

## Bovine casein as a new soil strengthening binder from dairy wastes



Ilhan Chang<sup>a</sup>, Jooyoung Im<sup>b</sup>, Moon-Kyung Chung<sup>c</sup>, Gye-Chun Cho<sup>b,\*</sup>

<sup>a</sup> School of Engineering and Information Technology (SEIT), University of New South Wales (UNSW), Canberra, ACT 2600, Australia

<sup>b</sup> Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Republic of Korea

<sup>c</sup> Geotechnical Engineering Research Institute, Korea Institute of Civil Engineering and Building Technology (KICT), Goyang 10223, Republic of Korea

### HIGHLIGHTS

- Bovine casein is introduced as a new soil strengthening binder in this study.
- Casein-soil mixtures show sufficient wet strength after saturation.
- Wet UCS shows 480–750 kPa for casein-treated soils.
- Utilization of casein binders can contribute to reducing dairy and milk wastes.
- Casein treatment can be used to enhance erosion resistance of earthen levees.

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### ABSTRACT

Approximately one-third of the edible parts of food is lost or wasted globally. For milk, 18.1% of its annual production is lost or wasted due to insufficient storage, logistics, and freshness (expiration date) issues. Presently, the most common method of managing waste milk is disposing large volumes of waste milk into landfills, which raises concerns on groundwater pollution and local ecosystem disturbance. Casein is a protein-type biopolymer that consists of approximately 24.4 kg from 1 ton of bovine milk. In this study, casein is introduced as a new binder for soil strengthening in geotechnical engineering and dairy waste management purposes. Bovine casein is provided in a solution state for proper mixing with soil. Casein-soil mixtures with different casein contents are prepared to evaluate unconfined compressive strengths at both dried and re-submerged conditions. Experimental results show significant soil strengthening induced by casein treatment even after 24 h of re-wetting, which implies the potential of applying casein-soil mixtures for water-resisting purposes. Feasibility analyses for casein utilization from dairy and milk wastes are provided with socio-, environmental, and engineering aspects, showing both future opportunities and challenges of recycling casein as a soil binder in engineering practices.

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## 1. Introduction

Recent studies have shown that soil improvement and strengthening techniques based on biological processes or accompanying materials can provide considerable strengthening and efficiencies [1–4]. The search for soil binders that can be derived from biological origins is primarily being driven by the need for more sustainable and eco-friendly soil improvement practices. As a result of growing environmental concerns, the establishment of sustainable materials and practices is very important to future societies [5]. Therefore, environmentally friendly approaches, such as the use of biological materials, are being intensively studied in order to

develop a natural and sustainable method of soil improvement that is capable of being used as an alternative material for cement [6–8].

Biological materials have numerous environmental and practical advantages when used for soil improvement, including low emissions of greenhouse gases [9,10], reduction in erosion [11], improvements in soil strength [12,13], aquatic suspension stabilization [14], and aseismic purposes [15]. Among such biological materials, the use of biopolymers has been shown to have substantial strengthening effects on the soil [3,16–18] and potential to be used for combat desertification purposes [11,19]. Moreover, the use of *exo*-cultured biopolymers for soil treatment have advances in quality control and engineering performance assurance, while *endo*-culture (e.g., Microbial Induced Calcite Precipitation) methods accompany uncertainty concerns depending on the culture environment (e.g., temperature, nutrient, pH) in soil [3].

\* Corresponding author.

E-mail addresses: [ilhan.chang@unsw.edu.au](mailto:ilhan.chang@unsw.edu.au) (I. Chang), [jooyoungim@kaist.ac.kr](mailto:jooyoungim@kaist.ac.kr) (J. Im), [mkchung@kict.re.kr](mailto:mkchung@kict.re.kr) (M.-K. Chung), [gyechun@kaist.edu](mailto:gyechun@kaist.edu) (G.-C. Cho).

Biopolymers are polymer materials that consist of bio-based raw materials and/or are biodegradable [20]. In general, biopolymers can be classified into three major groups: 1) nucleic acids and nucleotides, 2) proteins and amino acids, and 3) carbohydrates (e.g. polysaccharides) [21–23]. Most biopolymers developed in previous studies are composed of polysaccharides. Polysaccharides such as cellulose, chitosan, beta-glucan ( $\beta$ -1,3/1,6-glucan), xanthan gum, and gellan gum have been studied and demonstrated in various applications for geotechnical engineering practices and show promise to become eco-friendly soil binders in the sustainability aspects [8,24–27]. In particular, microbial polysaccharides such as beta-glucan [16,26] and xanthan gum [8,13] have shown significant strengthening efficiency in soils. The compressive strengths of beta-glucan treated soils were comparable to soils treated with 10% cement, when the beta-glucan concentrations were only 0.25% of the soil mass [16]. The use of polyacrylamide (PAM) has also been shown to reduce the erosion properties of the soil and to be suitable for use in agriculture, construction, and military applications [28].

However, the surface charge (mostly anionic) characteristic of polysaccharides that induces remarkable soil strengthening also accompanies hydrophilicity of polysaccharides, and this paradoxically shows that the soil strengthening effect with biopolymer treatment is susceptible to the presence of water (i.e., strength reduction with higher water content) [23,27]. A study where thermo-gelation polysaccharide was used to strengthen clayey and sandy soils showed that the dry compressive strengths of treated soils reached up to 13 MPa for clayey soils and 2.5 MPa for sandy soils, but when the specimens were saturated with water the compressive strengths were reduced to approximately 500 kPa and 250 kPa, respectively [27]. This strength reduction was found to be due to the hydrophilic water adsorption and accompanying swelling of polysaccharide gels, and their reactions and sensitivity to water had a large detrimental effect on the strengthening mechanisms of the biopolymer treated soils [4,27,29]. One possible solution to this problem is the use of hydrophobic biopolymers.

Among biopolymers, protein group biopolymers essentially consist of one or more connected amino acids. In protein structures the nonpolar side chains of amino acids have hydrophobic bonds, which have minimal interactions with water molecules [30]. Thus, the application of protein group biopolymers as soil binders may enhance the biopolymer treated soil's resistance to water. Among such protein group biopolymers, the use of casein for soil treatment was chosen as the topic for this study, since casein is already widely used and applied in various industrial fields [31].

## 2. Materials and methods

### 2.1. Materials

#### 2.1.1. Casein biopolymer

Casein is the name applied to a family of phosphoproteins typically found in mammalian milk. Casein makes up 80% of the proteins in bovine milk, and is generally found as a suspension of particles referred to as “casein micelles” [32]. These casein micelles are held together by calcium ions and hydrophobic interactions [33]. Isoelectric (acid) casein precipitates out of liquid milk via acidification at pH 4.6 (HCl is generally used) and by centrifugation or filtration [31]. Casein has a large variety of uses including in foods, industrial paints, glues, plastics [34], and medical and dental products [35]. Among industrial applications, casein has been used as binders with a high resistivity to water [36]. Therefore, for this study, casein derived from bovine milk was chosen as a soil enhancing binder, and the compressive strengths of casein treated soils were determined in both dry and wet states.

Casein molecules (average molecular mass = 20–25 kDa) tend to coagulate and form spherical shaped colloidal micelles with an average diameter = 120 nm and average mass =  $10^5$  kDa [31,37]. The general formation of a casein micelle is shown in Fig. 1. As can be seen, the casein submicelles come together to form a larger casein micelle. These submicelles are held together by calcium phosphate. The calcium phosphate particles interact directly with the surfaces of the submicelles, forming linkage points between the submicelles.  $\kappa$ -Casein peptide chains are attached to the outer surfaces of the micelle structure [38]. The phosphate groups allow the casein to bind with a relatively large number of cations, such as  $\text{Ca}^{2+}$  [31].

In this study, casein biopolymer is introduced to develop a new hydrophobic biopolymer adhesive for soil treatment. Powder form bovine casein product provided by Sigma Aldrich (CAS Number: 9000-71-9) is adopted for experimental programs. For casein adhesives, the effectiveness in applications is highly dependent on the flow properties of the solution, that is, its consistency and viscosity.

Several major factors that contribute to the flow properties of the casein solution are the casein concentration, salt effects, pH effects, and temperature. Hermansson [39] investigated the effect of casein concentrations in solution, and found that caseinate solutions did not show any yield stress at casein to water concentrations below 12%. It was found that below 12% the solution was almost Newtonian with a low viscosity; however, above 12% the solution was pseudoplastic and the consistency index greatly

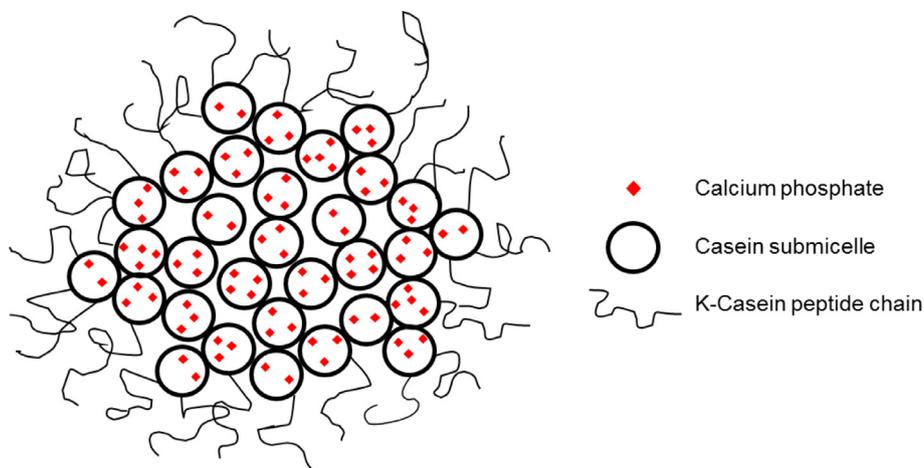


Fig. 1. Schematic diagram of casein micelle structure (reproduced after Fox et al., 2015 [31]).

increased with further increases in concentration. Additionally, it was observed that with the addition of salt, the viscosity of the solution was considerably increased, but the flow character was not altered; that is, swelling and solubility were reduced [39].

Dolby [40] reported that casein was soluble at pH values below 3.5 or above 5.4. The pH for the minimum apparent viscosity of the casein solution was found to be dependent on the casein sample [40] and the alkali used to dissolve the casein into the solution [41]. The casein molecules have a higher net negative charge at higher pH, and at a pH above 10, the casein molecules behave as separate entities. Below a pH of 8 the inter-molecular interactions are likely to be stronger, resulting in strong attractive interactions between the casein particles [39,42].

The correlation between temperature and strength has been fairly well established, showing casein to be stable at high temperature conditions. Towler [43] found that between 25 and 60 °C, the logarithm of the apparent viscosity had a linear relationship with the reciprocal of the absolute temperature. However, some casein solutions were found to deviate from this linear trend at higher temperatures. Sergeeva and D'Yachenko [44] observed that the viscosity of casein solutions generally decreased at higher temperatures, but at around 88 °C the solutions gelled reversibly.

### 2.1.2. Soil types

**2.1.2.1. Korean residual soil (KRS).** Korean residual soil (KRS), which is well known as 'hwangtoh' in the region due to its reddish-yellow color, is formed from weathering of granite rocks [5]. The KRS generally consists of silt, halloysite, kaolinite, quartz, and illite, and is classified as a silty soil (*ML*) due to its particle size distribution (i.e.,  $D_{60} = 0.065$  mm,  $D_{50} = 0.055$  mm, and  $D_{10} = 0.040$  mm) with  $LL = 44$  and  $PI = 18$  [16].

**2.1.2.2. Sand (Jumunjin sand).** Jumunjin sand is a poorly graded sand (*SP*) that is widely used as a standard sand material in Korea [45,46]. Jumunjin sand has a mean grain size of  $D_{50} = 0.52$  mm, a coefficient of uniformity of  $C_u = 1.35$ , and a coefficient of curvature of  $C_c = 1.14$ . It has a specific gravity ( $G_s$ ) of 2.65 and has minimum and maximum void ratios of 0.64 and 0.89, respectively. The particle size distributions of both jumunjin sand and KRS are shown in Fig. 2.

## 2.2. Experimental program

### 2.2.1. KRS–sand mixture

Traditional soil (earthen) buildings, typically adobe in Korea, where they are known as "hanok", generally use KRS and sand mix-

tures as the main material [5]. Sand is usually added to control and minimize dry shrinkage, which induces surface cracks when pure KRS or clayey soil is used as the main material for earthen (soil) constructions [47]. Moreover, the high fine contents of KRS make the mixing and workability of the soil difficult, and the ratio found to maximize aesthetics, workability, and performance is approximately a KRS to sand ratio of 1:1. Therefore, the soil used in this study was blended with a mixture of KRS and jumunjin sand at mass ratios of 1:1.

### 2.2.2. Casein solution production

Casein has a low solubility in neutral (pH 7) water, while solubility enhances in alkaline solutions with high pH [48]. Thus, a suitable alkaline solution was prepared to dissolve casein homogeneously for proper soil-casein mixing. Calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) was dissolved in distilled water up to pH = 10.0, to ensure full dissociation of casein micelles. The  $\text{Ca}(\text{OH})_2$  solvent was heated to 70 °C by enhancing the dissolvability of casein. Casein was added to the solvent and constantly stirred via a magnetic stirrer until all casein solids (powder) were fully dissolved and a homogeneous casein solution is formed at an isothermal condition (70 °C).

Unless otherwise stated, all casein solutions were prepared by an equivalent method. Casein solutions were prepared with casein concentrations of 8.00%, 10.64%, 13.32%, 16.00%, 20.00%, and 26.64% considering the final casein to soil ratio in mass, where all casein solutions show sufficient solubility at pH = 10.0 [49].

### 2.2.3. Specimen molding (casting), curing, and re-submerging

Casein solutions were mixed with a KRS-sand mixture via a laboratory automatic rotator with a mass ratio of solution:soil = 25:100 to obtain casein-soil mixtures of 2.00%, 2.66%, 3.33%, 4.00%, 5.00%, and 6.66% (casein content to the mass of soil), respectively (Table 1). Higher casein contents (>7%) were insufficient to provide uniform casein-soil mixtures due to difficulties (i.e., to viscous and poor workability) performing thorough mixing. The mixtures were then cast into 50 mm × 50 mm × 50 mm cube molds and air dried at room temperature (20 °C) for up to 28 days to achieve fully dried conditions. The specimens were compacted into the mold so that an initial dry density of 1.4 g/cm<sup>3</sup> was achieved.

### 2.2.4. Unconfined compressive strength measurement

For dry strength measurements, the fully dried specimens were used directly in compressive strength measurements using the Universal Testing Machine (UTM; Instron 5583), while dried specimens were re-submerged in water for 24 h before UTM testing to obtain (re-) wetted strengths. The axial strain rate was controlled at 0.5 mm/min (1%/min) and applied up to 7% total strain (3.5 mm), where the maximum unconfined compressive strength was observed by tracing the automatically displayed stress-strain relationships. Three samples were measured for each condition (casein content and moisture condition) and the average of their maximum strengths was taken to obtain the unconfined compressive strength, with a deviation of less than 5% from the average.

### 2.2.5. Scanning electron microscope (SEM) images

SEM images were obtained to observe the micro-scale interactions and structure of the casein-treated soils. Untreated (natural KRS-sand mixture) and casein-soil mixtures (2% and 5%) were used for SEM characterization by collecting representative 0.5 cm<sup>3</sup> bulk pieces from undisturbed cubes (50 mm × 50 mm × 50 mm) of each case after fully drying. The collected pieces were attached onto a SEM mount using carbon conductive tabs. Carbon paint was applied to the sample edges and bottoms to ensure sufficient electric grounding. Specimens were coated with an osmium tetroxide ( $\text{OsO}_4$ ) coating for 20 s using an osmium plasma coater

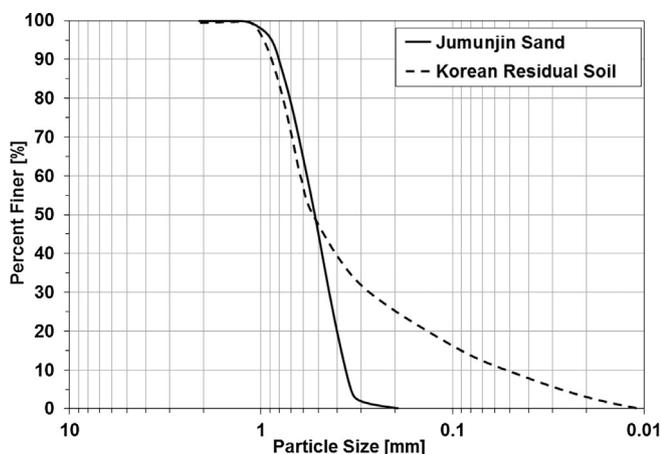


Fig. 2. Particle size distribution of jumunjin sand and Korean residual soil (KRS).

**Table 1**  
Strength and stiffness of casein treated soils.

Casein solution [%]	Solution:Soil ratio for mixing	Casein-soil mixture [%]	Compressive Strength [MPa]		Elastic Modulus $E_{50}$ [MPa]		Maximum strain [%]	
			Dry	Wet	Dry	Wet	Dry	Wet
			8.00	0.25	2.00	2.65	0.48	47.69
10.64		2.66	2.79	0.51	49.34	2.14	4.03	4.92
13.32		3.33	3.07	0.53	57.9	2.70	3.85	4.83
16.00		4.00	3.63	0.59	70.85	4.41	3.99	4.96
20.00		5.00	4.34	0.65	87.54	8.13	3.81	5.12
26.64		6.66	5.63	0.75	133.07	10.01	3.83	5.03

(OPC-60A). A Magellan 400L XHR device was then used to observe the microscopic structure and particle interactions of the casein-treated soils.

### 3. Results and analysis

#### 3.1. Stress-strain relationship

The stress strain relationships of casein-soil mixtures with different casein content and moisture conditions are summarized in Table 1 and Fig. 3. The water content of the dried specimens after 28 days of drying ranged from 2.6% to 2.9%, which is similar to the residual water content (3.0% or less) of untreated KRS [16]. On the other hand, the wet specimens exhibited moisture content of around 22% after 24 h of submergence. The reabsorbed water con-

tent of submerged casein-treated soils is restricted to be less than the initial water content for casein-soil mixing (25%), which is consistent with the wetting characteristic of polysaccharide type biopolymer-treated soils [27,29] and implies the inter-particle binding strength of casein binders is stronger than the swelling pressure during saturation. The compressive strengths of both dry and wet casein-treated soils increase with casein content increase. Moreover, the stiffness and compressive strength also increase with an increase in casein concentration (up to 5.63 MPa compressive strength and 133.07 MPa stiffness at 6.66% casein content to the mass of soil). The compressive strength of casein-treated soils is higher than that for typical (non-fired) adobe blocks (1.32–1.56 MPa in average) [50,51] which also satisfies the requirements of international recommendations for traditional adobe construction (unconfined compressive strength >1.18 MPa) [51].

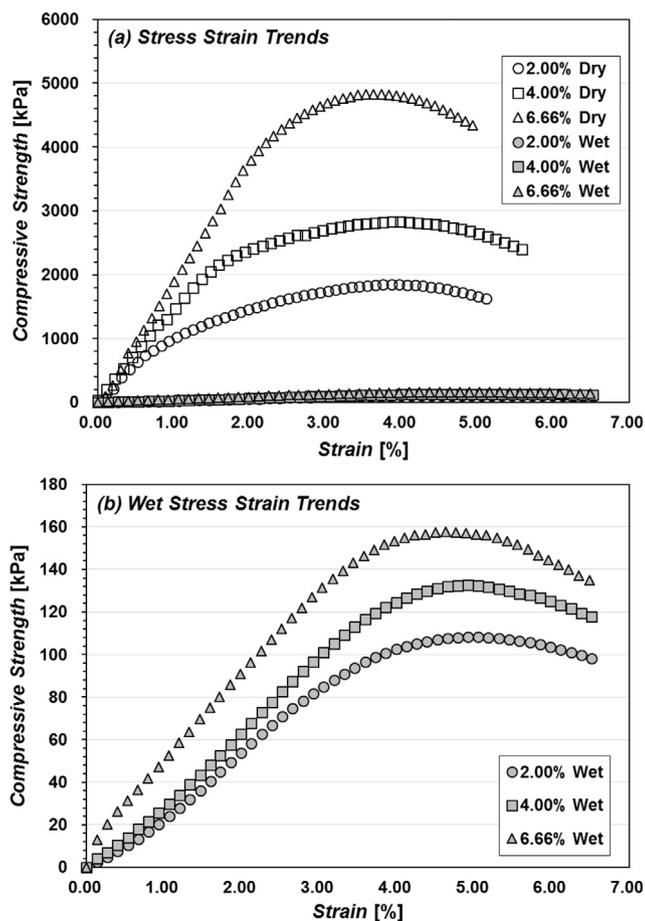
The modulus of elasticity of casein-soil mixtures is in the range of ordinary compacted soil blocks (40–225 MPa) [50,51]. Meanwhile, the strain at the peak strength of casein-soil mixtures, which remained similar (3.81–4.03% for dried condition) regardless of the casein concentration, is lower than that of untreated soil blocks (10% in average) [51], indicating an increase of brittleness due to casein treatment.

In addition, the results show that the unconfined compressive strength of the dry casein-treated soils is remarkably larger than that of the wet casein-soil mixtures, and gradually increases with higher casein concentrations, whereas the wet strength becomes less sensitive with casein concentration variation. The significant reduction in strength under the wet condition appears to be due to a combination of soil swelling and hydration of casein binders due to the presence of water, which results in looser inter-particle interaction of the soil as well as a reduction of the viscosity (or strength) of casein along soil particles.

#### 3.2. Binding performance of casein treated soil

Fig. 4 shows the unconfined compressive strength values of casein-treated soil with various casein concentrations. As mentioned above, the compressive strengths of the samples increased with an increase in casein concentration, but the increase in strength for the dry samples was far greater than that of the wet samples.

The dry strengths increased from 2.65 MPa at 2% casein to 5.63 MPa at 5% casein, whereas the wet samples only increased from 0.48 MPa at 2% casein to 0.75 MPa at 5%. For the wet condition, the average strength increase below 3.00% casein was 45 kPa per 1% of casein, and 65 kPa per 1% of casein for casein concentrations above 3.00%. Moreover, the compressive strength of dry casein-soil mixtures also shows different trends before and after the 3.0% casein to soil mass ratio. This difference can be attributed to the difference in the prepared casein solutions. At 3.00% casein to soil mass, the casein to water (25% to soil mass) concentration is 12%.



**Fig. 3.** Stress-strain curves of casein-treated soils. (a) Both dry and wet conditions. (b) Wet conditions.

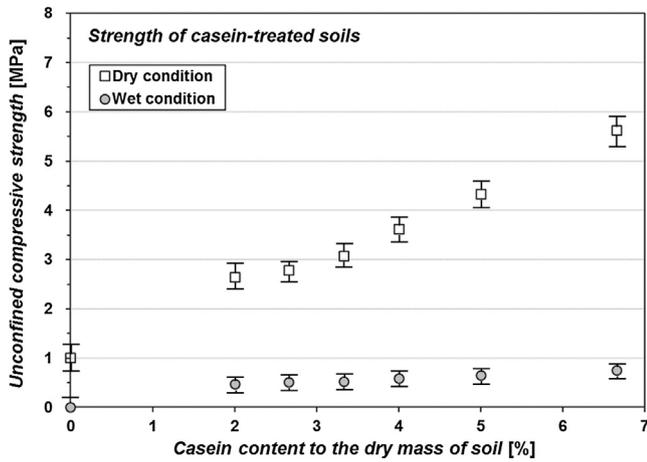


Fig. 4. Unconfined compressive strength values of casein-treated soils at wet and dried conditions with casein content variation.

According to previous studies conducted by Hermansson [39], 12% casein concentration is the dividing line between a solution with low viscosity and Newtonian behavior (which occurs below 12%), and a pseudoplastic solution (above 12%). In addition, the effects of pH and ions within the solution are known to play a large role in the formation of casein binders [42]. Thus, it can be concluded

that the initial sample preparation of the casein solution, including the casein concentration, before soil mixing is an important factor that affects the strengthening behavior of casein-treated soils.

### 3.3. Microstructure and interaction model

SEM images of the casein treated soils are shown in Fig. 5. Fig. 5 (a and b) show SEM images of untreated soils, while Fig. 5(c and d) present microscopic images of casein-treated soils. When casein is mixed with soil, the casein binder encompasses soil particles and forms a continuous casein coating covering soil particles inducing casein-soil conglomerates. These interactions with the soil particles allow for an increase in the total strength of casein-soil mixtures by enhancing 1) inter-particle bonding and 2) the conglomeration effect, which are also observed in polysaccharide biopolymer-treated soils [4]. Among casein-treated conditions (Fig. 5c and d), a difference in the microscopic casein structure is observed, and this is ascribed to the different rheology of casein solutions for mixing. Fig. 5(c) presents SEM images of 2% casein-treated soil (to the mass of soil) where casein monomers randomly attach onto the soil surfaces, forming a clumpy accumulated casein layer. However, for high casein content (5% casein to the mass of soil) (Fig. 5d), casein matrices form a smooth plastic-like substance on soil surfaces. This is due to the fact that the 5% casein-treated soil was mixed with a casein solution of 20%, which is above the 12% concentration dividing line (Fig. 4), resulting in a more pseudoplastic casein solution [39].

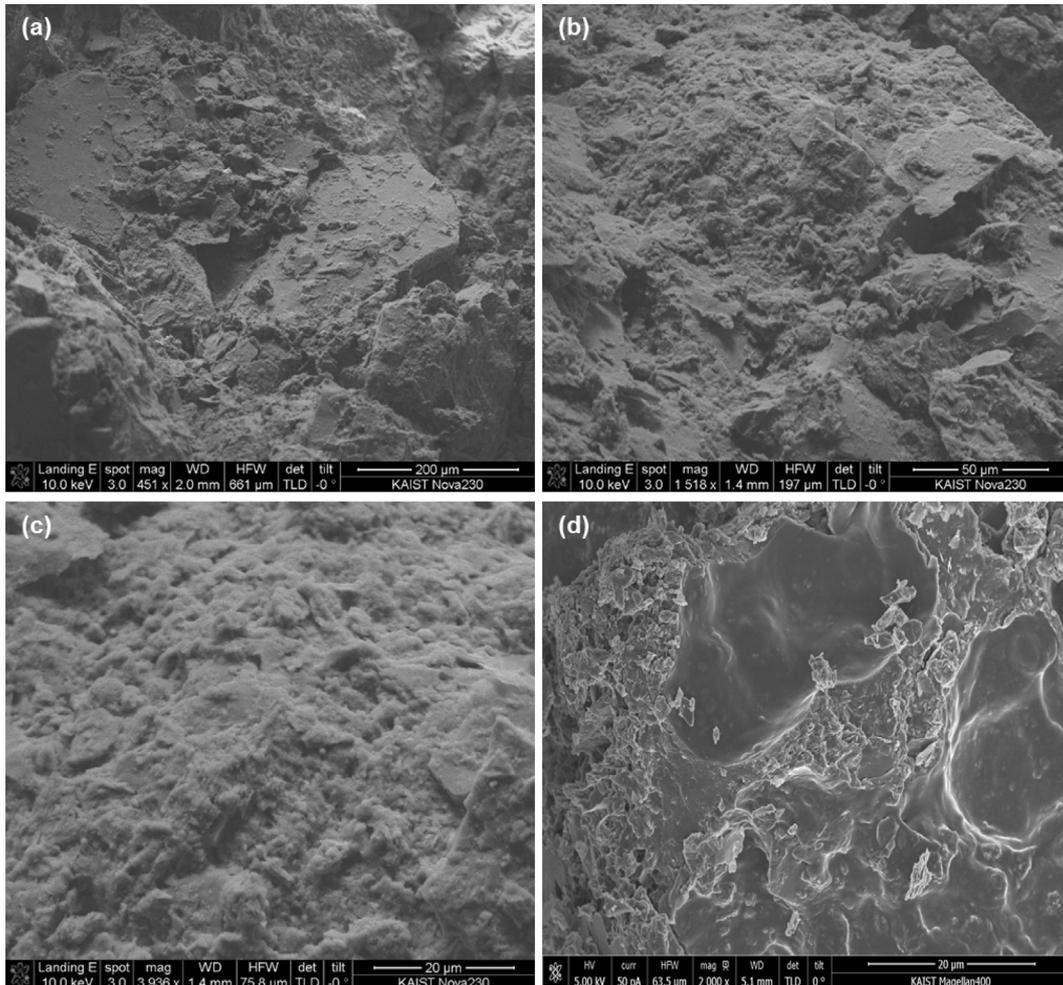


Fig. 5. SEM images of (a and b) Untreated soils, (c) Casein treated soils (casein content = 2%), and (d) Casein treated soils (casein content = 5%).

## 4. Discussion

### 4.1. Strength compared to other biopolymers

A comparison between the effects of 5% casein-treated soil and other previously attempted biopolymer treatments for soil strengthening ( $\beta$ -glucan [16], xanthan gum [8], gellan gum and agar gum [27]) is presented in Fig. 6. The results show that 5% casein content to the mass of soil significantly increases the unconfined compressive strength at a dried condition (i.e., 4.34 MPa) similar to the results for 1% xanthan gum and gellan gum (4.94 MPa and 4.59 MPa, respectively), and the strength is approximately double that of 10% cement-treated soils (i.e., 2.65 MPa) (Fig. 6a).

Although a large reduction in strength was observed when the casein treated specimens were submerged in water (Fig. 6b), the measured wet strength after 24 h of saturation shows significant improvement in comparison to the other biopolymer mixing attempts. The wet strengths of the previously used biopolymers were relatively insignificant; they retained 0–1.8% of their dry strengths, while the wet strength of casein treated specimens was  $\approx$ 15% of their dry strength even with around eight times as much water as the dry samples. Thus, it can be carefully concluded that the use of casein as a soil binder has potential for significantly increasing the wet strengths of biopolymer treated soils.

The casein treated soils were capable of retaining a larger degree of dry strength than the previous biopolymer-treated soils due to the lower water absorbance of proteins [52], which results

in a denser particle composition. In previous studies, the biopolymers tested were mainly polysaccharides, which the strengthening behavior is mainly governed by hydrogen bonding and biopolymer hydrogel rheology [3,4,13]. Those polysaccharide biopolymers form a viscous hydrocolloid solution when mixed with water, and are readily soluble in water due to their surface charges. In contrast, casein monomers associate via hydrophobic bonding to produce casein micelles, especially at higher temperatures [53].

Nonetheless, although the bonding is mainly hydrophobic, there was still a significant reduction in the wet strength of the soils. It is believed that this is due to the initial preparation of the casein solution. When the casein solution was initially prepared, the pH of the solution was controlled at 10.0. At this level the casein particles form ionic charges along their surfaces, which allows them to behave independently of each other. Through this increase in surface charges the casein particles may become more susceptible to water molecules. Therefore, if the casein solution preparation is optimized, a binding solution with a higher resistance to water may be possible. Meanwhile, although the compressive strength of casein-treated soils satisfies requirements to be used in typical adobe buildings, the compressive strength of casein-treated soil is lower than the minimum requirement of fired (900 °C to 1200 °C) clay bricks (compressive strength  $\geq$  10.3 MPa in average) [54]. Thus, further studies are recommended to enhance the mechanical properties of casein-treated soil to widen its application in various engineering practices.

### 4.2. Future strategy of casein application in construction practices

In the United States today, milk generally contains 3.69% fat and 3.05% true protein [55]. In 2007 the annual milk production in the United States was reported to be 84.2 million tons [55], while the entire global production is reported to be 748.4 M tons [56]. The world production of commercial casein was reported to be around 330,000 tons in 2008 [57], which represents 2% of all of the fresh milk produced globally in the same era.

Approximately one-third of the edible parts of food is lost or wasted globally, which amounts to as much as 1.3 billion tons per annum [56]. For industrialized regions (Europe, North America, Oceania, Korea, China, and Japan) milk waste mostly occurs at the consumption level (40–65%), while the post-harvest handling, storage, and distribution stages are dominant factors for milk losses and waste in developing regions (Africa, Asia, and Latin America) (Table 2). For instance, dairy losses and wastes account for 31% of total dairy production in the United States, which amounts to 11.5 M ton per annum [58]. Therefore, aside from providing an environmentally friendly method of soil improvement, the use of casein is a possible way of recovering and utilizing existing amounts of dairy and milk wastes.

The overall global ratio of losses and waste to production of milk is 18.1% on average, and developing regions have higher ratios than the global average (21.5–27.2%) as a result of less efficient storage facilities, packing, infrastructure, and transportation; lack of refrigeration and temperature control; and inadequate market facilities [56,59]. As a result, 135.8 M ton of milk are wasted annually, and in particular, 32.9% (44.6 M ton) is wasted at the consumption stage (best-before-dates, leftovers, and oversupply) [56].

Given the large percentage of dairy wastes being produced, the treatment and the disposal measures needed to manage such large quantities of waste materials are costly and problematic. Presently, the most commonly used method of managing waste milk is land spreading [60]. Disposing large volumes of waste milk into soils can inadvertently affect groundwater and local ecosystems. When such groundwater contamination leaks into local water reservoirs, wastewater treatment methods (i.e. aerated lagoons, activated sludge, sequencing batch reactors, etc.) may be required to clear

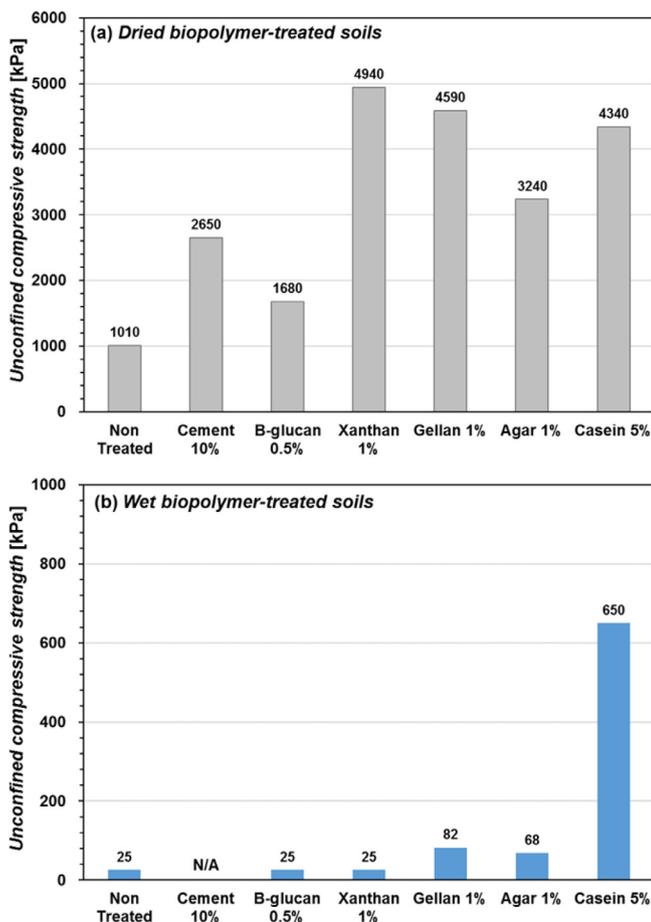
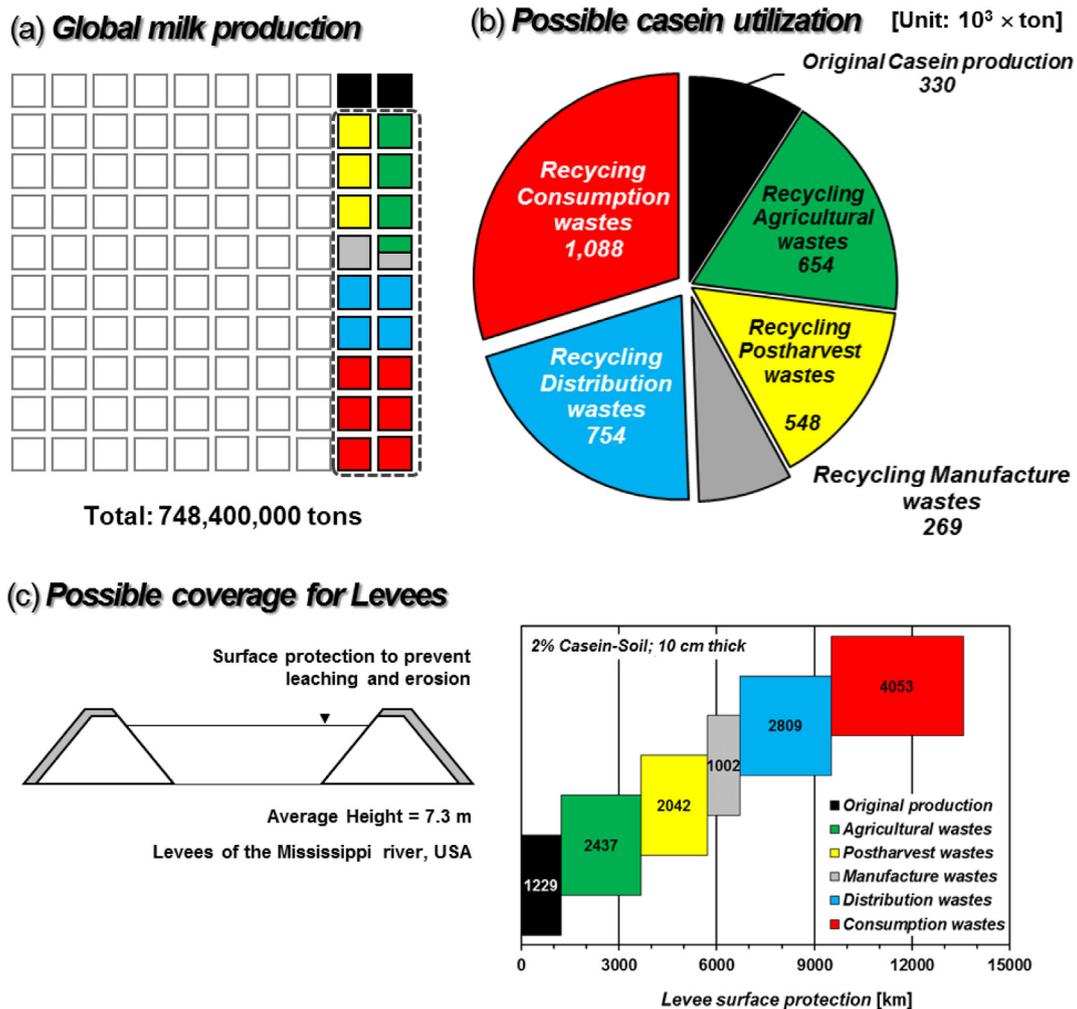


Fig. 6. Unconfined compressive strength of casein compared with different biopolymers. (a) Dried biopolymer-treated soils. (b) Wet biopolymer-treated soils (data from Chang et al., 2012 [16]; Chang et al., 2015 [8]; Chang et al., 2015 [27]).

**Table 2**  
Global milk production, losses, and waste status (data after [56]).

Region	Production [M tons/yr.]	Weight percentages of losses and waste [%]						Total	Total waste [M tons/yr.]
		Step 1	Step 2	Step 3	Step 4	Step 5			
Europe	233.9	3.5	0.5	1.2	0.5	7.0	12.7	29.7	
North America, Oceania	124.2	3.5	0.5	1.2	0.5	15.0	20.7	25.7	
Industrialized Asia	79.0	3.5	1.0	1.2	0.5	5.0	11.2	8.9	
Sub-Saharan Africa	24.2	6.0	11.0	0.1	10.0	0.1	27.2	6.6	
North Africa, West and Central Asia	43.6	3.5	6.0	2.0	8.0	2.0	21.5	9.4	
South and Southeast Asia	166.1	3.5	6.0	2.0	10.0	1.0	22.5	37.4	
Latin America	77.4	3.5	6.0	2.0	8.0	4.0	23.5	18.2	
Total	748.4						18.1	135.8	

Step 1: Agricultural production.  
 Step 2: Postharvest handling and storage.  
 Step 3: Postharvest handling and storage.  
 Step 4: Distribution: Supermarket retail.  
 Step 5: Consumption.



**Fig. 7.** Future strategy of casein utilization through milk loose and waste recycling. (a) Global milk production and waste status. (b) Milk waste status and proportion from production to consumption. (c) Potential usage of milk-recycled casein in geotechnical engineering practices (example in levee protection).

up the water contamination resulting from land spreading of milk wastes [61].

By making use of these waste dairy products, casein can be extracted and used in various types of soil improvement, thereby allowing for both efficient waste management and infrastructure development. Casein accounts for 80% of the total protein content in bovine milk, meaning that approximately 24.4 kg of casein can be extracted from 1 ton of cow milk [55,62]. It is therefore possible to produce and utilize 1.09 M ton of casein per annum by recycling

the milk wasted at the consumption level (44.6 M ton/yr), and the amount of recovered casein would exceed 3.3 M ton if the total amount of global milk losses and waste (135.8 M ton/yr) was recycled in this manner [56].

The potential use and overall wastage of milk products is shown in Fig. 7. Fig. 7 shows the global milk production, where each block represents 1% of the global production. The white boxes are the dairy products that are used and not wasted, the black blocks are the amount of dairy used to produce casein, and the remaining

colored blocks represent the wasted dairy. The types of dairy waste are represented in color and shown in Fig. 7(b).

For perspective, casein treatment could be applied to earthen levees or dikes to enhance surface resistance against breaching and erosion [63]. The amount of casein that could be produced annually by recycling waste milk (1.09 M ton) would enable the application of 2% casein mixed earthen protection layers of 10 cm thickness along both sides of the entire Mississippi River & Tributaries (MR&T) levees, which have an average height of 7.3 m and are approximately 2027 km long [64], as shown in Fig. 7(c).

In addition, recycling milk waste for casein utilization can have a meaningful impact on reducing greenhouse gas emissions. Although the major influence of the dairy industry on global warming involves eutrophication and acidification, which primarily occur (80–95%) during on-farm processes (i.e., 1.35 kg of CO<sub>2</sub> are emitted per 1 kg of milk production) [65,66], pouring 1 kg of wasted milk down the drain without consumption is known to produce 0.28 kg of CO<sub>2</sub> emission [67]. In more detail, the entire volume of CO<sub>2</sub> emissions related to milk waste in the United Kingdom is reported to be 100 kilotons per annum, which is equivalent to the CO<sub>2</sub> emitted by 20,000 vehicles during the same period [67].

Thus, recycling the milk waste produced at the consumption level (44.6 M ton/year) [56] has the potential to reduce 12.49 M ton of CO<sub>2</sub> emissions every year. Although the current level of casein-treated soil technology may not yet be suitable for it to be an eco-friendly replacement for modern urban construction processes, it may provide substantial advantages in soil improvement methods, particularly considering the benefits of waste management and recycling. By making use of locally available resources while simultaneously providing a method of waste management, soil improvement projects in underdeveloped areas may benefit from this technology.

## 5. Conclusions

This study demonstrated that the use of casein can be effective in soil improvement. The binding mechanism and strengthening effects of casein in soil treatment were shown to depend on the conditions used in preparing the casein solution. By altering the proposed method and optimizing the solution with the goal of increasing the water resistance of the biopolymer binder, such treatment is believed to be capable of sustaining sufficient strength for use in many engineering soil treatment applications. Additionally, the use of casein can help reduce the amount of wasted dairy, and it could instead be used for construction purposes.

Overall, this study showed that the hydrophobic bonding characteristics of casein were capable of enhancing the wet strength of biopolymer treated soils. Although this method of soil improvement may not yet be applicable at this stage in development, the present study suggests it has the potential for further development and improvement. Additionally, the water resistance of other biopolymer binders used for soil improvement could be enhanced by incorporating hydrophobic biopolymers such as casein, and as such it may serve as a basis for developing a more effective eco-friendly soil binder. There are a variety of methods of soil improvement and strengthening that can be accomplished by utilizing this development.

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