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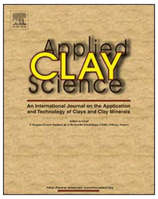

Research paper

Hydraulic performance of anionic polymer-treated bentonite-granular soil mixtures

Erol Guler[a], Hakki O. Ozhan[b,*], Selcuk Karaoglu[a]

[a] Bogazici University, Department of Civil Engineering, 34342 Bebek-Istanbul, Turkey
[b] Altinbas University, Department of Civil Engineering, Mahmutbey Dilmenler Cad., No. 26, Bagcilar-Istanbul, Turkey

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ABSTRACT

In this study, hydraulic conductivity and viscosity determination tests were performed on two different bentonite-granular soil mixtures having various amounts of bentonite in order to obtain the optimum mixture to be used as a liner for waste containment facilities. To enhance the hydraulic capability of these mixtures, an anionic polymer was added to the bentonite. In bentonite-granular soil mixtures, two different aggregate compositions were used: A typical aggregate composition used in the production of C20 type concrete with a void ratio of 0.33 and an aggregate composition with a void ratio of 0.21 that was the minimum void ratio determined by testing various granular soil compositions. In these two mixtures, the bentonite content varied from 8 to 15% whereas the polymer content was within the range of 0.5–10% by mass. Test results indicated that intrinsic permeability decreased drastically due to an increase in the bentonite content. 15% bentonite addition caused a decrease of almost 5.5 orders of magnitude when compared with the granular soils without any bentonite content. 2% anionic polymer addition resulted in a decrease of approximately 2.5 orders of magnitude in hydraulic conductivity. However, further increase in polymer content had almost no effect on lowering hydraulic conductivity. 2% polymer addition in bentonite-granular soil mixtures provided hydraulic conductivity values as low as 10^{-11} m/s. The decrease in hydraulic conductivity was attributed to the increase in the viscosity of the fluid. Due to polymer addition, an inverse relationship existed between hydraulic conductivity and intrinsic permeability. As a result, polymer-treated bentonite-granular soil mixtures can effectively be used as barrier layers in waste containment facilities.

1. Introduction

The main purpose of a waste containment facility is to protect the soil and the groundwater against a possible contamination due to the advection of the wastes through the soil. This protection is provided by placing a lining material over the soil that functions as a barrier. Compacted clay liners (CCLs), geosynthetic clay liners (GCLs), geomembranes, bentonite-sand mixtures and cement stabilized products are the most preferred lining materials that are used in waste containment facilities (Sallfors and Hogsta, 2002; Rowe et al., 2004; Chien et al., 2006; Müller, 2007).

Bentonite-sand mixtures are widely used as barriers to control the movement of leachates in waste containment facilities due to the fact that they have relatively high strength, low compressibility and very low hydraulic conductivity. These engineering properties are obtained by using a mixture that contains enough sand to ensure the stability of the compacted mixture and enough bentonite to fill the voids between the sand particles (Sallfors and Hogsta, 2002). Normally, the dry mass of the bentonite in the mixture should be within the range of 4–13% of the dry mass of the sand. Greater amounts of bentonite might result in high plasticity and consequently, it becomes difficult to compact the mixture. Furthermore, the decrease in hydraulic conductivity becomes marginal and cost-effective for a waste containment facility design (Chapuis, 1990). On the other hand, a coarse-grained material that has a high amount of sand might have a considerably higher hydraulic conductivity than a fine-grained material due to the enlargement of the voids (Sallfors and Hogsta, 2002).

The field hydraulic conductivity of the clay liners compacted at wet of optimum was found to be lower than that of the clay liners compacted at dry of optimum due to the numerous macropores observed on the clay textures when the clay liners were compacted at dry of optimum (Benson and Boutwell, 2000). Mitchell et al. (1965) also indicated that the lowest hydraulic conductivity values were obtained when the clay liners were compacted at a water content of slightly wet of optimum.

Some water-soluble polymers have been used to stabilize deep

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* Corresponding author.
E-mail addresses: eguler@boun.edu.tr (E. Guler), hakki.ozhan@altinbas.edu.tr (H.O. Ozhan).

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excavations such as pile bores and diaphragm wall trenches. In these civil engineering applications, polymer-treated fluids had several advantages over bentonite slurries including lower environmental impact, smaller site footprint and lower construction cost (Lam and Jefferis, 2014). Anionic polymers carry negative charges and they may contain nonionic polar groups such as OH^- or carboxyl groups such as COO^- (Güngör and Karaolan, 2001). The adsorption of nonionic or weakly ionic polymers is the consequence of the Van der Waals forces or hydrogen bonding between the polymer and the clay minerals. Most of the anionic polymers are manufactured from *co*-polymerization of acrylamide and acrylic acid or its inorganic salts. Güngör and Karaolan (2001) stated that the rheological properties of bentonites and the formation of gel structures that were in contact with water were altered by the addition of polyacrylate. A small concentration of polymer has a significant impact on the hydraulic conductivity of a marginal quality bentonite. According to the test results obtained by Güngör and Karaolan (2001), addition of 0.5% polymer resulted in a decrease of approximately 2 orders of magnitude (from 10^{-7} m/s to 10^{-9} m/s) in hydraulic conductivity. Razakamanantsoa et al. (2012) performed oedometer tests on Ca-activated GCLs treated with both anionic and cationic polymers that were in contact with chemical solutions having Ca^{2+} and Mg^{2+} ions. Test results indicated that adding either a cationic or an anionic polymer to the GCLs enhanced the hydraulic performance of the GCLs by decreasing the hydraulic conductivity. Hydraulic conductivity of the GCL without polymer treatment, anionic polymer-treated GCL and cationic polymer-treated GCL were measured as 8×10^{-10} m/s, 2×10^{-11} m/s and 5×10^{-11} m/s respectively. De Camillis et al. (2017) performed hydraulic conductivity tests on sodium bentonite and the same sodium bentonite treated with an anionic polymer with an amount of 2 and 8% by mass in the bentonite-polymer mixtures. The anionic polymer consisted of sodium carboxymethyl cellulose and the mixtures were subjected to wet-dry cycles and permeated with seawater that represented an aggressive solution. Hydraulic conductivity of the bentonite without polymer treatment and 2% anionic polymer-treated bentonite during the fourth cycle was measured as 3×10^{-7} m/s and 3.5×10^{-10} m/s respectively. Furthermore, 8% anionic polymer-treated bentonite had a hydraulic conductivity of 9.1×10^{-11} m/s during the third cycle. According to these results, polymer treatment improved the hydraulic properties of the bentonite even during wet-dry cycles. A bentonite slurry was prepared by mixing 5% amount of calcium bentonite and up to 1% amount of a polymer that was composed of sodium carboxymethylcellulose with water (Ben Azouz et al., 2016). The slurries flowed as liquids when the stresses were greater than a yield stress; on the other hand, the slurries behaved as gel-like structures when the stresses were lower than a yield stress. The polymer chains resulted in an elastic network of aggregate particles and these particles formed the gel-like structures that could be stated as an improvement in the barrier capacity of the bentonite.

Generally, polymer treatment improves the hydraulic capability of the soil. However, fluid loss tests performed on a sodium bentonite treated with a cationic polymer up to an amount of 2% by mass caused an increase in the flux of the bentonite that was permeated with deionized water (Liu et al., 2012a). On the other hand, increasing the amount of anionic polymer from 1 to 2% by mass did not cause any significant change in the flux of the sodium bentonite. Liu et al. (2012b) performed free swell tests on sodium bentonites treated with either an anionic or a cationic polymer. The permeant fluid was chosen as deionized water. According to the test results, swell index of the anionic polymer-treated bentonite increased almost linearly when the polymer amount in the mixture was increased up to 2%. However, swell index of the cationic polymer-treated bentonite decreased when 0.5% amount of polymer by mass was added to the mixture and then, increased non-linearly when the amount of polymer in the mixture was increased up to 2%.

The viscosity of a fluid treated with a polymer was measured lower than that of a bentonite slurry at lower shear rates (Lam et al., 2015). However, the polymer-treated fluid became more shear-thinning at higher shear rates which resulted in an increase in the viscosity. Generally, adding an anionic surfactant to the bentonite suspension causes a decrease in viscosity. However, addition of an anionic sodium dodecyl sulfate surfactant having a concentration range of 1×10^{-2}-2×10^{-2} M to the bentonite suspension resulted in an increase in viscosity (Abu-Jdayil et al., 2016). Moreover, Geng et al. (2016) performed viscosity tests on deionized water and 0.3 M NaCl solution that were mixed with an anionic polymer named as polyacryamide acrylic acid sodium salt. Polymer content varied from 2 to 5% by mass. Viscosity with 2 and 5% polymer was measured as 40 and 80 cP respectively in deionized water whereas 2 and 5% polymer-treated 0.3 M NaCl solutions had viscosities of 27 and 70 cP respectively. According to the results, viscosity increased with an increase in the anionic polymer content. Furthermore, low viscosity resulted in a coiled polymer distribution and these coiled polymer particles could be easily separated when the polymer was mixed with bentonite.

Ratkievicius et al. (2016) mixed a cationic polymer that contained high amounts of NH_4^+ cations with bentonite. The mixture was permeated with a fluid that was composed of soybean oil, lauryl alcohol triethoxylate, brine and barite. The results indicated that the cationic polymer caused an increase in the viscosity of the fluid. On the other hand, addition of a cationic cetyltrimethyl ammonium bromide surfactant having a concentration range of $1\times 10^{-3} - 1 \times 10^{-1}$ M to the bentonite suspension led to a decrease in viscosity. The reduction in viscosity might be attributed to the formation of layers on the clay particles having positive excess charges which created dense aggregates that settled to sediments (Abu-Jdayil et al., 2016).

The objective of this study was to investigate the effect of an anionic polymer on various amounts of bentonite-granular soil mixtures and establish a correlation between polymer treatment and hydraulic performance of the bentonite-granular soil mixtures and viscosity. Furthermore, the effect of the bentonite content in the bentonite-granular soil mixtures on intrinsic permeability was also investigated.

2. Materials

In bentonite-granular soil mixtures, two different aggregate compositions were used; first, the typical aggregate composition used in the production of C20 type concrete (TS 802, 2009), second, an aggregate with the minimum void ratio determined by testing various granular soil compositions. In this study, these two aggregate compositions were named as Aggregate I and Aggregate II respectively. Aggregate I was composed of 29% no 2 crushed stone (22–12 mm grain size diameter), 29% no 1 crushed stone (12–5 mm grain size diameter), 24% stone powder (5 mm–0 mm grain size diameter) and 18% sand by mass (TS802, 2009). On the other hand, Aggregate II was composed of 20% no 2 crushed stone (22–12 mm grain size diameter), 20% no 1 crushed stone (12–5 mm grain size diameter), 20% stone powder (5 mm–0 mm grain size diameter) and 40% sand by mass. Gradations for each soil type used in both Aggregate I and Aggregate II were shown in Fig. 1a, b, c and d.

The bentonite clay that was used in the bentonite-granular soil mixtures was a granular, sodium bentonite with a liquid limit and plastic limit of 324 and 39 respectively. The bentonite was composed of 61.3% SiO_2, 17.8% Al_2O_3, 4.5% CaO, 3% Fe_2O_3, 2.7% Na_2O and 2.1% MgO.

The polymer that was added to the bentonite was a dry, granular, synthetic, anionic polyacrylamide which was manufactured from *co*-polymerization of sodium acrylate. This synthetic, anionic polymer was mainly preferred to be used in slurries for drilling, walling and trenching applications in diaphragm walls, drilled shafts, bored piles and tunneling (CETCO, 2015). It had a very high molecular weight with negative charges on the backbone (Muthukumar, 1981; CETCO, 2015). Its molecular weight and chemical formula were given as 105.99 and $[C_3H_3NaO_2]_n$ respectively. It had a solubility in water of 220 g/L