CHAPTER-1

INTRODUCTION AND LITERATURE REVIEW

1.1 General

In recent years, numerous ground improvement technologies have been developed based on innovations and experiences by contractors and engineering researchers. With the current development in the civil infrastructure and construction industry, ground (soil/waste) improvement techniques have become an essential element in geotechnical engineering projects. Ground stabilization processes are generally categorized as mechanical, chemical, biological, and electrical [1-5]. Among these methods, the widely used chemical techniques are classified as traditional (cement, lime, fly ash) or nontraditional additives (lignin, resin, polymer) [6]. Using some chemical techniques as a conventional soil binder is reported to be toxic and hazardous with adverse environmental impacts. Since 1960, cement has been the most widely used traditional additive for ground improvement [7, 8]. Unfortunately, the use of cement in-ground stabilization increases its pH and neighboring groundwater. Also, cement production emits a significant amount of carbon dioxide (CO_2) and nitrogen oxide (NO_x) gases, with a certain level of air emission in the form of cement dust, which pollutes the environment and affects the health and safety of humans.

Moreover, 0.2% of global CO_2 emissions are linked to cement usage in geotechnical engineering practices. The cement industry is responsible for 5-8% of the world's CO_2 emissions and accounts for 12-15% of the universal total energy consumption in the industrial sector [9, 10]. The cement production is expected to grow from 2.5 billion tons in 2016 to 4.4

billion tons by 2050 [11]. For these reasons, significant research has devoted particular attention to the development of new types of binder to reduce the negative environmental impact associated with the use of cement as a binder.

To overcome the concerns and limitations of common ground chemical improvement techniques, bio-mediated and bio-inspired approaches have been actively studied in geotechnical engineering research. Recently many research programs have focused on the utilization of biopolymer as a potential stabilizing agent to enhance the stability and erosion resistance of engineered structures [12-14]. Biopolymers are polymeric substances of natural origin produced by living organisms like algae, bacteria, fungi, animals, and plants or manufactured chemically but developed biologically from amino acids, sugar, natural fats, or oil [15]. They consist of exopolysaccharides produced from a microorganism, which improves soil aggregation, bio-cementation, bio-clogging, mitigation of liquefaction potential, strengthening tailing dams against erosion, etc.[16]. Rapidly increasing demand for eco-friendly and sustainable methods has motivated geotechnical engineers to employ biopolymers to enhance the mechanical strength of soil and wastes against external loading and the environment.

1.2 Problem statement

Over the past decades, rapid industrialization and population growth have led to the production of enormous industrial waste worldwide, which gives rise to several environmental and geotechnical issues such as global warming and land degradation (erosion). Among them, red mud tailing is a highly alkaline waste or a by-product formed by the digestion of bauxite ore during the extraction of alumina contains toxic heavy metals. The amount of its production is vast, creating serious disposal problems [17]. About 0.3 to 2.5 tons of bauxite residue is generated from 1 ton of alumina production [18, 19]. The pH of bauxite residue is always between 9.2 and 12.8 because of sodium hydroxide (NaOH), resulting in limited geotechnical engineering applications. The processed bauxite ore is disposed of in the form of slurry in a storage pond, or as a stack of dry mud near industrial plants, or directly disposed into a nearby sea, which raises several environmental and safety concerns [20]. The disposal of bauxite residue entails vast land for constructing a tailing pond and is very prone to erosion (water and wind), mainly in dry and semi-dry regions. Occasional failure of bauxite residue embankments or ponds causes flooding the land and groundwater quality deterioration, affecting human health and has an economic impact. Tailing dams are also more prone to failure than water reservoir dams [21, 22]. Ajka Alumina, Hungary (2010), Henan province, China (2016), and Barcarena, Para, Brazil (2018) are a few reported cases of bauxite residue dam failures [23].

(a) (b)

(c)

Figure 1.1 (a) Ajka, alumina waste pond, Hungary [23] (b) The Pond of NALCO factory in Damandjodi (India) [24] (c) Coal mine Overburden waste dumping near Kusunda Opencast mines (India) [25]

The waste generated during coal mining is traditionally dumped on land in the form of an overburden or waste rock. Currently, India has the fifth largest coal reserve and stands third in terms of identified reserves [26]. The increasing size of opencast mines and the stripping ratio has substantially increased the removal of overburden dump. The two methods of a mining operation are underground and opencast mining. Opencast excavation involves removing overlying soil debris and fragmented rock, which is heaped in the form of overburden dumps [27]. These coal mine overburden (CMO) dumps damage the environment vigorously, affect the drainage system, and make the soil infertile for plant growth, leading to severe problems of soil erosion and environmental pollution. Tailing dams are mostly constructed from locally derived soil, waste rock, overburden dump material, and tailing are often used in construction [28-30]. These dump materials contain loose and fine particles, which become highly prone to wind erosion [31].

1.3 Application of Biopolymer in Geotechnical Engineering

Over the years, the demand to satisfy society's concern about environmental issues has forced engineers and researchers to draw attention to new procedures that combine microorganisms in innovative (soil/waste) improvement techniques. As a result, the amount of research based on microbial activities to stabilize soil/waste properties required by engineering has increased compared to the usual geotechnical practices that use Portland cement. Several studies on biotechnology engineering applications already exist, such as the use of vegetation, algae, bacteria, enzymes, and biopolymers. However, biocementation and bioclogging are the most widely used application that enhances soil/waste properties in a favorable way to engineering, by increasing stiffness and strength and even reducing permeability [32]. These two methodologies rely on the same chemical reactions that decompose urea into carbonate and ammonium ions. The carbonate ions combine with calcium ions to form precipitated calcium carbonate ($CaCO_3$) [33]. Bioclogging relies on the use of biopolymers.

Past studies have shown that the direct use of biopolymers in soil/waste stabilization can have several advantages over traditional biological treatment methods. This fact can be explained because different types of biopolymers have shown a good interaction with the soil. Additionally, biopolymers have distinct properties such as good viscosity, resistance to shear degradation, and stability over wide pH and temperature ranges, promoting significant strengthening effects in soils by enhancing cohesion, strength, and resistance to erosion and reducing its permeability [34]. The effect of biopolymers on the soil/waste is related to their ability to make a stable gel matrix within the particles without damaging the local ecosystem. Moreover, they can promote vegetation growth [35], which is also beneficial in terms of stabilizing shallow soil since it contributes to increasing soil resistance to erosion and the stability of the slope.

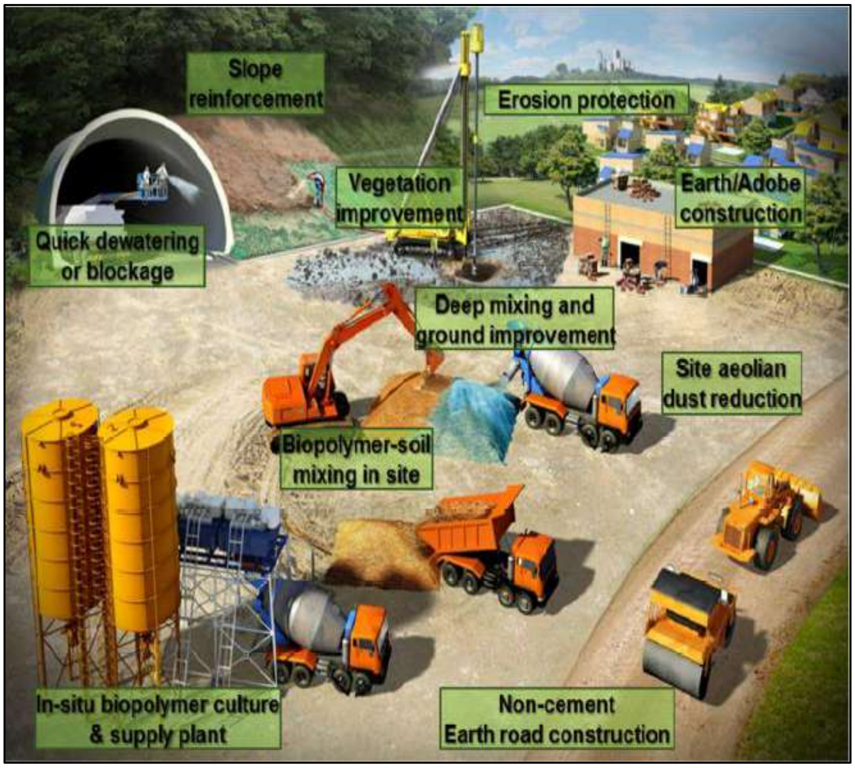

Figure 1.2 Biopolymer applications in geotechnical engineering practices [36]

1.4 Literature review

The literature review is based on biopolymer treatment in enhancement of geotechnical engineering properties and its potential application.

1.4.1 Soil Consistency

Chen et al. [37] reported the use of xanthan and guar gum on stabilizing mine tailings (MT). The simple fall cone method was adopted to evaluate the liquid limit, and undrained shear strength of biopolymer mixed MT at different concentrations. The result indicates that the inclusion of biopolymer increases both liquid limit and the undrained shear strength, which increases with an increase in biopolymer concentration. The increase is mainly attributable to the high viscosity of the biopolymer pore fluid and the bonding between the biopolymer and the MT particles.

Chang et al. [38] also explored the effect of biopolymer on soil behavior, and identified the geotechnical behavior of KRS (Korean residual soil) after treatment with beta-1,3/1,6-glucan biopolymer. As the biopolymer content increased, the treated soil showed an increase in compactibility (maximum dry density and optimal water content), Atterberg limits (*PL* and *LL*) and plasticity index (*PI*), swelling index (*Cs*), and shear wave velocity (*Vs* or shear modulus), but a decrease in the coefficient of consolidation (*cv*). Based on these limited test results, biopolymer treatment shows substantial potential to provide solutions to some geotechnical engineering problems in the forms of quick conditioners, water-reducing admixtures, temporary stabilizers, and slurry wall mixtures.

1.4.2 Soil strengthening

1.4.2.1 Unconfined compressive strength

UCS is one of the essential indicators of the geotechnical engineering behavior of soil/waste, its shows the maximum compressive strength that a sample can withstand under zero confining stress. Biopolymers enhance the compressive strength by inducing conglomeration and aggregation among soil/waste particles and/or generating electrostatic adhesion among particles and biopolymers. Latifi et al. [39] performed the experimental mechanical test on both untreated and xanthan gum–stabilized montmorillonite and kaolinite clays at various curing times, including unconfined compression strength (UCS) tests, direct shear tests, and one-dimensional (1D) consolidation tests. UCS test results indicated that 1 and 1.5% xanthan gum additive levels achieved optimal stabilization results for bentonite and kaolinite, respectively. The increased additive levels and curing times yielded increased shear strength and increased stiffness (i.e., a decreased tendency for compressibility) and increased yield stress values in 1D consolidation tests for tests conducted on stabilized specimens.

Lee et al. [40] explored the feasibility of biopolymer application on local soil stabilization, specifically for road shoulder construction in Sri Lanka, by comparing the unconfined compressive strength (UCS) of local soil samples treated with cement-ash–based binders and xanthan gum biopolymer. The result showed that the UCS of XG-treated soil was remarkably higher than others after 28 days of dehydration due to the firm biopolymer–soil matrix formation. Moreover, XG-treated conditions had higher ductility than cement-based-binder–treated soils; this is another distinctive feature of XG soil treatment.

1.4.2.2 Shear strength

Shear strength refers to the external load a soil/stabilized waste can sustain without structural failure, which is essential for the reliable and safe design of geotechnical engineering structures such as slopes, earth walls, embankments, and foundations.

Chang et al. [41] performed a series of laboratory experiments to evaluate the effect of soil–gellan gum interactions on the strengthening behavior of gellan gum-treated soil mixtures (from sand to clay). The experimental results showed that the strengths of sand-clay mixtures were effectively increased by gellan gum treatment over pure sand or clay. The strengthening behavior is attributed to the conglomeration of fine particles and the interconnection of fine and coarse particles by gellan gum. Gellan gum treatment significantly improved not only inter-particle cohesion but also the friction angle of clay-containing soils.

Khatami et al. [42] presented the guidelines for selecting potentially valuable biopolymers for strengthening cohesionless soil. Agar and six modified starches were identified for further study over a range of concentrations (1–4% agar and 0.5–1% starch). Depending on the biopolymer concentration, the unconfined compressive strength of the sand treated with agar and starch biopolymers ranged from 158 to 487 kPa. The addition of Starpol 600 and 136 at the same agar concentration was observed to significantly increase the value of cohesion intercept and also to enhance stiffness.

1.4.3 Soil erosion control

Surface soil erosion is an important concern in geotechnical engineering and other fields. Past researches have shown the control and reduction of soil erosion through irrigation control, afforestation, and soil stabilization with binder materials.

Orts et al. [43] added a series of biopolymers to irrigation water that were tested for their efficacy in reducing shear-induced erosion in a laboratory-scale mini-furrow. Suspensions of chitosan, starch xanthate, cellulose xanthate, and acid-hydrolyzed cellulose microfibrils, at concentrations of 20, 80, 80, and 120 ppm, respectively, reduced suspended solids by more than 80%. None of these biopolymers, however, exhibited the >90% runoff sediment reduction shown by the present industry standard, synthetic polyacrylamide polymers, PAM.

Kwon et al. [44] reported the surface erosion resistance of river-sand treated with several biopolymers that originated from micro-organisms, plants, and dairy products. They used a state-of-the-art erosion function apparatus with P-wave reflection monitoring. Experimental results have shown that biopolymers significantly improve the erosion resistance of soil surfaces. Specifically, the critical shear stress (i.e., the minimum shear stress needed to detach individual soil grains) of biopolymer-treated soils increased by 2 to 500 times. The erodibility coefficient (i.e., the rate of increase in erodibility as the shear stress increases) decreased following biopolymer treatment from 1×10^{-2} to 1×10^{-6} times compared to that of untreated river-sands.

1.4.4 Ground injection

Past studies have shown the efficiency of biopolymers in controlling the bleeding and washout of cement grouts due to their hydrophilic capacity and adhesive force for holding cement particles. Ghio et al. [45] reported that adding polysaccharide gums to cement pastes considerably affects their rheological properties. These admixtures are currently used in several practical applications such as anti-bleeding agents, anti-wash-out admixtures, and pump and sag resistance additives. The efficacy of these applications depends on the rheological properties of the grout. Experimental results showed that adding polysaccharide gum in cement paste systems significantly affects the viscosity at low shear rates than at higher shear rates. Additionally, a considerably high thixotropic behavior has been found in the form of an apparent viscosity recovery. This effect is higher for combinations of the polysaccharide gum and high-range water reducers.

Khayat et al. [46] reported the effects of combined additions of welan gum, a commonly used rheology modifier, and naphthalene-based high-range water reducer on the rheological properties of cement grouts are investigated for mixtures made with 0.40 water-to-cement ratios. Grouts with dosages of rheology-modifying admixture varying from 0 to 0.075 percent by mass of cement were prepared. Test results show that the increase in the rheology-modifying admixture dosage significantly increases the yield value and plastic and apparent viscosities of cement grouts. Combined with an adequate dosage of high-range water reducer, losses in fluidity are regained without significant reduction in stability. With the increase in high-range water reducer dosage, the apparent viscosity at low rates of shear decreases more dramatically than that at high rates of shear due to the pseudo-plastic behavior of such grouts.

1.4.5 Pavement and earth stabilization

The pavements are engineered with petroleum- or cement-based binders such as asphalt and concrete. Lee et al. [47] verified the feasibility of biopolymer application on local soil stabilization, specifically for road shoulder construction in Sri Lanka, by comparing the unconfined compressive strength (UCS) of local soil samples treated with cement-ash–based binders and xanthan gum biopolymer. The xanthan gum biopolymer–treated condition had significantly more UCS strengthening and high ductility than other treated conditions. Thus, xanthan gum biopolymer shows promising potential as an alternative material for road construction (particularly for shoulders and subbases) in Sri Lanka and other nations with similar climates and socioeconomic conditions.

1.4.6 Ground water control

In geotechnical engineering, hydraulic conductivity ground control is essential for soil liquefaction potential mitigation and ensuring the stability of soil dams or seepage structures.

Bouazza et al. [48] investigated the pore plugging effect of a series of biopolymers—guar gum, xanthan gum, and sodium alginate—and quantified their effectiveness in decreasing the hydraulic conductivity of a highly permeable silty sand soil. The result showed that the decrease in the initial hydraulic conductivity of the silty sand due to biopolymer induced-pore clogging exceeded three and four orders of magnitude, respectively, with 1% sodium alginate and xanthan gum. Furthermore, reducing at least four orders of magnitude can be achieved using as little as 0.5% xanthan gum, highlighting its superior pore-plugging effect.

Chang et al. [49] reported using gellan gum, a microbial polysaccharide in the food industry due to its hydrogel rheology was used to strengthen sand. The effects of gellan gum on the geotechnical behaviors of cohesionless sand were evaluated. The unconfined compression test results for the gellan sands (434 kPa) were comparable to 12% cement-treated sands (380 kPa). In terms of shear strength, the gellan sands showed considerable improvements in the cohesion and the friction angle of the sands. Also, due to the pore filling effects of the gellan hydrogels, the use of gellan is capable of decreasing the permeability of sands to 1×10^{-8} cm/s. The decrease in permeability when applying gellan gum into the soil is almost immediate; therefore, when used as a permeability-controlling barrier, gellan gum can provide a fast alternative to sufficiently reduce the permeability of soils.

1.4.7 Soil water retention

As biopolymers can adsorb an extreme amount of water relative to their own mass (e.g., 1 g of xanthan gum can adsorb 100 g of water), biopolymer treatment can change distinctive soil–water characteristics by enabling higher water retention.

Chang et al. [50] reported a soil treatment using biopolymers as an alternative method to prevent soil erosion and revitalization, considering engineering and environmental aspects. A series of laboratory simulations demonstrated that the presence of biopolymers has the potential to enhance soil erosion resistance and vegetation growth in arid and semi-arid regions by simultaneously improving inter-particle cohesion, producing relatively higher soil porosity under dry conditions, and increasing soil moisture retention due to the unique hydrogel characteristics of the biopolymer.

Chenu C [51] reported about the microorganization of complexes formed between clay minerals (Ca-kaolinite, Ca-montmorillonite) and a fungal polysaccharide (scleroglucan) with water content and apparent volume measurements. The results indicated that the strong water-stabilizing effect of fungal polysaccharides occurs without major microstructural rearrangements but could be related to the formation of stable organo-mineral networks.

1.5 Scope and objectives

This research is focused on the utilization of biopolymer as a potential stabilizing agent to enhance mechanical characteristics and hydraulic properties of Bauxite residue (red mud tailings) and Coal mine overburden waste, to show as a sustainable substitute material to cement and lime. The main objectives of this study are as follows.

- To investigate the effect of biopolymer individually and as a composite on the geotechnical properties of bauxite residue.
- To investigate the effect of biopolymer on the geotechnical properties of Coal mine overburden waste.
- To investigate the effect of thermo-gelation biopolymer on the mechanical characteristics and durability of bauxite residue.
- The Morphological study was performed for the determination of mineralogical and microstructural changes due to biopolymer stabilization.
- Economic feasibility and future challenges of biopolymer for soil/waste treatment.