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Bovine casein as a new soil strengthening binder from diary wastes

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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.

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].

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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 (β-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. κ-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 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

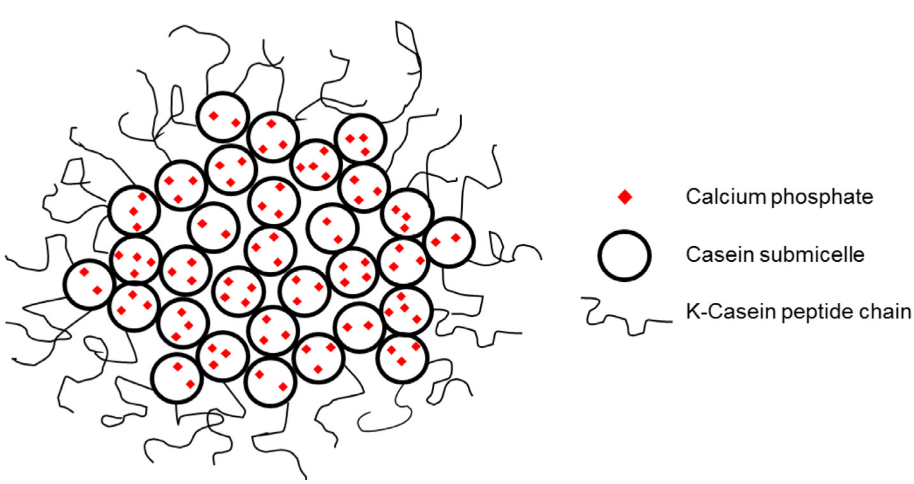

Fig. 1. Schematic diagram of casein micelle structure (reproduced after Fox et al., 2015 [31]).