The 2023 World Congress on
Advances in Structural Engineering and Mechanics (ASEM23)
GECE, Seoul, Korea, August 16-18, 2023

Preliminary study of sand-clay mixture strength improvement using crosslinked-induced biopolymer as binder

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ABSTRACT

Recently, extensive research on the soil-strengthening characteristics of biopolymers was conducted owing to the rising need for both eco-friendly and resilient construction materials. A polysaccharide xanthan gum (XG) has improved soil strength by forming a rigid matrix around coarse and fine soil particles. However, when the XG matrix is exposed to water, the hydrophilic biofilm rehydrates and becomes loose from the soil particles, causing a significant drop in strength. Previous work treated trivalent chromium ions (Cr^{3+}) in the XG hydrogel as a crosslinking agent to improve the strength of sand. To improve weathered surface soil layer, this study extends to measure the unconfined compressive strength (UCS) of sand-clay mixtures with different fine contents by treating them with Cr^{3+} crosslinked XG (CrXG) hydrogel in hydrated state. The overall strength increased in the initial stage due to the time effect of the gelation due to the cross-linkage between XG and Cr^{3+}. Noticeably, UCS decreases as the fine contents increases throughout the curing time which indicates a sufficient pore space is needed for the CrXG hydrogel gelation. Therefore, the possible application of the soil strengthening by CrXG treatment as an environmental grout material was shown which is governed by the gelation time, fine content, and exposed state.

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1. INTRODUCTION

Biopolymer-based soil treatment (BPST) has recently gained significant attention as a soil binding method to replace the conventional greenhouse gases emitting cement-based soil treatment. Previous studies conducted soil modification using various biopolymers' and showed that a small amount of biopolymer can achieve the desired engineering properties. Among them, a polysaccharide biopolymer xanthan gum has proved its soil modification properties alongside with convenience of preparing XG hydrogel at room temperature. Laboratory experiments were conducted to examine soil strengthening, soil permeability control, shear resistance, and erosion reduction of XG-treated soil; also, field-scale application of XG on levee reinforcement has been performed to be successful (Seo et al., 2021).

Even though xanthan-treated soil has demonstrated its conveniences of soil modification and potential strength, several drawbacks appear to be resolved. Drying or curing of XG-treated soil must precede to treat the given soil to facilitate a strong bonding between soil particles and XG hydrogel. However, cured XG-treated soil exhibits a significant drop in strength in submerged and hydrated states and disintegration of shape (Bagheri et al., 2023). This is due to the rehydration swelling of hydrophilic xanthan gum, and the attached hydrogel falls apart and loses its engineering properties. A stable and durable hydrated strength XG-based soil treatment must be established for a practicable application.

Therefore, trivalent cations, such as Fe^{3+}, Al^{3+}, and Cr^{3+}, were utilized to promote the gelation of XG hydrogel but have limited research on soil treatment and its ecological impact. Moreover, weathered soil layer mostly covers Korea's geography, experiments of soil with fine particles is needed. A cross-linkage XG hydrogel using a Cr^{3+} was proposed, demonstrating its compatible hydrated strength in both the gel and soil-treated state (Lee et al., 2023). However, compared to the dehydration and curing process of XG-treated soil, crosslink-induced XG treatment exhibits a time-dependent strength development as cement-based material. Therefore, this study examined the unconfined compressive strength of a CrXG-treated sand-clay mixture. In addition, the hyperbolic trend of strength development based on the curing time was quantified to propose an ultimate compressive strength.

2. MATERIALS AND METHOD

2.1 Materials

2.1.1 Biopolymer: Xanthan gum (XG)

XG, an ionic polysaccharide derived from the bacteria Xanthomonas campestris, was used as a soil-binding agent. XG possesses side chains of two mannose molecules and one glucuronic acid molecule, forming a viscous pseudo-elastic hydrogel when dissolved in water. Due to this characteristic, XG has been used in various fields, such as the food, cosmetics, and petroleum industries (Garcıa-Ochoa et al., 2000). Recently, reports of XG treatment on soil showed soil strengthening and its potential application (Chang et al., 2015). Research-graded XG powder (CAS: 11138-66-2; Sigma-Aldrich) was used throughout the experiment.

2.1.2 Crosslinking agent: Chromium nitrate nonahydrate

Cr^{3+} was used as a cross-linkage agent since it is the most stable state compared to other oxidate states of chromium, the most commonly naturally existing form, and less toxic to humans and the environment. The crosslinked XG and Cr^{3+} gel (CrXG) was induced by forming a dimeric or polymeric ionic bridge (Nolte et al., 1992). This study used research-graded chromium nitrate nonahydrate ($Cr(NO_3)_3 \cdot 9H_2O$, 99%, Daejung Chemical Co.) as the source of Cr^{3+} as an aqueous solution.

2.1.3 Sand-Clay mixture

Sand-clay mixtures with different fine contents (fine contents 0%, 5%, 10%, 15%, 20%, and 30%) were used throughout the experiment. Standardized Jumunjin sand was used as the coarse soil for the experiment. Jumunjin sand can be classified as poorly graded sand (SP) according to the USCS classification system. Engineering properties of Jumunjin sand are summarized in Table 1. Bintang Kaolin, a highly plasticity clay (CH) according to USCS, was used for the fine soil with engineering properties of listed in Table 2. All sand and clay were oven-dried before specimen preparation and mixed with the desired fine contents.

Table. 1 Engineering properties of Jumunjin sand

$USCS$	$\boldsymbol{D_{50}}$	$\boldsymbol{C_u}$	$\boldsymbol{C_c}$	$\boldsymbol{G_s}$	$\boldsymbol{e_{min}}$	$\boldsymbol{e_{max}}$
SP	0.5 mm	1.63	1.08	2.65	0.64	0.95

Table. 2 Engineering properties of Bintang Kaolin

$USCS$	PL	LL	SSA
CH	24%	70%	$22\ m^2/g$

2.2 Experiment method

2.2.1 Sample preparation of CrXG-treated sand-clay mixture

In this study, the samples were prepared into three stages; XG hydrogel mixing, CrXG hydrogel crosslinking, and soil treatment with CrXG. First, the pure XG hydrogel was mixed with a ratio of 5% of XG/m_w (where XG/m_w is the mass ratio between XG mass to water mass) with deionized water. The dried XG powder was thoroughly mixed using a laboratory hand blender to reach a fully hydrated hydrogel. Second, to crosslink the CrXG hydrogel, the Cr^{3+} solution was prepared with the mass ratio of 30% of Cr/XG (where Cr/XG is the mass ratio between $Cr(NO_3)_3 \cdot 9H_2O$ mass to XG mass). Additionally, 10% of the XG mass of NaCl was added to the Cr^{3+} solution as a surfactant to promote binding between XG and Cr^{3+} by restraining XG molecules from attraction (Bueno et al., 2013). Cr^{3+}, NaCl, and deionized water were stirred for 5 min using a magnetic stirrer under moderated speed and combined with the XG hydrogel to achieve the desired CrXG hydrogel with the laboratory hand blender was operated at high speed for 30 s. Finally, the CrXG hydrogel was treated with the desired sand-clay mixture with a ratio of 1% XG/m_s (where XG/m_s is the mass ratio between XG mass to soil mixture mass) with the initial water content (w) of 20%. CrXG-treated soil samples were molded in a cubic shape of 40 mm x 40 mm x 40 mm and cured, preventing water evaporation until desired curing time as shown in Table 3.

Table. 3 Sample conditions and experimental program

Fine contents [%]	0, 5, 10, 15, 20, 30
Curing time [hr]	1, 24, 48, 168

2.2.2 Unconfined compressive strength test

Uniaxial unconfined compressive strength (UCS) tests were performed to evaluate the compressive strength of the CrXG-treated sand-clay mixture. Using a universal testing machine (HM-5030.3F) in Figure 1, a uniform strain rate of 1%/min (0.4mm/min) was given until a 15% strain rate based on the ASTM D2166 (ASTM, 2016). The UCS of soil samples with each fine content at desired curing time of 1 hr, 1 d, 2 d, and 7 d were measured.

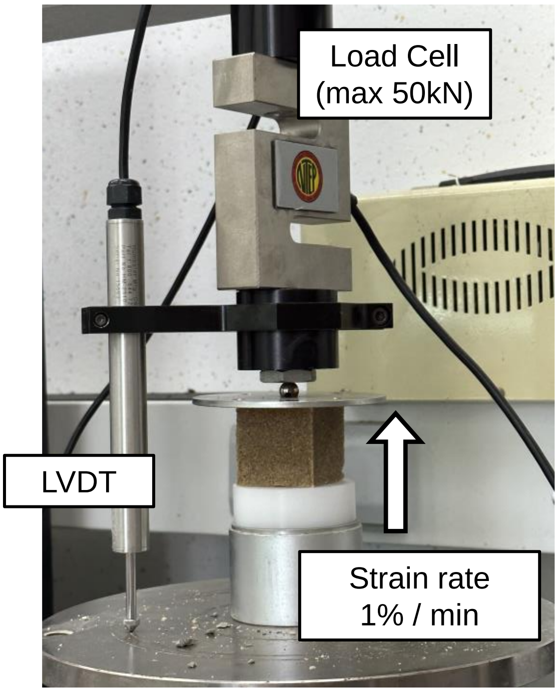

Fig. 1 Unconfined compressive strength apparatus

3. EXPERIMENTAL RESULTS

3.1 Stress-strain behavior of CrXG-treated sand-clay mixture

The stress-strain curves for the CrXG-treated sand-clay mixture cured for one day with respect to each fine contents are plotted in Figure 2. The peak UCS decreases as the fine content increases with the increase of the strain at failure. A stiffer behavior at 0% fine content with a rapid decrease in post-peak stress can be seen as owing to the larger pore size for gelation to occur compared to those with fines.

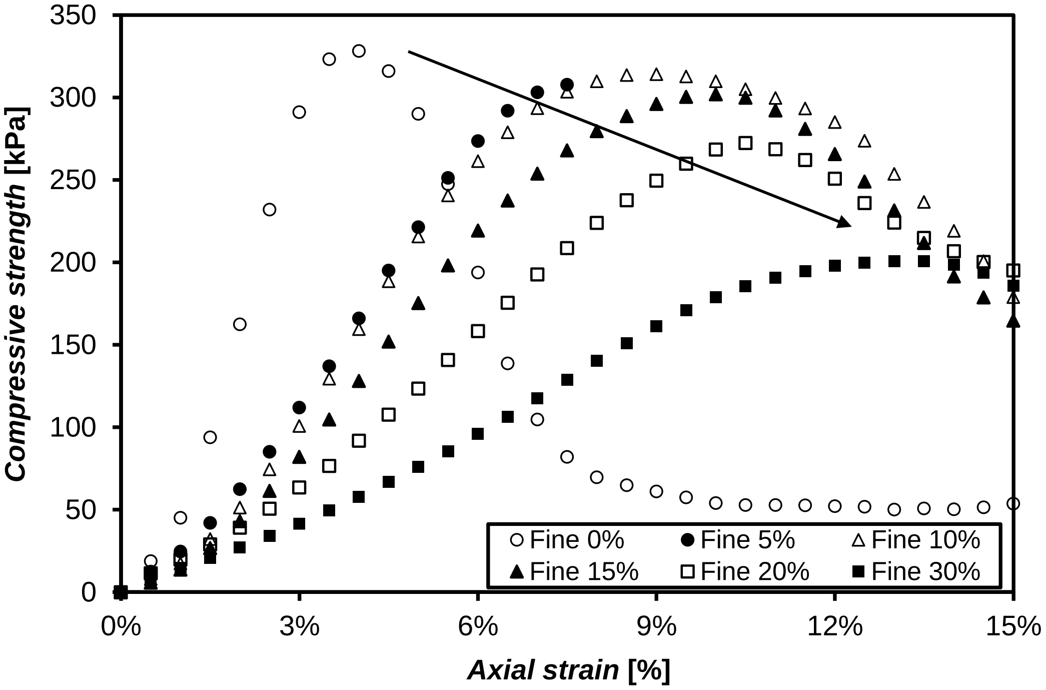

Fig. 2 Stress-strain curve of CrXG-treated sand-clay mixture after 1 day of curing

3.2 Time dependent strength development of CrXG-treated sand-clay mixture

The curing time-dependent UCS values are presented in Figure 3. The nonlinear strength development fits the hyperbolic trend line used to estimate the ultimate strength of cemented sand (Yoon et al., 2020). The estimated ultimate UCS value for each fine contents is the greatest at 0% and decreases as the fine contents increase. This can also be seen as the decrease in pore space for the gelation to occur with the increase in fine contents filling the pore space even with the same XG/m_s ratio.

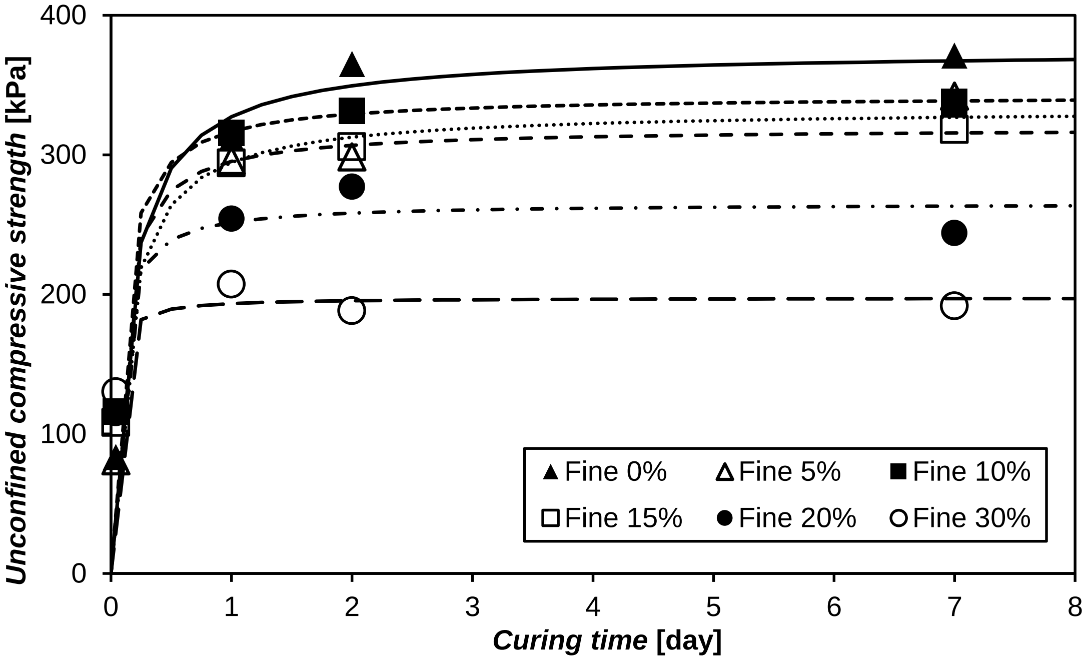

Fig. 3 UCS of CrXG-treated sand-clay mixture by curing time with hyperbolic trend line

4. CONCLUSIONS

This study examined the development of the compressive strength of CrXG-treated soil with different fine contents and curing times. The stress-strain relationship for each fine contents case shows that adding a fine exhibits more ductile behavior. Moreover, as the curing time increases, the compressive strength increases owing to the cross-linkage gelation of XG and Cr^{3+} in a hyperbolic shape. Additional research should be conducted using microscopic images to grasp the CrXG hydrogel interaction with the sand-clay mixture. In sum, even in a hydrated state, the CrXG-treated soil maintained its compressive strength, which can be later applied as ecofriendly grout materials for underground structures.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (2023R1A2C300559611).

This work is financially supported by Korea Ministry of Land, Infrastructure and Transport(MOLIT) as 「Innovative Talent Education Program for Smart City」

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