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Study on strength enhancement and reduction of PVA assited cement treated soil

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ABSTRACT: This study aims to develop cement treated soils that can be intentionally weakened to the required strength at the necessary time by incorporating polyvinyl alcohol (PVA) with thermoplastic properties. The goal is to reduce environmental impact during the dismantling and demolition of structures. In this study, cement treated soils were prepared using sand and clay as base materials, with varying amounts of PVA added. Their strength characteristics were examined through un-confined compression tests. Additionally, to simulate the removal process, the solidified samples were subjected to water immersion and heating, followed by un-confined compression tests to assess strength degradation.The results showed that cement treated soils with PVA exhibited greater strength compared to those without PVA. Up to a PVA solution concentration of 15%, higher concentrations led to greater strength enhancement. This increase in strength was more pronounced in sand-based cement treated soils. However, at a PVA concentration of 20%, the strength decreased compared to the 15% solution, suggesting a limit to strength enhancement. Furthermore, the initial slope of the stress-strain curve remained nearly unchanged with PVA addition, while the fracture strain increased, indicating improved ductility and toughness.In cases where un-confined compression tests were conducted after water immersion and heating, a noticeable decrease in strength was observed compared to samples without this treatment. The strength after water immersion and heating decreased to the same level as or lower than that of cement treated soils without PVA. The extent of strength reduction was greater at higher water temperatures and with longer immersion durations under the same conditions.These findings suggest the feasibility of cement treated soils that can be weakened by heating in groundwater at the necessary timing, making removal easier when needed.

KEYWORDS:Polyvinyl Alcohol, instructions.cement treated soils, un-confined compression strength, thermoplastic.

1 INTRODUCTION

Various ground improvement methods exist for different applications, such as the deep mixing method and chemical grouting. Although the deep mixing method is cost-effective and has been widely applied, it uses cement, which can lead to the leaching of hexavalent chromium, raising environmental concerns. On the other hand, challenges with the chemical grouting method include its high cost and limited applicability to certain ground types. As the properties of the improved ground differ from those of the original ground, the improved ground is likely to be treated as "waste" during structural renewal. Therefore, the authors have been working on the development of a new ground improvement material aimed at reducing the environmental impact during the removal and demolition of structures. This study focuses on polyvinyl alcohol (hereinafter referred to as PVA), which is characterized by its high hydrophilicity and solubility in warm water.

PVA is a synthetic resin produced by the hydrolysis of polyvinyl acetate, a polymer of vinyl acetate, and is used in everyday products like laundry starch. The properties of PVA vary depending on its degree of polymerization and degree of saponification. The degree of polymerization refers to the number of linked vinyl acetate molecules, while the degree of saponification indicates the proportion of hydroxyl groups relative to the total number of acetyl and hydroxyl groups in the PVA. The degree of polymerization affects the viscosity of the aqueous solution and the film strength, with higher degrees resulting in greater viscosity and strength. The degree of saponification, on the other hand, influences cross-linking formation and water resistance (Saki et al., 2019; Japan VAM & POVAL Co., Ltd.,). Fully saponified PVA, with a saponification degree of 98% or higher, is reported to have a strength-enhancing effect (Toshihiro et al., 2022). Therefore, its use as an admixture in cement-treated soil is expected to increase strength. Furthermore, due to its property of dissolving only in warm water, it is anticipated that the strength of the solidified ground can be reduced by immersion in warm water, facilitating easier removal and demolition during structural renewal.

In this research, cement-treated soil specimens were prepared with varying amounts of fully saponified PVA, and their strength enhancement characteristics were investigated using unconfined compression tests. Additionally, to simulate the removal of improved ground associated with structural renewal, the solidified cement-treated soil was immersed in and heated with water to confirm whether a reduction in strength occurred. This paper reports on these findings.

2 EXPERIMENTAL METHOD

Specimens were prepared by mixing a sample soil with cement and PVA. After being cured in air for 28 days in a constant-temperature room, an unconfined compression test was performed to investigate the strength enhancement characteristics. Additionally, some specimens were heated while immersed in water before the unconfined compression test to confirm whether a reduction in strength occurred. The experimental conditions are summarized in Table 1.

Two types of soil were used for the specimens: Mizunami silica sand No. 7 as the sand sample (specific gravity G s =2.642, minimum dry density ρ_{dmin} =1.202 Mg/m^3, maximum dry density ρ_{dmax} =1.591 Mg/m^3, mean particle size D_{50} =0.19 mm, and uniformity coefficient U_c =2.2), and Kibushi clay as the clay sample (specific gravity Gs =2.659, liquid limit w_L =45.0 %, plastic limit w_P =19.3 %, and plasticity index I_p =25.7). Ordinary Portland cement was used. The PVA used was a fully saponified type (product name: JF-17) in powder form, with a degree of polymerization of 1700 and a degree of saponification of 98.0–99.0 %.The specimens, measuring 50 mm in diameter and 100 mm in height, were prepared with reference to JGS 0821 (Method for Making Cement-Treated Soil Specimens for Unconfined Compression Tests). The mix proportions for the specimens are shown in Table 1. The water content for the sand sample was 14.3 %, which corresponds to the optimum water content (w_{opt}) of Mizunami silica sand No. 7. The water content

Table 1. Experimental Conditions.

Test Case	Sample soil		Water content (%)		Cement content (kg/m³)		PVA Solution concentration (%)					Water immersion heating conditions							
												Not	50°C	60°C	70°C			80°C	90°C
	Sand	Clay	14.3	66.7	75	100	Not	5	10	15	20		1h	1h	1h	2h	3h	1h	1h
Sand only	○		○		○		○					○							○
Sand-5%	○		○		○			○				○							○
Sand-10%	○		○		○				○			○			○	○	○		○
Sand-15%	○		○		○					○		○							○
Sand-20%	○		○		○						○	○							○
Clay only		○		○		○	○					○							○
Clay-5%		○		○		○		○				○							○
Clay-10%		○		○		○			○			○	○	○	○			○	○
Clay-15%		○		○		○				○		○							○

for the clay sample was 66.7 %, which is 1.5 times the liquid limit (w_L) of Kibushi clay. The cement content was set to 75 kg/m^3 for the sand samples and 100 kg/m^3 for the clay samples. The specimen preparation was conducted using the following procedure.

First, a PVA solution was prepared in advance. Granular PVA was added to tap water to achieve the prescribed concentration. This mixture was then heated in a water bath to approximately 80 °C for about one hour while being stirred with a mixer to create the PVA solution. The solution was subsequently stored in a constant-temperature room at 20 °C until it was time for specimen preparation.

Next, the soil mixture was created. The specified amounts of sample soil and cement were blended in a soil mixer for one minute. The prepared PVA solution was then added, and the entire mixture was blended for a total of five minutes. The five-minute mixing sequence was composed of two minutes of mechanical mixing, one minute of manual kneading, and a final two minutes of mechanical mixing. However, for the high-concentration sand mixture (Sand-20 %), which was difficult to blend, an additional one minute of manual kneading and two minutes of mechanical mixing were performed.

Finally, the mixture was placed into a plastic mold in three layers. Compaction was achieved by tamping with a rod for the sand specimens, and by tapping the mold and its sides for the clay specimens. After filling, the top of the mold was covered with plastic wrap, and the specimens were air-cured in a constant-temperature room at 20 °C.

After 27 days of curing, the specimen was demolded and the top surface of each specimen was trimmed flat with a straight knife. The specimens were then wrapped in plastic wrap and cured for an additional day in the constant-temperature room before being subjected to the unconfined compression test at an age of 28 days. For the specimens designated for immersion heating, they were placed in a water bath at a specified temperature for a prescribed duration. Subsequently, they were allowed to cool to room temperature, and their surfaces were wiped dry before the unconfined compression test was performed. The unconfined compression test was carried out in accordance with JIS A 1216.

The immersion heating conditions for all cases were set to 90°C for 1 hour. Furthermore, to investigate the influence of immersion temperature and duration on strength reduction, additional conditions were established. For the Sand-10% specimens, conditions were added in which the immersion duration was varied from 1 to 3 hours at 70 °C. For the Clay-10% specimens, conditions were added with temperatures ranging from 50 °C to 80 °C in 10 °C increments. The immersion duration for all of these latter conditions was 1 hour.

3 EXPERIMENTAL RESULTS

3.1 *Strength Enhancement with PVA*

To investigate the strength increase caused by the addition of PVA, the stress-strain curves for specimens tested under unconfined compression without prior immersion heating are presented in Figures 1 and 2. Furthermore, Figure 3 shows the relationship between the unconfined compressive strength (q_u) and the PVA solution concentration, and Figure 4 shows the relationship between the failure strain (ε_f) and the PVA solution concentration.

From Figures 1 and 3, a strength increase due to the addition of PVA is observed in the sand samples. For example, at a 15 % concentration, an average unconfined compressive strength ($q_{u,ave.}$) of 1684 kPa was obtained, which is 3.8 times the strength of the specimens without PVA ($q_{u,ave.}$ = 446 kPa). It is also apparent that a higher PVA solution concentration leads to a greater strengthening effect. However, the strength at a 20 % concentration was lower than at 10 % and 15 %, suggesting that there may be a limit to the strength-enhancing effect. As the PVA solution concentration increased, the soil mixture became fluffy and tended to form lumps, making it difficult to fill the plastic molds. During compaction, the mixture also adhered to the tamping rod, hindering the process. The dry density of the specimens was also lower at higher concentrations. Additionally, the quality of the specimens was poor, as they were non-homogeneous and contained residual air voids. These factors may have influenced the effectiveness of the strength enhancement. As shown in Figures 2 and 3, a strength increase is also observed in the clay samples, but the effect is less pronounced compared to the sand samples. At a 15 % concentration, the strength ($q_{u,ave.}$ = 626 kPa) was approximately 1.9 times that of the samples without PVA ($q_{u,ave.}$ = 323 kPa). This strength increase ratio is half of that observed for the sand samples, and at a 5% concentration, there was almost no increase in strength.

Regarding the failure strain, Figures 1, 2, and 4 confirm that it increases with the PVA concentration. In particular, the Clay-15 % sample in Figure 2 exhibits ductile failure behavior, showing no peak in its stress-strain curve. A characteristic feature of the stress-strain curves is that the initial modulus does not change significantly, while the failure strain becomes larger. This suggests that the addition of PVA may not only increase strength but also impart toughness without significantly altering the deformation modulus.

3.2 *Strength Reduction by Immersion Heating*

As an example of the results for specimens immersed in 90 °C water for 1 hour, the stress-strain curves for the 10 % concentration case are presented in Figures 5 and 6. For comparison, the results for specimens tested without immersion

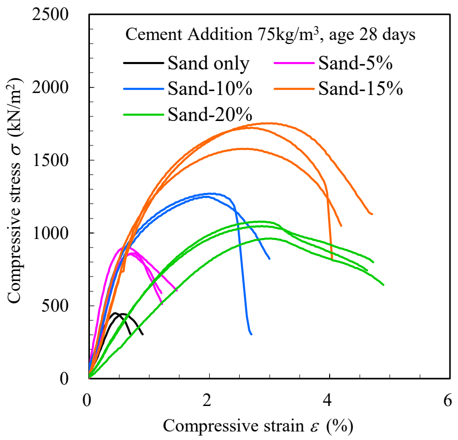

Figure 1. Stress-Strain curves (sand).

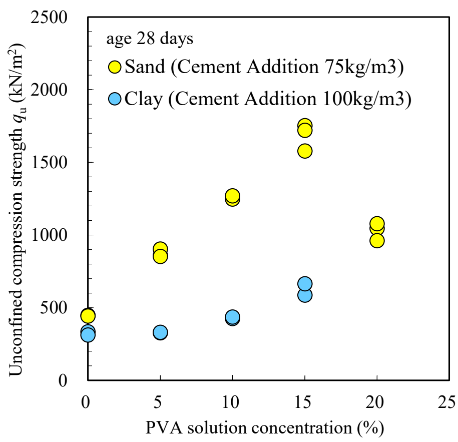

Figure 3. Effect of PVA concentration on q_u.

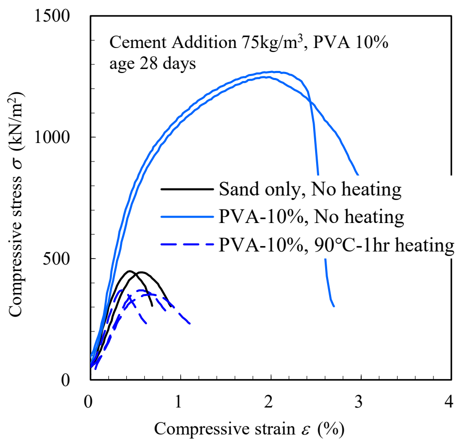

Figure 5. Stress-Strain curves (sand, with heating).

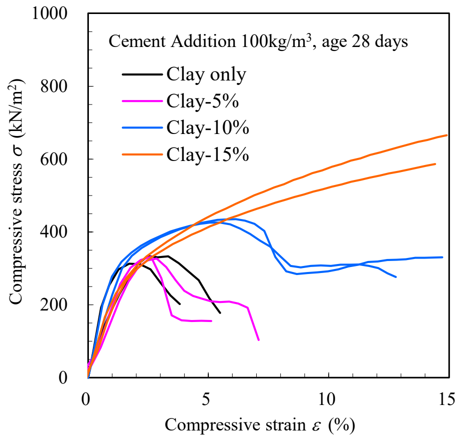

Figure 2. Stress-Strain curves (clay).

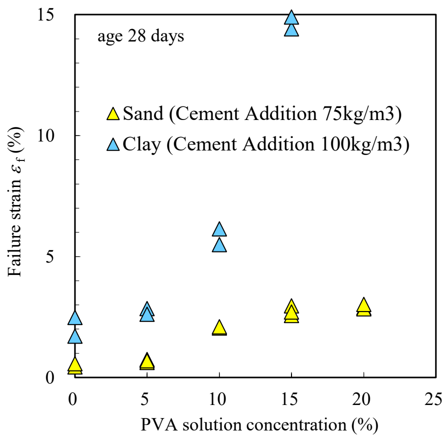

Figure 4. Effect of PVA concentration on ε_f.

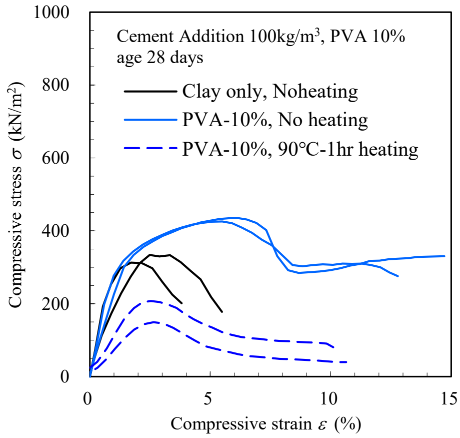

Figure 6. Stress-Strain curves (clay, with heating).

heating and those without PVA are also shown. For both sample types, immersion heating reduced the strength to a level below that of the PVA-free specimens. The failure strain also became comparable to the PVA-free case, suggesting that the properties imparted by the PVA were eliminated by the immersion heating.

The strength reduction caused by immersion heating is detailed in Figures 7 and 8, while the corresponding changes in failure strain are shown in Figures 9 and 10. As seen in Figures 7 and 8, the strength of all treated specimens decreased to a level comparable to or lower than that of the specimens without PVA. For the sand samples (Figure 7), a higher PVA concentration resulted in a lower post-immersion strength, with the degree of strength reduction being more pronounced up to a 15% concentration. This suggests that in addition to the PVA dissolving, the soil structure itself may have been damaged. As mentioned in Section 3.1, higher PVA concentrations produced non-homogeneous specimens. It is believed that the formation of weak zones in these specimens led to greater damage during immersion heating.

In the clay samples (Figure 8), although strength was also reduced by immersion heating, the extent of this reduction was smaller than in the sand samples. Furthermore the relationship between strength reduction and PVA concentration was not clear. In this study, the PVA solution concentration was varied while the total water content of the mixture (i.e. mass ratio of PVA solution to cement mass) was kept constant. Therefore, a change in solution concentration altered not only the amount of PVA added but also the quantity of water. Since the clay samples have a much higher water content than the sand samples, this variation in water quantity was more significant.

Regarding the change in failure strain after immersion heating, for sand samples up to a 15% concentration and clay samples up to a 10% concentration, the failure strain decreased to a level nearly identical to that of the specimens without PVA. Although the failure strains for the Sand-20% and Clay-15% samples also decreased, they remained higher than those of their PVA-free counterparts, suggesting that some of the PVA's properties may have persisted in these cases.

3.3 *Effect of Immersion Temperature and Duration on Strength*

The results of the unconfined compression tests for the Sand-10% and Clay-10% samples, conducted with varied immersion temperatures and durations, are presented in Figures 11 and 12. The vertical axis represents the ratio of the unconfined compressive strength after immersion heating (q_{uh}) to the strength without heating (q_u). From these figures, it is evident that strength decreases as the water temperature rises. For instance, immersion at 90 °C for 1 hour reduced the strength to 40% of its original value, while immersion at 70 °C for 1 hour reduced it to approximately 60 % or less. The effect of immersion duration is not as distinct, but a comparison of the results for 1 hour and 3 hours at 70 °C in Figure 11 suggests that a longer immersion time leads to a greater reduction in strength.

The results above suggest that it may be possible to reduce the strength of the ground to a desired level at a specific time by controlling the water temperature and immersion duration. Considering on-site applicability and workability, heating at a lower temperature for the shortest time possible is preferable. The feasibility of this method was suggested by the confirmation that strength could be reduced without using boild water.

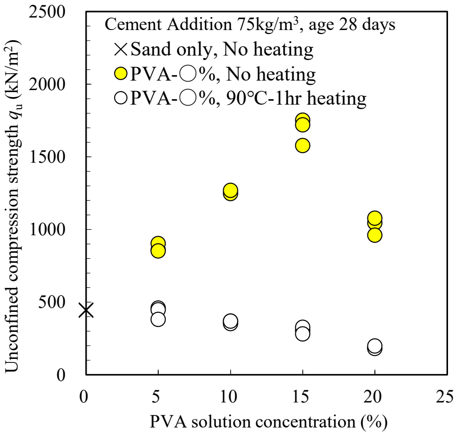

Figure 7. Stress reduction with heating (sand).

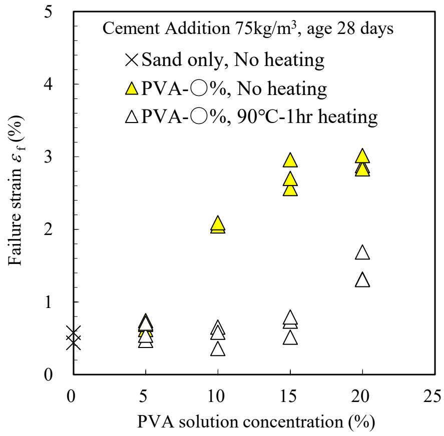

Figure 9. ε_f changing with heating (sand).

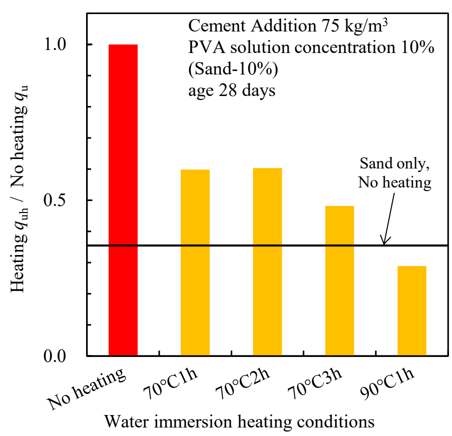

Figure 11. Effect of heating condition on q_u (sand).

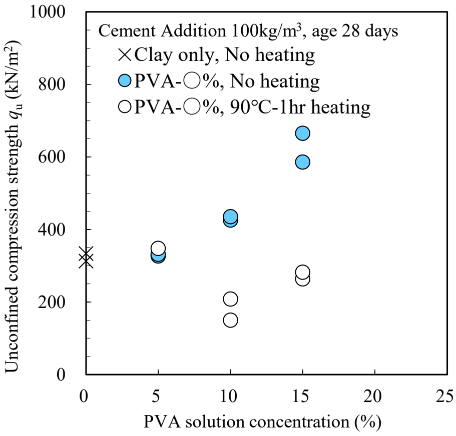

Figure 8. Stress reduction with heating (clay).

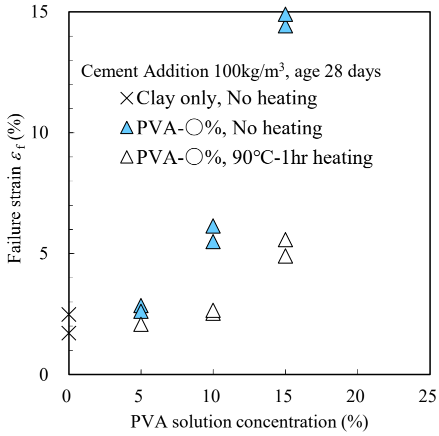

Figure 10. ε_f changing with heating (clay).

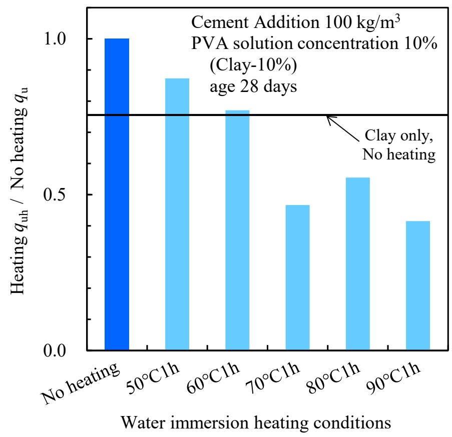

Figure 12. Effect of heating condition on q_u (clay).

4 CONCLUSIONS

Cement-treated soil specimens were prepared with varying amounts of PVA to investigate their strength enhancement characteristics using unconfined compression tests. Moreover to simulate the removal of improved ground during structural renewal, the solidified specimens were subjected to immersion heating to confirm any resulting strength reduction. The main findings are as follows:

- The addition of PVA was confirmed to increase strength. Up to a PVA solution concentration of 15%, a higher concentration led to a greater increase in strength.
- The rate of strength increase due to PVA addition was greater for the sand samples than for the clay samples. When compared at a 15% concentration, the strength increase was 3.8-fold for sand, versus 1.9-fold for clay.
- The addition of PVA increased the failure strain without significantly changing the initial modulus of the stress-strain curve, suggesting that toughness was enhanced.
- Immersion heating after solidification was found to reduce the strength to a level comparable to or lower than that of the specimens without PVA. For the sand samples, the degree of strength reduction increased with concentration up to the 15% level. While the clay samples also showed a reduction in strength, the effect was smaller than in the sand samples, and the relationship between strength reduction and PVA concentration was not clear.
- Immersion heating also changed the failure strain, reducing it to the level of the PVA-free specimens in all cases except for the Sand-20% and Clay-15% samples.
- Regarding the immersion heating conditions, higher water temperatures resulted in greater strength reduction. For a given temperature, a longer immersion duration also led to a greater reduction in strength.

In summary, it was demonstrated that the addition of PVA can increase the strength and failure strain of cement-treated soil, while subsequent immersion heating can reverse these effects, reducing the strength to below its original (PVA-free) level and returning the failure strain to its original value. This indicates that the properties imparted by PVA can be effectively eliminated. These findings suggest the potential to control the ground strength as needed over time, showing promise for the method's on-site application.

The hypothesized mechanism for the change in the physical properties of the improved soil caused by this immersion heating is that the elution of PVA destroyed the inter-particle bridging structures that were originally formed by the polymer. However, observations via electron microscopy, which were conducted to elucidate this mechanism, could not provide conclusive evidence for this hypothesis.

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