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Strength enhancement of expansive and non-expansive clays using colloidal silica

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Abstract. Expansive and soft clays pose major challenges in infrastructure development due to their high compressibility, low shear strength, and significant volume changes upon wetting and drying. Conventional cement-based stabilisers are effective but carbon-intensive, motivating the search for sustainable alternatives. Colloidal silica (CS) has emerged as a sustainable, low-carbon alternative to traditional cementitious binders for stabilising problematic soft soils. This study investigates the potential of CS to improve the unconfined compressive strength of both expansive (Bentonite) and non-expansive (Kaolinite) clay samples. The gelling time results show that increasing CS concentration and the presence of NaCl significantly reduce gelation time, while bentonite–CS mixtures gel faster than kaolinite–CS mixtures due to higher surface activity and cation-exchange capacity. Laboratory experiments were conducted at 30% CS and 15% NaCl concentrations with two curing periods of 7 and 14 days to evaluate changes in unconfined compressive strength (UCS). Kaolinite exhibited approximately 50–55% increase in peak strength between 7 and 14 days of curing, while bentonite showed about 20–25% higher UCS than kaolinite under identical treatment conditions. The findings demonstrate that CS is an effective and environmentally friendly stabiliser that can improve both expansive and non-expansive clays, making it a promising alternative for sustainable ground improvement applications.

1 Introduction

The use of nanomaterials as a sustainable solution for ground improvement is gaining increasing attention nowadays. Unlike traditional stabilisers, nanomaterials have a particle size of 10^{-9}m, high surface reactivity, large surface area, and distinctive characteristics that distinguish them from traditional stabilisation materials[1]. Some of the nanomaterials used for ground improvement in recent times include carbon nanotubes, nano calcium carbonate (NCC), nano MgO, nano clays (NC), nano-SiO_2, and Colloidal silica (CS)[2].

Among various stabilisation materials, colloidal silica (CS) has emerged as a promising and environmentally sustainable binder for geotechnical applications, serving as a low-carbon alternative for ground improvement [3-5]. Colloidal silica (CS) consists of nanoscale silicon dioxide (SiO_2) particles uniformly dispersed in water, forming a stable suspension[6]. The material exhibits a very low viscosity (approximately 1 cP) and is non-toxic, which makes it particularly suitable for ground improvement techniques that require injection, such as permeation grouting[5, 7]. The addition of electrolytes, commonly sodium chloride (NaCl), destabilises the silica particles and initiates gelation. As a result, the initially fluid grout gradually evolves into a solidified silica gel after a predetermined gel time[1, 5, 8]. This controllable transition from liquid to gel enables CS to effectively enhance the mechanical properties and stability of soils.

Numerous laboratory studies have investigated the effects of colloidal silica (CS) grouting on the mechanical and hydraulic behaviour of sands [4]. These studies report that CS treatment can significantly enhance unconfined compressive strength (UCS), improve liquefaction resistance, increase shear strength, and reduce permeability [3-5, 9-11]. In sandy soils, the low-viscosity CS grout penetrates the pore spaces between particles and subsequently forms a gel network, thereby improving density and strength[10]. However, compared with sands, the application of CS for the stabilisation of fine-grained soils such as clays remains relatively less explored, particularly due to their lower permeability and different particle interactions[12].

Previous studies have investigated the use of silica-based additives for stabilising fine-grained soils such as loess and clays [12]. Significant improvements in strength have been reported, with some studies showing strength increases exceeding 500% after 28 days of curing, highlighting the strong influence of curing time on strength development [12-14]. Research on kaolin clay treated with colloidal silica has also indicated improvements in shear strength, although limited enhancement in cohesion was observed [5, 12]. The improvement is generally attributed to the formation of viscous gel bonds and to particle-dispersion mechanisms between soil particles and silica

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nanoparticles, rather than to purely chemical reactions[12, 14, 15].

Expansive soils like bentonite have a high swelling potential mainly due to their high specific surface area, weak van der Waals forces, and layered structure, which attract and trap water, leading to swelling [16, 17]. This results in a significant reduction in strength as the moisture content increases, due to particle dispersion, weaker van der Waals forces, and an expanding diffuse double-layer thickness [16, 18]. Similarly, the non-expansive kaolinite clay with high moisture content exhibits very low strength due to the lubrication effect between clay particles, which reduces friction and cohesion[19, 20]. Undrained shear strength values for both high moisture content (almost slurry-like consistency) bentonite and kaolinite range from 2 to 30 kPa, which is very low [21]. This results in a corresponding UCS value in the range of 4-60 kPa, depending on the soil structure and moisture content [22].

CS acts as a stabilising agent, unlike water, at high moisture levels due to its gelling property [5]. When CS is added to soil samples, it initially behaves as a liquid slurry that eventually hardens over time, depending on the gelling time of the specific mix used for treatment [5, 9, 23]. This gel binds the clay particles in the soil matrix, reducing their mobility and increasing interparticle bonding [5]. Increasing the strength, even at high moisture content, makes it more advantageous than other stabilisers

In addition, nano-silica used as a secondary additive has been shown to increase the unconfined compressive strength of cement-treated clays [24, 25]. Overall, these findings suggest that silica-based treatments can enhance the mechanical performance of clays, particularly at longer curing periods.

In this study, the gelling times of 30% CS with 15% NaCl for different clay samples (bentonite and kaolinite) and their effects on the UCS of 7-day- and 14-day-cured CS-stabilised samples were studied in detail.

2 Materials and methods

Two different clay samples, expansive (bentonite) and non-expansive (kaolinite), as shown in Fig.1, were used in this study.

The properties of clay are illustrated in Table 1. Oven-dried clay samples were used for testing. The CS solution used for this study was LUDOX® HS-30 (30% w/w) [26], and the electrolyte used was Sodium Chloride (99% NaCl).

The gelling time studies were conducted by combining CS and the electrolyte (NaCl solution) in a 5:1 ratio(by volume) [5] into a plastic centrifuge tube, and the gelling time was defined as the time taken by the mixture to stop flowing [5, 23]. Gelling time studies with CS gel, for 30% CS + 15%. For gelling time studies, 30%, 20% and 10% CS solutions were treated with 10% and 15% NaCl solutions. Fig.2 illustrates the completely gelled CS sample made with 30% CS and 15% NaCl. The tests were repeated with bentonite and kaolinite. The tests were conducted using plastic centrifuge tubes. 10g clay samples were placed inside the centrifuge tube, and 15ml CS gel was added onto the clay samples, mixed well, and left to gel. The time taken by the gel alone or the mixture of clay and gel to stop flowing was noted as the gelling time[23]. Fig.3 illustrates the gelling time tests for clay samples.

Fig. 1. Na-Bentonite (expansive clay)–(left) and Kaolinite (non-expansive clay)–(right).

Table 1. Clay specifications.

Properties	Kaolinite	Bentonite
Specific gravity	2.65	2.70
Liquid Limit (LL) (%)	71	430.2
Plastic Limit (PL) (%)	32	68
Plasticity index (PI) (%)	39	362.2
Unified Soil Classification System (USCS)	CL	CH

For the unconfined compressive strength (UCS) tests, cylindrical specimens were prepared using 3D-printed split moulds. Clay samples were placed into the moulds up to a height of 10 cm, after which 200 ml of CS grout was added and thoroughly mixed with the clay to ensure uniform distribution. The prepared specimens were then sealed in airtight containers and cured for 7 and 14 days prior to testing[5]. Due to bentonite's swelling behaviour, the cured samples expanded beyond the mould height; therefore, they were trimmed to a final height of 10 cm before UCS testing. The samples were tested according to Australian standards (AS 5101.4-2008)[27].

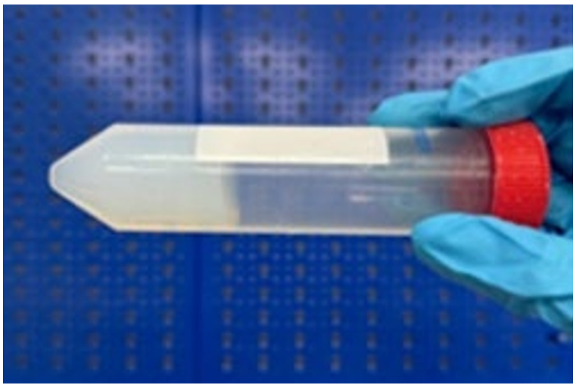


Fig. 2. Completely gelled 30% CS+ 15% NaCl sample.

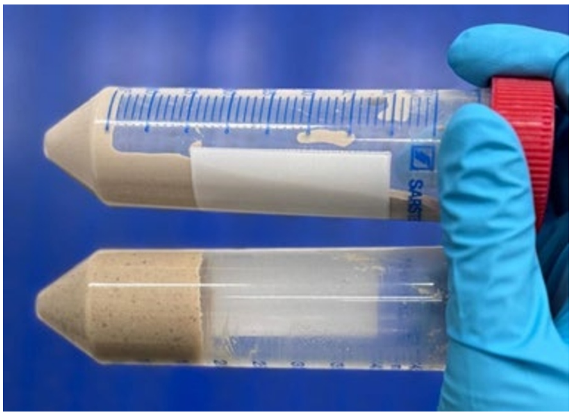


Fig. 3. Clay samples undergoing gelation with colloidal silica (30% CS + 15% NaCl) prepared at the same time: kaolinite (top) and bentonite (bottom).

3 Results and discussion

In this section, the gelling time and UCS test results are discussed in detail.

3.1 Gelling time results

The gelling time curves for CS gel alone and the CS gel and clay sample are illustrated in Fig.4.
For all samples, as the CS concentration increased, the gelling time decreased. At lower concentrations, gelation occurs over a longer duration due to a larger separation (electrostatic repulsive forces dominant) between silica particles, thereby reducing particle interactions and resulting in a delayed continuous gel network[6, 7, 9, 28]. The addition of NaCl reduces the double-layer thickness around the silica particles, further accelerating the interparticle interactions (Van der Waals attraction dominant force) and gelation[6, 7, 9]. As a result, the mixture with a higher NaCl concentration exhibits shorter gelling times[29].

Similar behaviour was also observed in clay and CS gel samples. At the same CS concentration, bentonite and CS gel samples gelled faster than kaolinite and CS gel samples. This can be attributed to the high surface area and cation-exchange capacity of bentonite, which result in faster inter-particle interactions between silica and dissolved ions[30]. This reduces the repulsive forces between the silica particles and increases the Van der Vaal attractive forces, resulting in more collisions between silica particles and quicker gelation [5, 28]. In contrast, kaolinite has a weaker surface charge, leading to weaker interactions and delayed gelation [30].

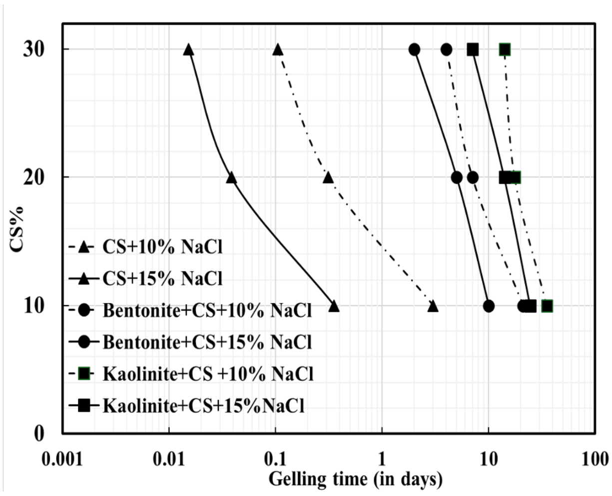


Fig. 4. Gelling time curve for CS gel alone and clay and CS gel samples.

The results indicate that both CS concentration and ions (from salt and clay samples) affect gelation kinetics, which is important for controlling injection time and gel formation in ground improvement activities.

3.2 Stress-displacement behaviour from UCS tests

The UCS stress-displacement graphs for CS-treated kaolinite and bentonite clay samples cured for 7 and 14 days are illustrated in Figs. 5 and 6, respectively. Both clays were treated with 30% CS and 15% NaCl.

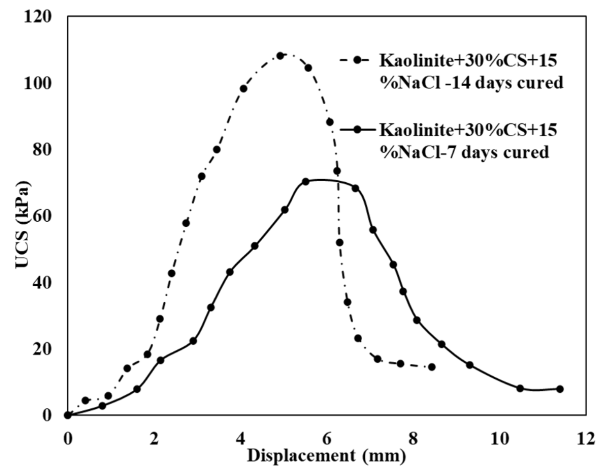


Fig. 5. Stress–displacement curves obtained from unconfined compressive strength (UCS) tests on kaolinite treated with 30% colloidal silica and 15% NaCl after 7 and 14 days of curing.

The UCS-displacement curve for CS-treated kaolinite samples represents an approximate 50-55% increase in peak strength as the curing period increased from 7 to 14 days. The specimen cured for 7 days achieved a peak UCS of ~74 kPa at a displacement of around 6 mm, whereas the 14-day-cured specimen exhibited a substantially higher peak strength of ~116 kPa at a lower displacement of around 4.5 mm. This reduction in displacement at peak strength represents that as curing time increased, the soil structure became stiffer and more brittle. Also, the post-peak response of 14 days cured CS stabilised kaolinite sample shows a sharper stress drop, indicating strain-softening associated with stronger interparticle bonding. A similar strain-softening behaviour was observed in other studies as well for nanomaterial-stabilised soil[2, 31].

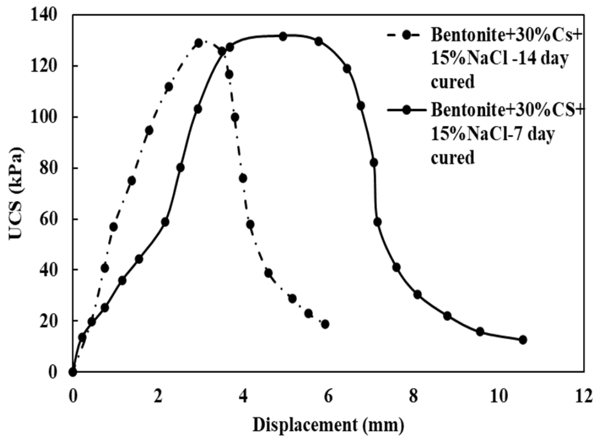
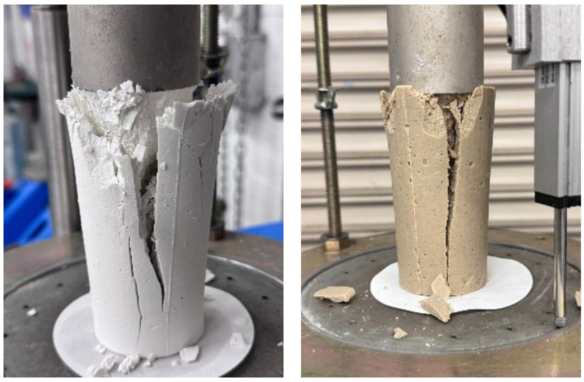


Fig. 6. Stress–displacement curves obtained from unconfined compressive strength (UCS) tests on bentonite treated with 30% colloidal silica and 15% NaCl after 7 and 14 days of curing.

On the other hand, the UCS-displacement curve for CS stabilized bentonite samples shows a different behaviour. The 7-day cured sample achieved a peak UCS of ~ 130 kPa at a displacement of 4.5 mm, while the 14-day cured sample exhibited a peak UCS of 125-130 kPa at a much lower displacement of 3 mm. Although the peak strengths were comparable, the 14-day specimen shows a slightly earlier peak and a steeper post-peak decline, indicating stiffer soil structure and brittleness with curing time. The 7-day cured sample exhibited a broader peak and a more gradual post-peak reduction, indicating more ductile behaviour than longer-cured samples.

The results indicate that bentonite exhibits higher UCS values than kaolinite under identical treatment conditions. The peak strength of CS treated bentonite is ~25% higher than that of treated kaolinite after 14 days of curing. Bentonite has a higher surface area and cation-exchange capacity, resulting in stronger interactions between colloidal silica particles. This difference highlights the importance of soil minerology and surface activity in determining the effectiveness of colloidal silica stabilisation. The failed sample images are shown in Fig.7.

Untreated clay samples were not tested directly for this study. From the literature review, we know that the UCS values of bentonite and kaolinite clays with high moisture content are less than 80 kPa, whereas UCS values of 116 and 130 kPa were obtained for 14-day-cured CS-treated kaolinite and bentonite clay, respectively.



(a) (b)

Fig. 7. Failed CS stabilised samples during UCS testing: (a) Kaolinite and (b) Bentonite.

Both CS stabilized kaolinite and bentonite depicted strain softening behaviour as the curing period increased. The stress–displacement curves for bentonite display a broader peak and more gradual post-peak softening than kaolinite, indicating a relatively more ductile response. Overall, the results indicate that CS stabilisation improves the compressive strength of both clays (expansive and non-expansive), and as curing time increases, strength increases and the samples exhibit a brittle failure response.

4 Conclusion

This study investigated the influence of colloidal silica (CS) concentration, NaCl content, and curing time on the gelation behaviour and strength characteristics of kaolinite and bentonite soils. Based on the experimental results, the following key findings were observed:

- The gelling time of colloidal silica decreases with increasing CS concentration. Higher concentrations reduce the double-layer thickness, thereby reducing repulsive forces and increasing the attractive forces between silica particles, enhancing particle interactions and promoting faster formation of a continuous silica gel network. The gelling time helps select the CS+NaCl combination for ground improvement, depending on the time required.
- The addition of NaCl significantly accelerates gelation by compressing the electrical double layer around silica particles, thereby reducing electrostatic repulsion and increasing attractive forces between particles.
- Clay mineralogy also influences gelation behaviour. Bentonite–CS mixtures exhibited faster gelation than kaolinite–CS mixtures, which is attributed to the higher specific surface area and cation-exchange capacity of bentonite that enhance interactions between silica particles and dissolved ions.
- The UCS results demonstrate that CS stabilisation improves the compressive strength of both kaolinite and bentonite soils. For kaolinite, increasing the curing period from 7 to 14 days resulted in an approximate 50–55% increase in peak strength, indicating progressive development of silica gel bonding within the soil matrix.

- The UCS results indicate that CS is good stabilizing agent for increasing the strength of expansive and non-expansive clays with high moisture content.
- Bentonite stabilised with CS exhibited higher UCS values than kaolinite under identical treatment conditions, with peak strengths approximately 25% greater after 14 days of curing. This behaviour highlights the importance of soil mineralogy and surface activity in determining the effectiveness of CS stabilisation.
- Increasing curing time resulted in stiffer soil structures and more brittle failure behaviour, as indicated by lower displacement at peak strength and sharper post-peak stress reduction.

Overall, the findings indicate that colloidal silica is an effective stabilisation method for both expansive and non-expansive clays, improving compressive strength while allowing control over gelation time. These characteristics make CS stabilisation a promising technique for ground improvement and grouting applications in clayey soils.

Further studies are required to investigate the influence of a wider range of colloidal silica concentrations on the behaviour of clayey soils. In addition, other important geotechnical properties such as shear strength, permeability, and long-term durability should be evaluated to better understand the overall effectiveness of colloidal silica stabilisation for ground improvement applications.

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