close to 1.0 MPa after 14 d of curing and up to 1.5 MPa after 28 d of curing. Moreover, an optimal $CaCl_2$ content corresponding to the highest value of q_u was identified. That is, q_u increases with an increase in $CaCl_2$ content up to the optimal point, after which it shows a decreasing tendency with a further increase in $CaCl_2$ content. Nevertheless, the addition of $CaCl_2$ led to a significant increase in the strength of the cured soil. The optimal $CaCl_2$ content was primarily attributed to the increased pozzolanic reaction in the treated soil caused by the increased Ca^{2+} concentration in the pore solution when $CaCl_2$ was added to the slurry. Additionally, the alkaline environment formed by $CaCl_2$ from the hydration reaction accelerates the pozzolanic reaction. Consequently, the increased content of $CaCl_2$ leads to an increase in the strength of the treated soil at the early stage up to the optimal $CaCl_2$ content. When the $CaCl_2$ content exceeded the optimal $CaCl_2$ content, q_u decreased because the additional $CaCl_2$ content led to an increase in the Cl^- concentration in the pore fluid of the treated soil. At a certain level, Cl^- reacts with $3CaO{\cdot}Al_3O_3$ to form calcium chloroaluminate hydrate ($3CaO{\cdot}Al_3O_3{\cdot}3CaCl_3{\cdot}32H_2O$), which does not belong to the cementitious products and can be expressed as follows:

$$3CaO \cdot Al_3O_3+3CaCl_2+32H_2O \rightarrow 3CaO{\cdot}Al_3O_3{\cdot}3CaCl_2{\cdot}32H_2O \quad (1)$$

In other words, the overdosage of $CaCl_2$ content causes a decline in the amount of cementitious products such as $3CaO{\cdot}2SiO_2{\cdot}3H_2O$ (calcium silicate hydrate, C-S-H) and $3CaO{\cdot}2SiO_2{\cdot}Ca(OH)_2{\cdot}12H_2O$ (calcium aluminate hydrate, C-A-H), causing a reduction in strength. In summary, the strength of the soil treated with $CaCl_2$ was attributed to the combined effects of Ca^{2+} and Cl^-. Therefore, an optimal concentration of $CaCl_2$ to optimize the strength of the treated soil exists.

The variation of unconfined compressive strength with $Ca(OH)_2$ content is shown in Figure 4. As expected, the q_u value and curing time were positively correlated. After 28 d of curing, the maximum value of q_u can exceed 1.0 MPa. Unlike $CaCl_2$, the q_u of soil treated with $Ca(OH)_2$ shows an increasing trend when $Ca(OH)_2$ content is low and with a slight reduction as the $Ca(OH)_2$ content increases, followed by a further increase in $Ca(OH)_2$ content. Overall, the unconfined compressive strength of the solid treated with $Ca(OH)_2$ was higher than that of the soils without $Ca(OH)_2$. This is mainly attributed to the pozzolanic reaction between $Ca(OH)_2$, SiO_2, and Al_2O_3 in clay minerals, forming cementitious products such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), thereby reinforcing the treated soil. Owing to the low solubility of $Ca(OH)_2$ in water, the Ca^{2+} content in the treated soil did not increase monotonously with increasing $Ca(OH)_2$ content. Therefore, the q_u value changing with the $Ca(OH)_2$ content mainly occurs in the low content range, up to 0.6% of $Ca(OH)_2$. When $Ca(OH)_2$ content exceeds 0.6%, the formation of cementitious material covering the soil particles owing to the pozzolanic reaction from the contact between $Ca(OH)_2$ and clay minerals is hindered to a certain extent; therefore, the pozzolanic reaction is slowed down, corresponding to a macroscopic reduction in the strength of the treated soil. Furthermore, as the $Ca(OH)_2$ content increased to 2.4%, a large amount of $Ca(OH)_2$ that did not participate in the pozzolanic reaction with clay minerals reacts with the CO_2 in the air to produce water-insoluble calcium carbonate, which produces additional cementitious products, making the microstructure of treated soil denser. Consequently, when $Ca(OH)_2$ content exceeded 2.4%, q_u increased. Note that, as q_u continuously increased with $Ca(OH)_2$ content, the peak value of q_u may correspond to a $Ca(OH)_2$ content higher than 5%. However, the usage of high $Ca(OH)_2$ content will show economic disadvantages. Hence, it is

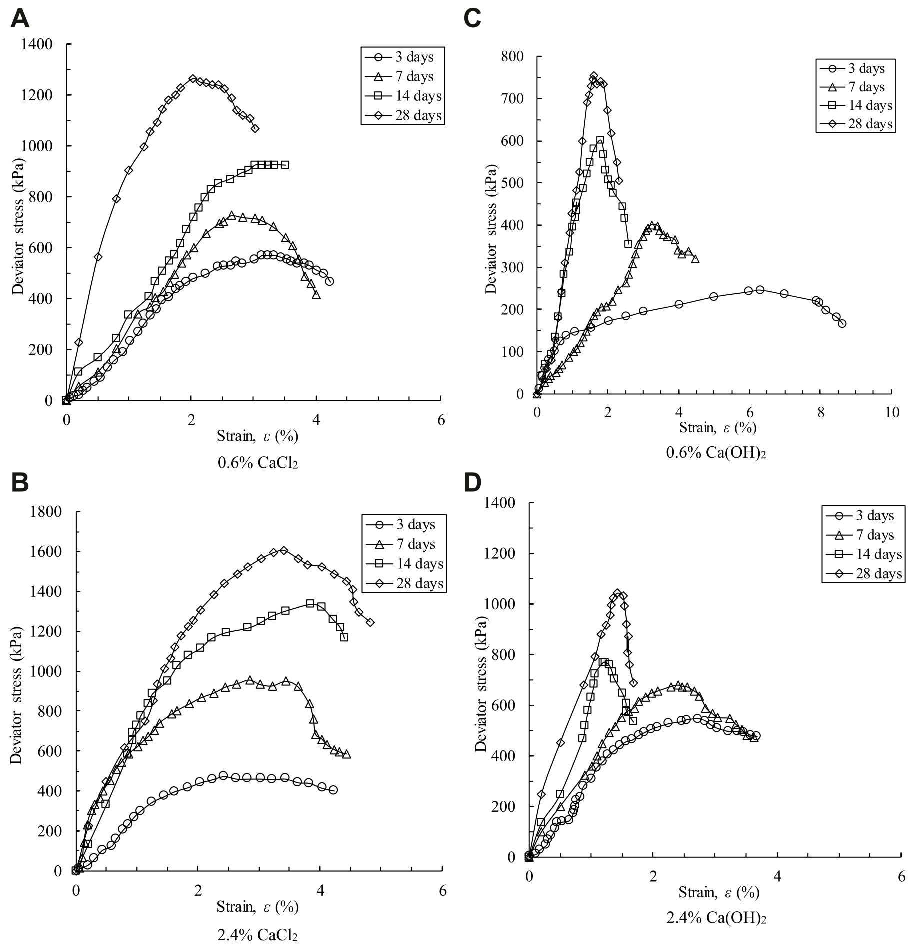

FIGURE 2
Stress-strain relation of different flocculants content. **(A)** 0.6% $CaCl_2$. **(B)** 2.4% $CaCl_2$. **(C)** 0.6% $Ca(OH)_2$. **(D)** 2.4% $Ca(OH)_2$.

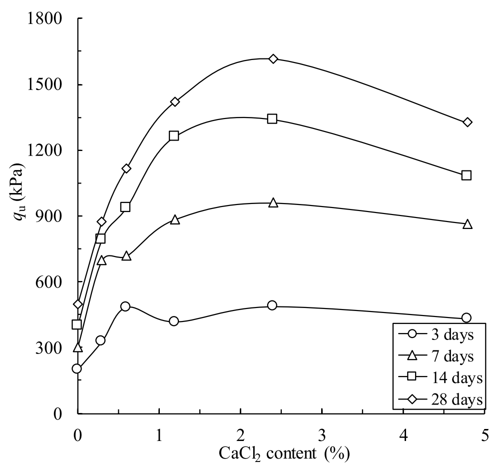

FIGURE 3
Variation of q_u with $CaCl_2$ content.

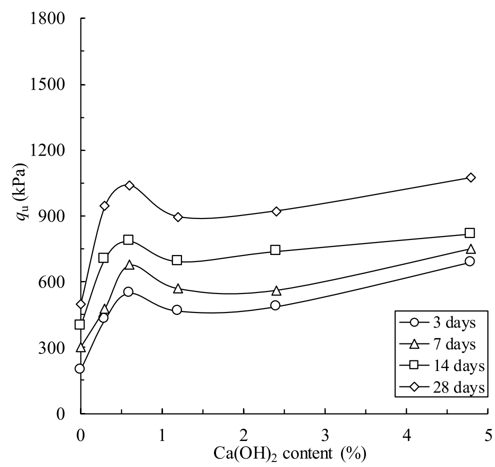

FIGURE 4
Variation of q_u with $Ca(OH)_2$ content.

not practical available to implement $Ca(OH)_2$ content higher than 5%. Thus, the range of 1%–5% of $Ca(OH)_2$ content is used in this study.

In addition, because of the solubility of $Ca(OH)_2$, the ionization of $Ca(OH)_2$ dissolved in water produced a lower amount of Ca^{2+} than that of $CaCl_2$ at the same flocculant concentration. Macroscopically, the increase in the strength of the treated soil caused by $Ca(OH)_2$ was less than that caused by $CaCl_2$.

To further identify the effect of flocculant content on the strength of treated soil, the parameters Δq_u are introduced for analysis, where q_{u0} is the unconfined compressive strength of treated soil without flocculant, q_u is the unconfined compressive strength of treated soil with flocculant, and Δq_u ($=q_u$-q_{u0}) is the difference between the unconfined compressive strength of cured soil with and without flocculant. The results are shown in Figure 5. When the $CaCl_2$ content increases from 0.3% to 4.8%, Δq_u at the same curing time increases from 28.1 to 683.3 kPa. Except for the 0.3%, Δq_u increases with the increase in curing time at the same $CaCl_2$ content. For $Ca(OH)_2$, when increasing from 0.3% to 4.8%, Δq_u increases from 17.5 to 343.3 kPa. However, unlike $CaCl_2$, most of the increase in strength due to $Ca(OH)_2$ occurs in the early curing period.

In summary, the addition of calcium flocculant is beneficial for increasing the strength of treated soil. However, the amount of flocculant should be designed according to the actual engineering purposes.

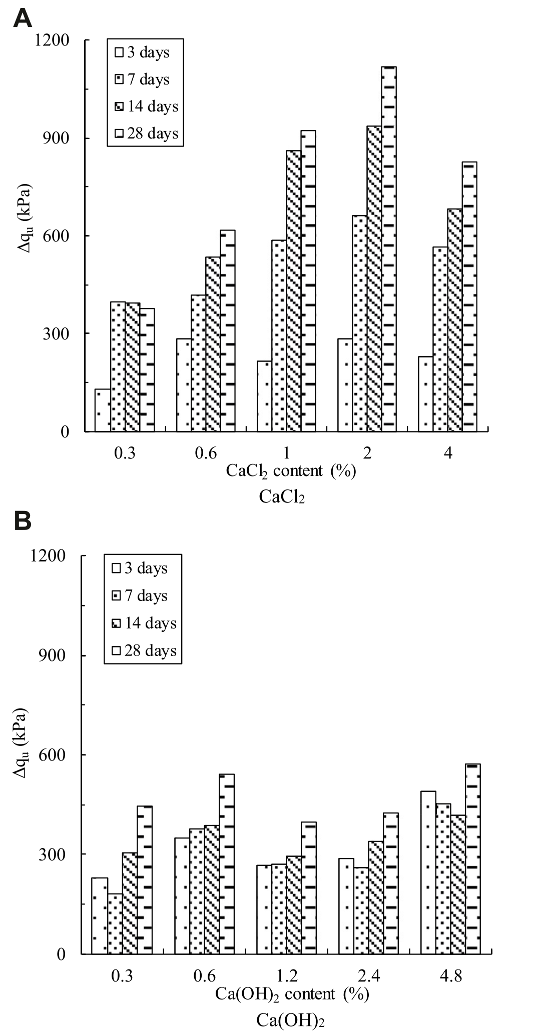

FIGURE 5
Variation of Δq_u with flocculants content. **(A)** $CaCl_2$. **(B)** $Ca(OH)_2$.

3.3 Failure strain

The failure strain ε_f is an important indicator for characterizing the deformation characteristics of treated soil and its magnitude can reflect the compressibility of treated soil after curing. Typically, the larger the failure strain, the stronger the treated soil; conversely, the smaller the damage strain, the more brittle the treated soil. The strain corresponding to the peak stress on the stress–strain curve of the treated soil is generally considered to be the failure strain. When there is no peak point on the stress–strain curve, a strain of 15% is selected as the failure strain.

According to the stress–strain curves of the cured soils with different $CaCl_2$ and $Ca(OH)_2$ contents, the corresponding failure strains were obtained, as shown in Figure 6. The corresponding damage strains are shown. When the $CaCl_2$ flocculant is used, the presence of $CaCl_2$ in the early curing period (3 and 7 d) led to a decrease in the failure strain of the treated soil with an increase in $CaCl_2$ content. At longer curing times (14 and 28 d), the failure strain was observed to increase with increasing $CaCl_2$ content. This indicates that the brittleness of the soil was reduced at longer curing times in the presence of $CaCl_2$, showing more optimized deformation characteristics of the treated soil for projects such as embankments or foundations. Notably, the failure strain was almost unaffected by the curing time at $CaCl_2$ of 2.4% and 4.8%. When the curing time reached 28 d, the failure strains of the treated soil with different $CaCl_2$ concentrations showed little change, remaining at basically the same magnitude.

Unlike $CaCl_2$, the failure strain of the soil treated with $Ca(OH)_2$ was negatively correlated with the curing time. In addition, the failure strain decreased with increasing $Ca(OH)_2$ content. Compared with the cured soil without flocculant, the addition of $Ca(OH)_2$ caused a significant decrease in the failure strain during the early curing period (3 and 7 d) owing primarily to the enhancement of the early strength of the treated soil by the presence of $Ca(OH)_2$. Subsequently, when the curing time exceeded 7 d, the failure strains of the treated soils with different $Ca(OH)_2$ contents were essentially the same. The addition of $Ca(OH)_2$ has little effect on the long-term deformation and brittleness of the treated soil.

Several researchers proposed that the relationship between failure strain ε_f and q_u of cement-treated soils follows an approximate power function (Bian et al., 2021; Zeng et al., 2021; Bian et al., 2022a; Bian et al., 2022b). Figure 7 shows the relationship between the ε_f and q_u of treated soil at different curing times and different flocculants. For the soil treated with $CaCl_2$, ε_f basically remains within the range of 2.4% and 4.8% with increasing soil q_u and does not show a decreasing pattern. This may be due to the fact that the excessive Cl^- disrupts the pozzolanic reaction and leads to the formation of non-cementitious materials calcium chloroaluminate hydrate ($3CaO{\cdot}Al_3O_3{\cdot}3CaCl_3{\cdot}32H_2O$). Therefore, the variation in the failure strain of the soil treated with

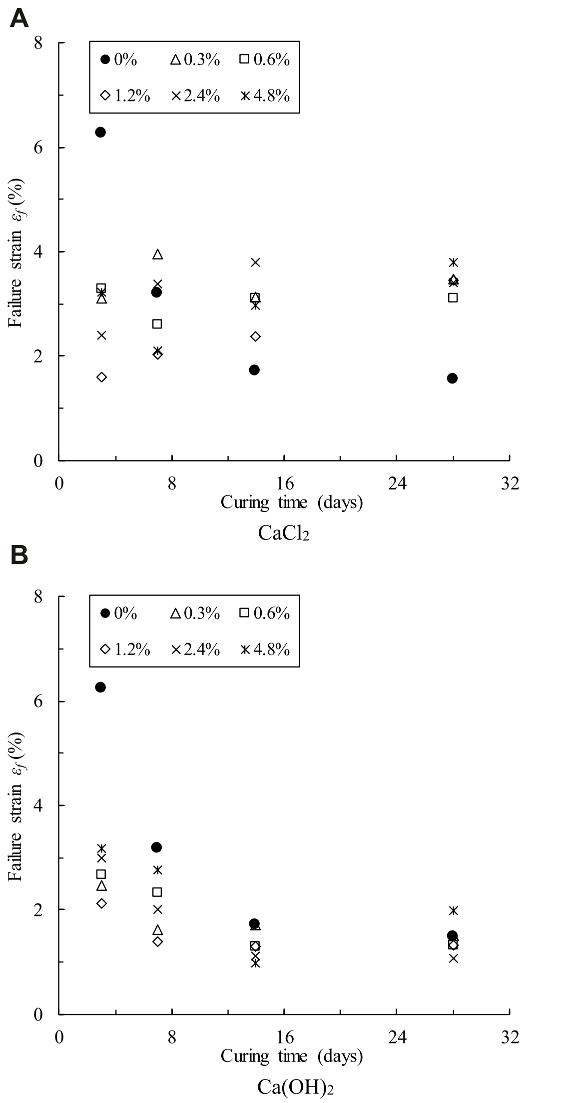

FIGURE 6
Variation of failure strain ε_f with curing time. **(A)** $CaCl_2$. **(B)** $Ca(OH)_2$.

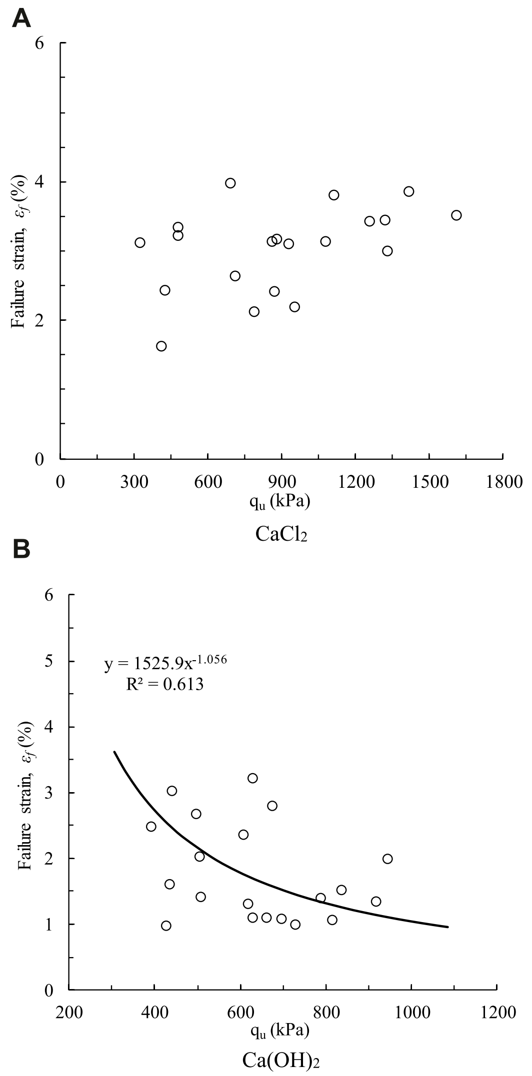

FIGURE 7
Relationship between ε_f and q_u. **(A)** $CaCl_2$. **(B)** $Ca(OH)_2$.

$CaCl_2$ differed from that of the cement-treated soil. Conversely, the general power relation between ε_f and q_u for soil treated with $Ca(OH)_2$ is observed in Figure 7B. A fair correlation coefficient (R^2 = 0.613) suggests that the derived power function can be used as a useful engineering tool for the first-order estimation of failure strain. This is because the mechanisms of strength enhancement, such as pozzolanic reactions, ion exchange, and carbonation for the $Ca(OH)_2$ treated soil were similar to those of cement. Therefore, when the flocculant is $Ca(OH)_2$, the failure strain ε_f tends to gradually decrease as q_u increases.

3.4 Deformation modulus E_{50}

E_{50} is an important parameter for the quantitative estimation of the undrained settlement of soft ground, which is essential for the design of practical projects (Bian et al., 2021). The deformation modulus E_{50} can be calculated from the stress–strain curve measured by the unconfined compressive test as follows:

$$E_{50} = \frac{\sigma_{1/2}}{\varepsilon_f/2} \tag{2}$$

where $\sigma_{1/2}$ is the stress corresponding to a vertical strain of half the failure strain.

Figure 8 depicts the deformation modulus E_{50} of the soil treated with different flocculants; notably, the E_{50} of the soil treated with $CaCl_2$ increased with an increase in curing time at 3 and 7 d, followed by a decreasing trend with increasing curing time at 14 and 28 d. At early curing times (3 and 7 d), the increase in $CaCl_2$ content caused an increase in E_{50}. Conversely, a decrease in E_{50} with increasing $CaCl_2$ content was observed at curing times of 14 and 28 d. Moreover, at longer curing times, the E_{50} of treated soil with $CaCl_2$ contents of 1.2%, 2.4%, and 4.8% were higher than those without flocculant, whereas the E_{50} at $CaCl_2$ of 0.3% and 0.6% were smaller than those without flocculant. The deformation properties ε_f and E_{50} as shown in Figures 7A, 8A illustrate that when $CaCl_2$

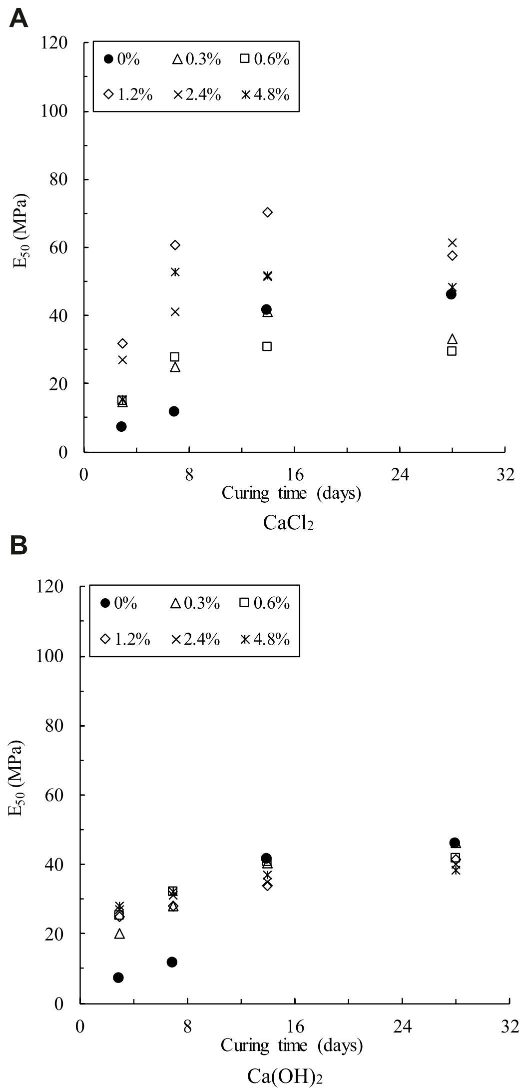

FIGURE 8
Variation of E_{50} with curing time. **(A)** $CaCl_2$. **(B)** $Ca(OH)_2$.

flocculant is used to improve the strength and deformation characteristics of treated soil, the appropriate amount of $CaCl_2$ should be selected according to the actual project requirements to meet the requirements of engineering purpose and economy perspective.

Similar results on E_{50} were observed for $Ca(OH)_2$ treated soil. At early curing times (3 and 7 d), E_{50} was observed to increase significantly with an increase in $Ca(OH)_2$ content. This was due to the significant enhancement in the early strength of the $Ca(OH)_2$ treated soil as shown in Figure 6. Evidently, E_{50} for $Ca(OH)_2$ treated soil in the early curing stages (3 and 7 d) was higher than that without flocculants, owing to the increase in q_u as mentioned above. When the curing time exceeded 14 d, E_{50} showed a decreasing tendency with curing time and $Ca(OH)_2$ content and was gradually lower than that without flocculants.

E_{50} and q_u in cement-treated soils are positively correlated ((Bian et al., 2016; 2022a). The relationship between E_{50} and q_u for soils treated with flocculants for different curing times is shown in Figure 9. As expected, E_{50} increased with increasing q_u, which is consistent with previous findings (Bian et al., 2016, 2021; 2022a). The relationship between $CaCl_2$ and $Ca(OH)_2$ treated soil ranges from E_{50}= (20–110) q_u. This relationship depends on the flocculant type, flocculant content, and slurry water content. Compared with the results of cemented soil (Kang et al., 2017), this relationship is slightly weak because of the lower level of pozzolanic reaction from the flocculants. The relationship between E_{50} and q_u in this study can provide a first-order estimation of the stiffness of $CaCl_2$ or $Ca(OH)_2$ treated soil. However, detailed determination still needs to be conducted in the field.

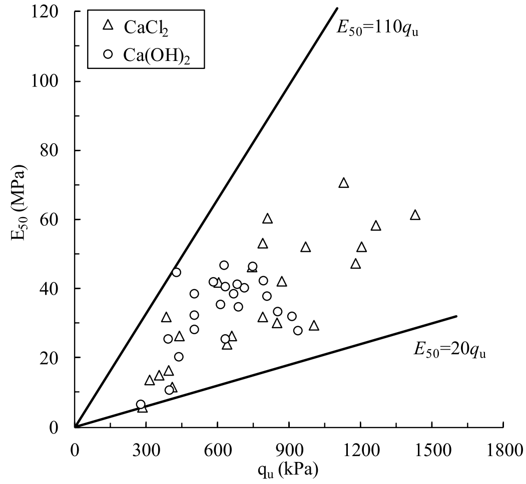

FIGURE 9
Relationship between E_{50} and q_u.

3.5 Influence of strength improvement by flocculants in vacuum efficiency

As proposed by Yan et al. (2020), calcium-based flocculants [$Ca(OH)_2$ and $CaCl_2$] significantly influence vacuum transmission within the slurry, thereby improving the vacuum treatment efficiency. Hence, this influence can be inferred to result from the change in flocculant strength, as discussed in the previous sections. Therefore, relating the vacuum transmission with q_u at different flocculant contents illustrates the mechanism of improvement in vacuum treatment efficiency with calcium-based flocculants. Figure 10 shows the relationship between the degree of vacuum at the bottom of the model test proposed by Yan et al. (2020) and the strength variation in this study. Evidently, the vacuum degree shows a strong positive relationship with q_u of the treated soil in the range of calcium-based flocculants in this study. This behavior indicates that the increase in q_u in the presence of calcium-based flocculants significantly improves the vacuum-treatment efficiency, that is, a higher undrained shear strength of the treated soil leads to a lower water content after vacuum treatment at the same preloading period. This is primarily because by adding calcium-based flocculants to the slurry, larger soil aggregates are formed, thus increasing the strength and

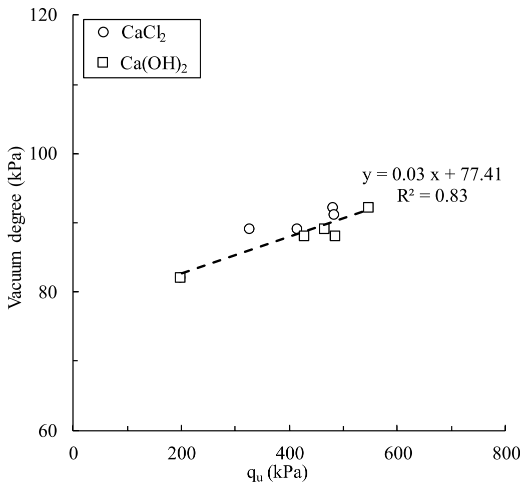

FIGURE 10
Relationship between vacuum degree and q_u.

accelerating soil settlement, consequently easing water extraction from the slurry (Mallela et al., 2017; Wang et al., 2019; Yan et al., 2020).

Furthermore, Figures 3, 4 show that the change in q_u with $CaCl_2$ and $Ca(OH)_2$ content did not increase monotonously. This means that the vacuum-treatment efficiency should not linearly increase with the $CaCl_2$ and $Ca(OH)_2$ content. For example, q_u decreased with $CaCl_2$ amount exceeding 2.4%. Therefore, an optimal calcium-based flocculant content that corresponds to the highest vacuum-treatment efficiency exists. When the calcium-based flocculant content is lower than the optimal content, larger soil aggregates owing to the flocculation effect of calcium-based flocculants lead to the formation of a large net-frame structure, resulting in a water transmission path, thereby increasing the vacuum transmission rate. Once the optimal calcium-based flocculant content is exceeded, excessively large soil flocs block the drainage materials, reducing the drainage capacity and eventually attenuating the vacuum transmission efficiency (Yan et al., 2020).

These phenomena suggest that when using calcium-based flocculants such as $CaCl_2$ and $Ca(OH)_2$ to improve vacuum efficiency, an adequate dosage is recommended to significantly improve the vacuum treatment efficiency, rather than applying an overdose of calcium-based flocculants to block the drainage materials, thus reducing the vacuum treatment efficiency. Note that, the mechanism of $CaCl_2$ or $Ca(OH)_2$ on the improvement of vacuum efficiency corresponded to the microstructure changes induced by the Ca-based flocculate, which need to be further studied. In addition, the detailed microstructure analysis at pre- and post-vacuum preloading should be conducted to clarify the change in the strength of slurry with the alternation of microstructure at two stages, consequently proposing the optimal treatment combination.

It should also be mentioned that there are some new and environmentally friendly agents such as geopolymer or microbial have emerged to improve the mechanical behavior of soils (Leong et al., 2015; Omoregie et al., 2016). However, these types of agent were mainly dealt with the improvement of soils with water content less than its liquid limit. Hence, the application of geopolymer or microbial in the treatment of slurry with high water content as well as the combination of vacuum preloading method needs to be further studied.

4 Conclusion

This study analyzed and identified the effects of two calcium-based flocculants [$Ca(OH)_2$ and $CaCl_2$] on the strength and deformation properties of slurry. Accordingly, the efficiency of vacuum preloading is discussed based on the relationship between the strength properties after treatment and the vacuum transmission rate. The main results of this study are as follows:

1) Calcium-based flocculants [$CaCl_2$ or $Ca(OH)_2$] increased the unconfined compressive strength (q_u). q_u increases with increasing $CaCl_2$ content up to 2.4%, then decreases when $CaCl_2$ content exceeds this concentration. However, $Ca(OH)_2$ significantly enhanced q_u at an early curing time, decreased slightly up to 2.4% flocculant concentration, and then increased until 4.8% flocculant concentration.
2) For the soil treated with $CaCl_2$, the failure strain ε_f basically remains within the range of 2.4%–4.8% with no clear correlation with q_u. However, the failure strain exhibited a decreasing trend with increasing q_u for $Ca(OH)_2$.
3) The E_{50} of soil treated with $CaCl_2$ shows an increasing trend with increasing curing time at 3 and 7 d, followed by a decreasing trend with increasing curing time at 14 and 28 d. E_{50} for the $Ca(OH)_2$ treated soil in the early curing stages (3 and 7 d) was higher than that without flocculants owing to the increase in q_u as mentioned above. When the curing time exceeded 14 d, E_{50} tended to decrease with increasing $Ca(OH)_2$ content.
4) The vacuum-treatment efficiency shows a clear increasing trend with the increase in q_u in the presence of calcium-based flocculants; that is, a higher undrained shear strength of the treated soil leads to a lower water content after vacuum treatment at the same preloading period.
5) Further studies should be focused on the microstructure analysis of the effect of Ca-based flocculate and vacuum preloading to investigate the mechanism of improvement of vacuum efficiency induced by Ca-based flocculate.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

JY: Conceptualization, Data curation, Funding acquisition, Methodology, Software, Writing–original draft, Writing–review and editing. LL: Conceptualization, Data curation, Supervision, Writing–review and editing. YM: Funding acquisition, Resources, Supervision, Writing–review and editing. ZW: Data curation, Investigation, Software, Validation, Writing–review and editing. TR: Data curation, Investigation, Software, Validation, Writing–review and editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. The authors wish to acknowledge the support of the China Geological Survey Project (Grant No. DD20211314), the Project for the Chinese Academy of Geological Sciences (Nos JKY202122 and HX 2023-05).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Bian, X., Wang, Z. F., Ding, G. Q., and Cao, Y. P. (2016). Compressibility of cemented dredged clay at high water content with super-absorbent polymer. *Eng. Geol.* 208, 198–205. doi:10.1016/j.enggeo.2016.04.036

Bian, X., Zeng, L. L., Ji, F., Xie, M., and Hong, Z. (2022a). Plasticity role in strength behavior of cement-phosphogypsum stabilized soils. *J. Rock Mech. Geotechnical Eng.* 14 (6), 1977–1988. doi:10.1016/j.jrmge.2022.01.003

Bian, X., Zeng, L. L., Li, X. Z., and Hong, J. T. (2021). Deformation modulus of reconstituted and naturally sedimented clays. *Eng. Geol.* 295, 106450. doi:10.1016/j.enggeo.2021.106450

Bian, X., Zhang, W., Li, X. Z., Shi, X. S., Deng, Y. F., and Peng, J. (2022b). Changes in strength, hydraulic conductivity and microstructure of superabsorbent polymer stabilized soil subjected to wetting-drying cycles. *Acta Geotech.* 17 (11), 5043–5057. doi:10.1007/s11440-022-01573-x

Cai, Y., Xie, Z., Wang, J., Wang, P., and Geng, X. (2019). Reply to the discussion by Mesri and Kane on "New approach of vacuum preloading with booster prefabricated vertical drains (PVDs) to improve deep marine clay strata". *Can. Geotechnical J.* 56 (12), 2017. doi:10.1139/cgj-2019-0250

Cao, Y., Xu, J., Bian, X., and Xu, G. (2019). Effect of clogging on large strain consolidation with prefabricated vertical drains by vacuum pressure. *KSCE J. Civ. Eng.* 23 (10), 4190–4200. doi:10.1007/s12205-019-1884-2

Chai, J., Hong, Z., and Shen, S. (2010). Vacuum-drain consolidation induced pressure distribution and ground deformation. *Geotext. Geomembranes* 28 (6), 525–535. doi:10.1016/j.geotexmem.2010.01.003

Chu, J., Bo, M. W., and Choa, V. (2006). Improvement of ultra-soft soil using prefabricated vertical drains. *Geotext. Geomembranes* 24 (6), 339–348. doi:10.1016/j.geotexmem.2006.04.004

Gao, Y. F., Hang, L., He, J., and Chu, J. (2019). Mechanical behaviour of biocemented sands at various treatment levels and relative densities. *Acta Geotech.* 14 (3), 697–707. doi:10.1007/s11440-018-0729-3

He, J., Gao, Y. F., Gu, Z., Chu, J., and Wang, L. (2020). Characterization of crude bacterial urease for $CaCO_3$ precipitation and cementation of silty sand. *J. Mater. Civ. Eng.* 32 (5), 04020071. doi:10.1061/(asce)mt.1943-5533.0003100

Indraratna, B., Rujikiatkamjorn, C., Balasubramaniam, A. S., and McIntosh, G. (2012). Soft ground improvement via vertical drains and vacuum assisted preloading. *Geotext. Geomembranes* 30, 16–23. doi:10.1016/j.geotexmem.2011.01.004

Kang, G., Tsuchida, T., and Kim, Y. (2017). Strength and stiffness of cement-treated marine dredged clay at various curing stages. *Constr. Build. Mater.* 132, 71–84. doi:10.1016/j.conbuildmat.2016.11.124

Leong, H. Y., Ong, D. E. L., Sanjayan, J. G., and Nazari, A. (2015). A genetic programming predictive model for parametric study of factors affecting strength of geopolymers. *RSC Adv.* 5 (104), 85630–85639. doi:10.1039/c5ra16286f

Liu, C., Xu, G., and Xu, B. (2018). Field study on the vacuum preloading of dredged slurry with wheat straw drainage. *KSCE J. Civ. Eng.* 22 (11), 4327–4333. doi:10.1007/s12205-018-1555-8

Mallela, J., Von Quintus, H., Kelly, P. E., and Smith, L. (2017). *Consideration of lime-stabilized layers in mechanistic-empirical pavement design*.

Moghal, A. A. B., Vydehi, V., Moghal, M. B., Almatrudi, R., AlMajed, A., and Al-Shamrani, M. A. (2020). Effect of calcium-based derivatives on consolidation, strength, and lime-leachability behavior of expansive soil. *J. Mater. Civ. Eng.* 32 (4), 04020048. doi:10.1061/(asce)mt.1943-5533.0003088

Omoregie, A. I., Senian, N., Li, P. Y., Hei, N. L., Leong, D. O. E., Ginjom, I. R. H., et al. (2016). Ureolytic bacteria isolated from Sarawak limestone caves show high urease enzyme activity comparable to that of Sporosarcina pasteurii (DSM 33). *Malays. J. Microbiol.*, 463–470.

Wang, J., Cai, Y., Ma, J., Chu, J., Fu, H., Wang, P., et al. (2016). Improved vacuum preloading method for consolidation of dredged clay-slurry fill. *J. Geotechnical Geoenvironmental Eng.* 142 (11), 06016012. doi:10.1061/(asce)gt.1943-5606.0001516

Wang, J., Huang, G., Fu, H., Cai, Y., Hu, X., Lou, X., et al. (2019). Vacuum preloading combined with multiple-flocculant treatment for dredged fill improvement. *Eng. Geol.* 259, 105194. doi:10.1016/j.enggeo.2019.105194

Wang, J., Ni, J., Cai, Y., Fu, H., and Wang, P. (2017). Combination of vacuum preloading and lime treatment for improvement of dredged fill. *Eng. Geol.* 227, 149–158. doi:10.1016/j.enggeo.2017.02.013

Wu, D., Xu, W., and Tjuar, R. (2015). Improvements of marine clay slurries using chemical–physical combined method (CPCM). *J. Rock Mech. Geotechnical Eng.* 7 (2), 220–225. doi:10.1016/j.jrmge.2015.02.001

Xu, G. Z., Yin, J., Feng, X. S., and Ji, F. (2020). An improved method for dewatering sewage sludge using intermittent vacuum loading with wheat straw as vertical drains. *KSCE J. Civ. Eng.* 24 (7), 2017–2025. doi:10.1007/s12205-020-2216-2

Yan, J. K., Ji, F., Bian, X., Xu, G. Z., Liu, L., Liu, X. L., et al. (2020). Ultra-soft ground treatment of vacuum preloading combining with calcium-based flocculants. *Adv. Civ. Eng.*, 6691565.

Zeng, L. L., Bian, X., Zhao, L., Wang, Y. J., and Hong, Z. S. (2021). Effect of phosphogypsum on physiochemical and mechanical behaviour of cement stabilized dredged soil from Fuzhou, China. *Geomechanics Energy Environ.* 25, 100195. doi:10.1016/j.gete.2020.100195

Zeng, L. L., Hong, Z. S., and Cui, Y. J. (2015). On the volumetric strain–time curve patterns of dredged clays during primary consolidation. *Géotechnique* 65 (12), 1–6. doi:10.1680/geot.15.t.003