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APPLICATIONS OF BIOPOLYMERS IN DAM CONSTRUCTION AND OPERATION ACTIVITIES

Mohammad Aminpour* **and Brendan C. O'Kelly***

*Department of Civil, Structural and Environmental Engineering,
Trinity College Dublin, Dublin, Ireland
e-mail: aminpoum@tcd.ie; bokelly@tcd.ie

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Abstract. *The investigation of innovative and sustainable solutions is a continuing concern within civil engineering activities. The use of environmentally friendly materials in place of traditional chemical substances is a key aspect. Biopolymers are high-molecular-weight molecules produced by many species of biological cells. Biopolymers are recognised as an alternative to conventional chemical polymers because of their potential cost savings, low environmental impact, non-toxicity and non-secondary pollution. Some geotechnical and geoenvironmental applications of biopolymers currently being explored include: cementation of soils to enhance strength; bearing capacity and liquefaction resistance; soil erosion control; reducing hydraulic conductivity; groundwater flow control and remediation of soil and groundwater impacted by metals and radionuclides. This paper reviews reported applications of biopolymers in dam construction and operation activities, highlighting some geotechnical applications that should be investigated further in practice to examine their feasibility and efficiency. The implementations discussed include the biopolymer trench method for construction of filters/drains, the biopolymer slurry technique for installation of permeable reactive barriers, and the treatment of highly turbid raw water in dam reservoirs by coagulation/flocculation processes using biopolymers. Generally, this paper aims to draw more attention to potential applications of biopolymers as potential alternatives to traditionally used chemicals which could lead the construction sector to more sustainable development.*

1 INTRODUCTION

Growing environmental concerns and awareness for greater strides towards sustainability have stimulated renewed interest in the use of biomaterials in civil engineering activities, with an expected improvement in environmental friendliness on account of lower energy consumption and carbon-dioxide neutrality. Biopolymers are naturally occurring polymers derived from plant, animal, algae, fungus or bacteria sources and are primarily comprised of polysaccharides. Agricultural scientists first considered the application of biopolymers to soil as a stabilizing agent in the 1940s. However the inadequate pace of advancement of biotechnology and lack of understanding of the interaction mechanisms between the soil and biopolymer have been major concerns in using this technology.

When mixed with water, commercially available biopolymer powder functions as a colloid to thicken water-based systems producing gels, which can act as emulsion

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stabilizers, binders or lubricants. Biopolymers currently have a wide range of applications in various industries; e.g. as a drilling fluid or for enhanced oil recovery in the oil industry or as food additives in the food industry[1]. Recently, several studies have examined the application of biopolymers in the geotechnical field, demonstrating the promising potential of this technology in soil strengthening, reduction in permeability coefficient, stabilization, liquefaction hazard mitigation, etc. This paper presents an overview of the potential applications and experiences to-date in using biopolymers for various activities related to dam construction and operation.

2 GENERAL APPLICATIONS OF BIOPOLYMERS FOR GROUND IMPROVEMENT

Following significant concerns about the production of environmentally unfriendly chemicals, a progressive approach has evolved over the last decades to examine the possibility and efficiency of using eco-friendly materials in industrial activities. Ground improvement techniques, as major activities in the construction sector, are no exception to this trend. A number of researchers have studied the potential applications of biopolymers as non-hazardous materials for ground improvement, especially for soil cementation and clogging. Some research achievements regarding the application of biopolymers as soil modifiers are listed in Table 1.

3 BIOPOLYMER APPLICATIONS IN DAM CONSTRUCTION

3.1 Biopolymer slurry method for drain/filter/reactive barrier trench excavation

When seepage emerges on the downstream slope of an embankment dam, it can cause sloughing of the slope and (or) lead to piping (internal erosion) of the dam materials. Conventional methods to protect the embankment against through-seepage include toe drains and chimney drains. When an embankment is located on pervious deposits overlain by little or no impervious material, a partially penetrating toe trench including a perforated collector pipe can substantially reduce seepage occurring near the embankment toe[9]. In such cases where drainage and (or) filtration are required at the downstream toe, a high groundwater table or confined aquifer can make drain/filter installation difficult in open excavation construction. An alternative method to install the drain and (or) filter is the slurry trench excavation method.

When the reservoir of a dam is subject to intermixing with contaminated aquifers, permeable reactive barriers (PRB) are one of the most widespread techniques used for groundwater remediation. Over the past two decades, the use of iron-based PRBs has evolved from innovative to accepted standard practice for the treatment of a variety of groundwater contaminants. The concept of PRBs is relatively simple: reactive material mixed with the trench backfill intercepts the subsurface contaminated plume moving under natural gradient. Physical and chemical processes occurring inside the barrier transform the contaminants into less harmful or immobile species[10].

The use of a slurry trench for drain/filter/reactive barrier construction seems counterintuitive since slurry trenches are often used to construct cut-off walls through dams. The use of bentonite slurry material is also contrary to construction of a drainage element that provides high permeability relative to the surrounding ground. To overcome these obstacles, a slurry trench method has been developed using a degradation technology. Instead of the more commonly used bentonite admixture in slurry applications, a synthetic biopolymer or other organic admixture is employed in this method. These admixtures are mixed with water to produce slurry that supports the trench for long enough to allow the installation of a perforated pipe system, geomembranes, etc., before placement of the filter/drain/reactive backfill material. The slurry material remaining in the trench biodegrades, thereby allowing the trench to function as a flow interceptor[9].

3.1.1 Case histories

Permeable reactive barriers excavated using biopolymer slurry method

One of the earliest applications of the biopolymer slurry method was reported in 1988 and concerned the successful remediation of an underground diesel fuel spill in San Jose, California, USA[11]. In this project, a pair of gravel-filled extraction trenches was constructed (the first 107 m long and 13.5 m deep; the second 73 m long and 14 m deep) using guar-gum based slurry in the process. A similar methodology was apparently used earlier (pre 1982) in France for the construction of drains for dewatering and slope stabilization[12].

Soil type	Biopolymer material	Test	Soil parameter: Initial	Soil parameter: After remediation	Reference
Clay (kaolinite)	Guar gum	1D consolidation	Compression index, $C_c = 0.62$	$C_c = 0.42$ and 0.64 for 0.5% and 2% biopolymer, respectively	Nugent et al.[2]
	Xanthan gum			$C_c = 0.64$ and 1.03 for 0.5% and 2% biopolymer, respectively	
Fontainebleau sand	- Agar - Modified starches	Unconfined compression. Triaxial compression	Cohesion intercept, c = 0; Friction angle, $\phi = 32.3°$	- c = 190 kPa for 4% agar; - $\phi = 26.3°$ for 4% agar - c = 240 kPa for 1% agar plus 1% Starpol 136; - $\phi = 17.6°$ for 1% agar plus 1% Starpol 136	Khatami and O'Kelly[3]
Medium quartz sand	Xanthan gum	Constant head permeability. Using a triaxial cell	Permeability coefficient, $k_o = 8.46\times10^{-5}$ m/s	8.65×10^{-10} and 3.14×10^{-8} m/s for 0.5% biopolymer after 1 and 28 days, respectively	Wiszniewski and Cabalar[4]
				2.84×10^{-11} and 6.84×10^{-11} m/s for 1.5% biopolymer after 1and 28 days, respectively	Wiszniewski, et al.[5]
Korean residual soil (Hwangtoh)	Beta-1,3/1,6-glucan polymer	Laboratory elastic wave velocity test	Shear wave velocity, $v_s = 255$ m/s	$v_s = 307$ and 347 m/s for 0.05% and 0.25% biopolymer, respectively	Chang and Cho[6]
Ottawa sand	Xanthan, polyhydroxy butyrate (PHB), guar gum, polyglutamic acid (PGA) and chitosan	Laboratory-pressurized pumping flow system	$k_o = 1.75\times10^{-4}$ m/s	Decrease in permeability ratio (k_o/k) observed: dramatic reduction in ratio by factor of 10^{14} for PHB; 10^7 for PGA and chitosan; 30 for guar gum and 8 for xanthan.	Khachatoorian et al.[7]
Korean residual soil (Hwangtoh)	Commercial beta-1,3/1,6-glucan polymer solution (Polycan™)	Unconfined compression	Compressive strength = 1.05 MPa	2.17 and 4.31 MPa for 2.46 and 4.92 g/kg (biopolymer/soil), respectively	Chang and Cho[8]

Table 1: Experimental research achievements for soil improvement using biopolymers

A permeable iron-reactive barrier (68.5 m long, 0.6 m wide and 9.1 m deep (reaching bedrock)) was installed in 1997 at Oak Ridge, Tennessee, USA[13]. Guar-gum biopolymer slurry was used during trench excavation to prevent the sidewalls from collapsing. Almost three years of monitoring data indicated that the barrier was performing effectively in removing contaminant radionuclides, such as uranium and technetium.

A permeable reactive barrier (120 m long, 0.6 m wide and 13 m deep) was designed in 2006 to remediate a chlorinated hydrocarbon plume at an old industrial landfill site in Avigliana, near Torino, Italy[10]. The barrier installation was achieved using a clamshell for the trench excavation and guar-gum slurry to support the sidewalls. The performance of this technique was outstanding and allowed the installation of the PRB in 7 days.

Filters/drains excavated using biopolymer slurry

In 1994, the United States Bureau of Reclamation rehabilitated 24 km of the Central Arizona Project dikes near Phoenix using a synthetic biopolymer slurry trench-excavation method, with tremie placement of the sand backfill to form a chimney drain[9,14]. Also in 1994, a wall drain was constructed using biopolymer slurry at Hays Creek Dam, Hunua Gorge, South of Auckland, New Zealand[15]. This dam is a rolled-earth embankment, 27 m high at its deepest section, having a crest length of 77 m. Investigations performed between 1989 and 1992 into the safety and operation of the dam concluded that the reliability (factor of safety against instability) of the dam should be increased by installing a graded sand chimney drain along the downstream edge of the clay core. The wall drain was excavated using biopolymer slurry support[16]. Monitoring data from seepage volume and piezometer instruments gathered over a two-year period after completion of the dam rehabilitation works indicated that retrofitting had enhanced the operational safety of the Hays Creek Dam[15].

Another successful biopolymer slurry drain construction project is Wasco Dam, Clear Creek, USA[17,18]. This zoned embankment dam was built in 1959, with a structural height of 15.5 m and crest length of 127 m. In 1996, heavy precipitation caused the reservoir to fill to the normal maximum pool for the first time in the proceeding 20 years, causing significant seepage through the dam, giving urgency to dam safety concerns. The most viable repair works involved the construction of a filter toe drain having dimensions of 76 m long, 1.0 m wide and up to 6 m deep. The new drain was constructed in the fall of 1999 using a modified polyacrylamide drilling fluid as degradable biopolymer slurry. It was reported that the success of the filter and drain rehabilitation was demonstrated by the elimination of downstream seepage and the lack of sand/fines deposited in the sediment trap within an inspection well located beyond the newly installed drain[17,18]. In other words, the filter prevented piping from occurring within the dam, with the piezometer data showed that the filter was sufficiently permeable.

The susceptibility of the embankment materials to liquefaction, the presence of alluvial soils near the toe in addition to an unfiltered drain led the owner of the Piute Dam (Utah, USA) to construct a new deep drain beneath its downstream toe. The 100-year-old dam, with a crest length of 427 m and height of 27.5 m, was constructed during the early 1900s by local farmers and ranchers. The rehabilitation scheme included the construction of a 139 m long by 10 m deep trench excavated by biopolymer slurry in 2005. Post-construction piezometer data showed that the phreatic surface upstream of the drain was at the target design level and that the drains were flowing at about the expected volume[19,20].

3.1.2 Materials and methods

The most common biopolymer used for slurry trenching is guar gum; a naturally occurring carbohydrate polymer derived from the bean of the guar bush. This biopolymer is relatively low cost, is easy to break down and its characteristics as slurry material can be maintained using additives[21]. Guar-gum based slurries normally have an effective life of only about one day. By adding preservatives to the guar gum during hydration, the life of the slurry can, with subsequent treatment, be extended to up to a few weeks[22]. Slurry treatment involves the addition of pH modifiers and preservatives. The slurries effective life is also affected by environmental conditions, soil type and construction expertise. Standard tests include viscosity, filtrate loss (a measure of the slurries ability to form a low permeability filter cake) and other tests specified in ASTM D4380. Guar gum-based slurries provide high gel strength (viscosity > 40 cP) and low water loss (filtrate < 25ml), which permits the efficient transfer of the elevated hydrostatic head of the slurry to the trench sidewalls, thereby providing trench stability. Note that, as an alternative or combinative to guar slurries, some synthetic polymers can be employed and which degrade in a similar fashion. To date, synthetic polymers have seen limited use and only in applications where trench stability is not critical[22]. For instance, equal proportions by mass of powdered guar gum and synthetic polyacrylamide solution mixed with water (along with small quantities of other chemicals to buffer the pH and extend the effective life) was used to support the trench sidewalls for the Piute Dam project[19].

The effective life of guar-gum slurry is a function of the soil and groundwater chemistry, temperature as well as the frequency and type of retreatment in the slurry trench. Figure 1 shows the relationships between viscosity, filtrate loss and pH of guar gum slurry against elapsed time from laboratory testing[11]. On approximately the eighth day, the slurry begins to naturally breakdown, as indicated by the decrease in pH value and large increase in filtrate loss. The viscosity remains consistent until the twelfth day, indicating that while the slurry is no longer functional, it must degrade further in order to activate the drain[11]. Soda ash (sodium carbonate) can be used to maintain an appropriate pH for the slurry. Glutaraldehyde is used as a preservative to extend the slurry life by slowing its degradation process expected from naturally occurring microbes.

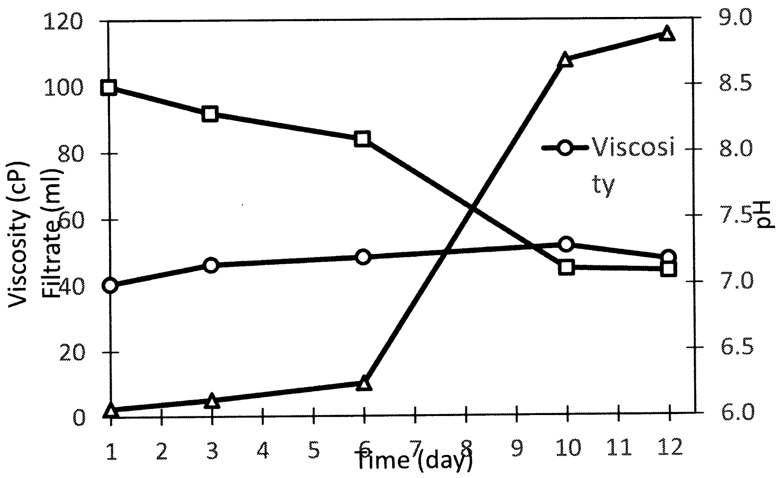

Figure 1: Viscosity, filtrate loss and pH against time period for guar-gum slurry (adopted from Hanford and Day[11])

Once installation is complete, the trench can be sluiced with dilute chlorine solution (e.g. 50/50 water/Clorox®) in order to break the polymer strands and facilitate pumping of the slurry from the trench during placement of the backfill material to develop the drain[9]. For instance, in the case of Hays Creek Dam, water and sodium hypochlorite were pumped through the sand/slurry in the trench to degrade and remove slurry, leaving the sand as a filter at the required permeability in the trench. Degraded slurry remaining in the trench can be 'polished' to reduce potential odours by adding oxidizers; e.g. chlorine or hydrogen peroxide. Oxidizers are not added to reactive backfills such as zero-valent iron, where they could reduce the reactivity of the backfilled material[21].

3.1.3 Typical construction procedure

The phases undertaken during the installation of drain/filter/reactive barrier trenches using biopolymer slurry can be broadly summarized as follows. A level working platform is prepared and panel walls (curbs) are installed to guide the crane and contain the slurry. For drain rehabilitation applications, a driven sheet-pile wall temporarily isolates the existing drain so as to minimise slurry loss into the old drain. The trench is excavated in bays (panels) using the slurry method, with steel separating tubes positioned to avoid slurry exchange between neighbouring bays. For drain rehabilitation applications, geomembrane sheets are placed, as required, in the trench to permanently assist in isolating the existing drain. A network of perforated pipelines is installed in the slurry trench allowing the circulation of enzymes to degrade the contained biopolymer slurry. The pipe network is removed from the trench after which the filter/drain/reactive material is placed. This is achieved using a tremie operation or by sliding the backfill down the slope of previously placed material, displacing the slurry and minimizing segregation, before compaction[9,10,20].

4 BIOPOLYMER APPLICATIONS IN DAM OPERATION

4.1 Reservoir water treatment

Drinking water treatment aims to produce biologically and chemically safe water for human consumption which is also aesthetically pleasing in terms of odour, appearance and taste. Turbidity is one of the most important factors in determining drinking water quality. Turbidity is caused by impurities or colloidal and suspended substances; e.g. dissolved minerals (as iron), silt, fine organic and inorganic matter, algae (phytoplankton) and other microscopic organisms (virus, bacteria, etc.). A combination of physical and chemical processes are used to produce potable water, including coagulation/flocculation (considered the most important process), followed by settling, filtration and (or) flotation. Biopolymers can, as environmentally-friendly coagulants, be proposed as important alternatives for drinking water treatment. These materials are efficient at low dosage, which gives them the added benefit of a reduction in sludge volume while not significantly impacting on pH and alkalinity[23].

4.1.1 Case studies

In 2002, Divakaran and Pillai[24] reported the successful use of the biopolymer chitosan in reducing the turbidity of water, with a removal efficiency of greater than 90% achieved in their study. Subsequently, in 2006, Sekine et al.[25] reported the use of chitosan in the treatment of turbid river water. Their results showed that the turbidity removal efficiency was good when the turbidity was less than 1000 NTU (Nephelometric Turbidity Units), but the coagulation process failed for greater than 1000 NTU. Hence the use of monocoagulants, such as chitosan, may not prove an appropriate means of purifying highly turbid water.

From laboratory testing, Hu et al.[26] found that coagulation using a mixture of coagulants (namely chitosan and aluminium chloride) can effectively purify extremely turbid water (~10000 NTU). The residual turbidity was less than 10 NTU and the sludge volume ratio was ~30–40 ml/l of raw water. The residual aluminium concentration in the water treated using the coagulant mixture was significantly less than that for coagulation with aluminium chloride alone. These results suggest that greater economic and environmental benefits can be achieved if this coagulant mixture were used instead of traditional coagulants for the treatment of high turbid water.

In another study in 2012, the raw water from Keddara Dam (east of Algiers, Algeria), characterized by low turbidity, was treated using chitosan alone and as coagulant aid with aluminium sulphate (alum). The results showed that, when used as the primary coagulant, chitosan was not as efficient as alum for treating the Keddara raw water. However, when used as a coagulant aid with alum, the highest turbidity removal (97%) achieved was for 0.2 mg chitosan/l raw water[23].

Furukawa et al.[27] investigated the effect of different types of organic matter (OM) species (i.e. anionic biopolymer, non-ionic biopolymer and humic substances) on the flocculation of suspended particles in water. Their study employed a series of laboratory experiments in which an aqueous suspended mineral (montmorillonite clay) was mixed with different OM species (xanthan gum, guar gum and humic acid) to produce a range of OM-to-clay loading ratios and then with further water to produce a range of salinity values. Their results indicated that biopolymers promote flocculation but its amount depends on the biopolymer type and concentration. Non-ionic guar gum produced much larger flocs than anionic xanthan gum, with flocculation for both biopolymers most pronounced for intermediate OM loading; i.e. total organic carbon concentration of about 5 mg/l. Further, the effect of guar gum was independent of salinity whereas the effect of xanthan gum was pronounced at higher salinity (7–17.5 psu (practical salinity units)).

Zemmouri et al.[28] reported on the treatment of the raw water from Beni-Amrane Dam (Algeria) using chitosan as primary flocculant and also as a coagulant aid with alum. The performance was evaluated by measuring the supernatant's residual turbidity for different chitosan concentrations. At low concentrations, chitosan when used as primary flocculant was able to reduce the initial turbidity by 85%. As a coagulant aid with alum, the highest turbidity removal (97%) was observed for 0.15 mg/l of chitosan and 20 mg/l alum.

4.1.2 Materials

Flocculation is caused by the addition of minute quantities of chemicals known as flocculants. Inorganic and organic flocculants have been investigated in a number of studies. Among biopolymers, guar gum, xanthan gum, starch and alginic acid have been frequently used as flocculants and coagulant aids[29]. Chitosan, a natural biodegradable linear cationic polymer, has shown a promising capability to act as a coagulant having been used to treat metal ions, colloidal particles, humic acids, cryptosporidium cysts and other bio-microspheres. Chitosan has similar properties to synthetic polymers but it has relatively low toxicity for humans and aquatic species. Moreover, it contains amino and hydroxyl functional groups, which show significant adsorption capacity for various pollutants[26].

5 DISCUSSION

5.1 Advantages

Biopolymers can be sustainable, non-toxic for human health, carbon neutral and are renewable because they are mostly made from plant materials (from agricultural non-food crops) that can be grown indefinitely. Hence the more widespread use of biopolymers in civil engineering would create a sustainable industry. In contrast, the feed stocks for polymers derived from petrochemicals will eventually deplete. Further, biopolymers have the potential to cut carbon emissions and reduce CO_2 quantities in the atmosphere. This is because the CO_2 released when they degrade can be reabsorbed by crops grown to replace them, thereby making the process close to carbon neutral.

The biopolymer slurry method for drain/filter/reactive barrier trench excavation has several significant advantages over conventional excavation methods (e.g. sheet piling, trench boxes, dewatering and mass excavation), including:

- *Economy*. Installation costs are considerably lower (typically half of conventional construction) since the technique does not require dewatering or sheeting and shoring. For instance, by using the slurry-trench method of construction at Piute Dam, cost savings of approximately $2 million were realised.
- *Schedule*. The construction time is much shorter than for conventional trenching methods for the reasons cited above.
- *Safety*. Nobody enters the excavation with the biopolymer slurry technique so it leads to much safer construction. There is also less potential for damage to surrounding structures from dewatering and (or) excavation activities compared with, for example, open cut construction.
- *Environmental*. In addition to the generic eco-friendliness of biopolymers, another important advantage, especially for PRB construction, is that the biopolymer slurry method requires a narrower trench and hence generates less excavation spoil. There is also no water generated by temporary dewatering systems. These features are particularly advantageous for applications on contaminated sites[22].

5.2 Disadvantages/challenges

While a major advantage in drain excavation activities, degradability of the biopolymer materials can be the main concern when used in ground improvement applications. The durability of bio-cemented/bio-clogged soils is currently the subject of further studies.

For biopolymeric slurries, the guar-gum slurry formulation is more complex than bentonite slurry (up to 10 additives may be required) and, furthermore, this slurry can be broken down by naturally occurring microorganisms and (or) by the introduction of chemicals or enzymes. The challenge when using biopolymer slurry in construction is to keep the slurry active for long enough to allow completion of the required construction activity. Without additives, the slurry may lose viscosity and its ability to support the open trench. With additives (biocides) and (or) pH control, the effective life of the slurry can be extended to up to a few weeks. While biopolymer slurry is resistant to most chemical contaminants, higher temperatures and concentrated microorganisms (e.g. from a septic field) can create a situation where the stability of the slurry is more difficult to control. Low temperatures, variable groundwater chemistry and sterile conditions may reduce the efficiency of the slurry breakdown[21].

6 CONCLUSION

A number of applications for biopolymers in the construction and remediation of dams (e.g. potential uses in ground improvement, slurry trenching) and as flocculants for water treatment have been presented. The paper emphasized the continuing promise for the potential application of biopolymers in dam construction and operation activities. Although many studies have reported the successful use of biopolymers in soil improvement experiments, it appears that a series of full scale long-term field studies are required in order to confirm the feasibility of biopolymer technology as an alternative to traditional approaches for soil cementation and water-proofing. Further research should be encouraged to account for the possibility of some other potential applications of biopolymers in construction and environmental activities; e.g. construction of impervious zones for earth dams, compacted soil covers for landfills, encapsulation of hazardous materials, zonal bioremediation, etc.

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