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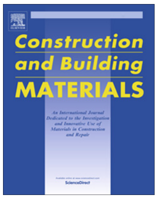

Soil strengthening using thermo-gelation biopolymers

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HIGHLIGHTS

- Thermo-gelation biopolymers are introduced as new construction materials.
- Micro interaction between thermo-gelation biopolymers and soils is investigated.
- Strength change with time, biopolymer quantity, and water content is evaluated.
- Thermo-gelation biopolymers form hydrogen bonding with clayey particles.
- Sandy soil shows hysteretic strength path along drying and wetting.

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ABSTRACT

A new biopolymeric construction material for soil treatment/improvement is introduced in this study in an effort to develop an environmentally-friendly construction engineering approach to replace the use of conventional materials that have high environmental impact. Thermo-gelation biopolymers dissolve and form a suspension in heated (*i.e.*, 85–90 °C) water, and then coagulate (*i.e.*, gelate) upon a decrease of temperature (*i.e.*, below 50 °C). Gellan gum and agar gum are typical thermo-gelation biopolymers with potential as soil strengthening construction materials due to their hydrogen bonding characteristics, and were used to treat two types (*i.e.*, clayey and sandy) of soil in different quantities and treatment conditions. The results showed that thermal treatment is an important prerequisite as well as air-drying (*i.e.*, hardening), and produced higher strengthening (up to 12 MPa) and durability in an immersed condition. Moreover, gellan gum is preferable to agar gum for soils with significant fine contents due to the interaction (*e.g.*, hydrogen bonding) between biopolymers and fine particles, which produces firm biopolymer–soil matrices. Consequently, thermo-gelation biopolymers have strong potential application as construction materials for both land (*i.e.*, dry) and waterfront purposes.

1. Introduction

Studies on ground improvement have been performed and utilized throughout the history of human civilization. With the current high demand for civil infrastructure, ground improvement techniques have become an important element in geotechnical engineering projects. Such techniques have been developed in accordance with advances in current technology and human resources and make many civil engineering projects feasible.

For admixture type ground improvements, materials such as cement, epoxy, acrylamide, phenoplasts, polyurethane, and glass water are typically used for soil improvement [1]. These materials, however, give rise to environmental concerns owing to their harmful nature [2,3]. The development of eco-friendly materials for soil improvement is thus necessary.

Biopolymers are biodegradable polymers produced by living organisms such as algae, fungus or bacteria. They consist of polysaccharides, which are compounds consisting of monosaccharides linked at certain locations. They are broadly distributed in nature and serve as skeletal structure-forming substances, assimilative reserve substances, and water-binding substances [4]. With their natural behavior, polysaccharides act as thickening agents, stabilizers, sweetening, and gel-forming agents. Accordingly, most applications utilizing biopolymers are in the fields of food production, agriculture, cosmetics, medicine, and pharmaceuticals [5–7]. Recently, some researchers have studied the utilization of biopolymers in the field of geotechnical engineering [8–10]. Also, recent studies have shown that biopolymers such as β-1,3/1,6-glucan,

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xanthan gum, can successfully improve the mechanical properties [11,12] and erosion resistance of soil, while remaining the porosity and hydraulic conductivity high [13]. Compared to cement mixture improvement, biopolymer-treated soils have higher strengths, even though the amount of biopolymer used is less than the amount of cement in the soil. Moreover, in terms of economic costs, based on the costs of materials and pollution effects, biopolymer-treated soils have advantages over cement-treated soil [11].

Nevertheless, the durability of biopolymer-treated soil against water has not yet been comprehensively discussed by researchers and remains uncertain. Therefore, this study introduces a thermo-gelation biopolymer group as a new construction material with the aim of improving the durability of soil immersed in water, and to provide high performance building components such as bricks, blocks, and indoor finishing materials. The biopolymers used in this study are agar gum and gellan gum.

2. Material and methods

2.1. Materials

2.1.1. Agar gum

Agar gum is a biopolymer composed of polysaccharides (complex sugar) made of linked galactose molecules. Agar gum is a galactan made of alternating sequences of (1–4)-linked 3,6-anhydro-α-L-galactose and (1–3)-linked β-D-galactose residues [14]. Agar gum has been used as a food additive material since it was discovered decades ago. Its properties as a stabilizer, thickener, emulsifier, flavor enhancer, and absorbent make it one of the more important additives for food products, including use in bakery products, confections, dairy products, and meat and fish products by forming gels to thicken and provide texture [15]. In addition, agar gum is also used in the fields of dentistry, microbiology, and medicine [16].

The agar gum used in this study was manufactured by Samchun Chemical Company. Essentially, agar gum is extracted from *rhodophyceae* (an algae group), such as the *Gelidium* and *Gracilaria* species [16], and the biopolymer is highly dependent on the species and environmental conditions of the source *algae*. Agar gum is a hydrophilic colloid that consists of two different compounds: a firmly gelling complex sugar called *agarose* and a weakly gelling charged polymer called *agaropectin* [17]. Agar gum starts to dissolve in boiling water at 85 °C and forms a gel when cooled to 32–43 °C [15]. It has a neutral polymer chain with a limited reactivity to other materials. Agar gum is white to pale yellow, shiny, semi-translucent, tasteless, and odorless [17].

2.1.2. Gellan gum

Gellan gum, usually employed as a substitute gelling agent for agar gum, is a high molecular weight polysaccharide fermented from the *Spingomonas elodea* microbe (formerly known as *Pseudomonas elodea*). Gellan gum is a linear anionic heteropolysaccharide made of four molecules: (1,3)-β-D-glucose, (1,4)-β-D-glucuronic acid, (1,4)-β-D-glucose, and (1,4)-α-L-rhamnose [18]. It has the properties of a thickening or gelling agent and is often used as a food additive. Products using gellan gum are typically confections, bakery fillings, dairy products, jams and jellies, microwavable foods, puddings, and toppings [16].

Gellan gum's chemical structure contains four linked monosaccharides: one molecule of rhamnose that can be found in plants, one molecule of oxidized glucose named glucuronic acid, and two molecules of glucose (common sugar). In usual commercial production, gellan gum is modified to become a deacylated polymer that is soluble in water at temperatures above 90 °C, and it form gels when suitable cations are present or when cooled to gelling temperatures (*i.e.*, 30–70 °C depending on the gel concentration, presence of cations, and cooling rate) [19,20].

2.1.3. Agar gum and gellan gum gels

Hydrogen bonds play an important role in the formation and structure of agar gum and gellan gum gels during thermo-gelation. Before gelation, continuous stirring and heating in water allows the biopolymer chains to disperse thoroughly and form a hydrocolloid solution. Then, as the solution cools, the biopolymer chains twist together and form double helices with other chains or molecules to form a rectangular matrix via hydrogen bonding [21,22].

The compressive strengths of pure agar and gellan gum gels have been reported to show similar values (*i.e.*, 30–50 kPa) in low concentration ranges (*i.e.*, 1–2%) [23]. We prepared pure gel cubes (*i.e.*, 40 mm × 40 mm × 40 mm) in the laboratory with higher concentration values (*i.e.*, w_b/w_w = 2–8%, where w_b/w_w is the weight of biopolymer to the weight of water) by dissolving biopolymers into heated (*i.e.*, 100 °C) distilled water. The hot biopolymer solution coagulated to a firm gel upon cooling and the compressive strength was immediately measured when the gel temperature reached room temperature.

Fig. 1 shows that the compressive strength of agar gels remains constant (*i.e.*, 50 kPa) above 2% concentration, while the compressive strength of the gellan gel increases significantly up to 300 kPa at w_b/w_w = 7.5%. Thus, it is expected that gellan gum would be more effective in soil strengthening in higher biopolymer concentrations (*i.e.*, w_b/w_w). However, the reduced workability of gellan gum (*e.g.*, thorough mixing) due to the increased viscosity and gelation temperature (*i.e.*, faster gelation) induced by higher gellan concentration becomes a drawback [24].

2.1.4. Clayey soil (Korean residual soil)

Red Yellow Soil is a Korean residual soil formed from the weathering of rocks, and is locally known as hwangtoh due to its reddish-yellow appearance. In this study, Red Yellow soil was obtained from Gochang, Korea. It mostly consists of silt, halloysite, kaolinite, quartz, and illite. It has a plastic limit and liquid limit of 35% and 52.4%, respectively, and a specific gravity of 2.60. The soil can be classified as sandy lean clay (*CL*) due to its particle size distribution (*i.e.*, D_{60} = 0.065 mm, D_{50} = 0.055 mm, and D_{10} = 0.040 mm), as shown in Fig. 2. Further descriptions of Red Yellow soil can be found in Chang and Cho [11]. Red Yellow soil represents clayey soil in this study.

2.1.5. Sandy soil

Sandy soil used in this study was surface soil sampled from Cheonan, Korea. By particle size distribution data (Fig. 2) sandy soil is classified as poorly graded sand with silt (SP–SM). With a C_u (uniformity coefficient) of 3.02 and C_c (coefficient of gradation) of 0.92 due to its grain size characteristics (*i.e.*, D_{60} = 0.56 mm, D_{50} = 0.031 mm, and D_{10} = 0.16 mm), sandy soil represents coarse type soil in this study.

2.2. Experimental program

2.2.1. Thermo-gelation biopolymer–soil mixing

The biopolymers were dissolved in hot (*i.e.*, 100 °C) distilled water to prepare a thermally-treated biopolymer solution that was suitable for mixing due to its low viscosity [15,20]. The biopolymers were poured into a 100 °C solvent and stirred constantly via a magnetic stirrer (WiseStir® MSH-20D) at the desired biopolymer

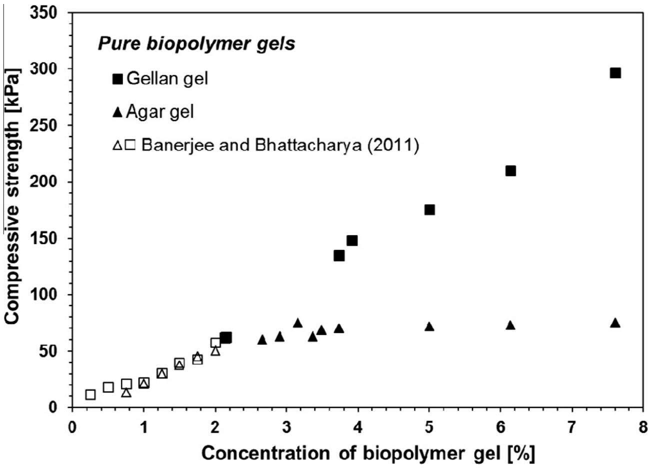

Fig. 1. Compressive strength of pure gellan gum and agar gum gels with different biopolymer to water concentrations (w_b/w_w).

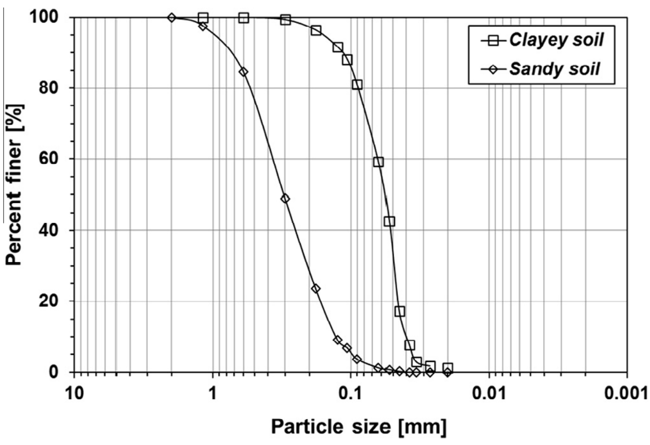

Fig. 2. Particle size distribution of clayey soil and sandy soil.