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Development of a new cementless binder for marine dredged soil stabilization: Strength behavior, hydraulic resistance capacity, microstructural analysis, and environmental impact

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HIGHLIGHTS

- A new cementless binder is developed for marine dredged soil (MDS) stabilization.
- General properties of the stabilized MDS mixtures showed significant improvements.
- The proposed MDS mixtures are classified as non-hazardous materials.
- The newly developed binder can be used to replace cement in the MDS stabilization.

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ABSTRACT

The primary goal of this study is to evaluate the strength behavior, hydraulic resistance capacity, microstructure, and environmental impact of marine dredged soil (MDS) after stabilization and its improvement without the use of cement. In this study, a new cementless binder, referred to as Fa-RmLG, was derived from fly ash (Fa), lime (L), gypsum (G), and red mud (Rm). During the MDS stabilization stage, a pilot experimental program (phase I) was conducted to identify the optimum water content in mixtures. Subsequently, MDS mixtures were synthesized with various proportions of Fa-RmLG, and the optimum water contents were determined (phase II). The general properties of MDS mixtures, including strength, stiffness (evidenced by the secant modulus), and hydraulic resistance capacity (e.g., critical shear stress, critical velocity, and scour rate), microstructure, and environmental impact (e.g., corrosivity, heavy metals), were measured. As a result, all general properties of the stabilized MDS mixtures demonstrated significant improvements (strength, stiffness, and hydraulic resistance capacity) as compared to those of the untreated MDS. In addition, in terms of environmental impact, it was found that the hardened MDS mixtures made with the new cementless binder were classified as nonhazardous materials as their corrosivity and heavy metal leachates were within the acceptable ranges listed in the Code of Federal Regulations of the US government (40 CFR 268.40). In conclusion, the feasibility of using the developed Fa-RmLG binder for the stabilization of MDS has been proven.

1. Introduction

Every year, large amounts of industrial by-products are generated from thermal power plants and chemical industries in South Korea. Among these, the main wastes are coal ash, red mud, and gypsum. Various problems arise from these wastes, including ash disposal. Correspondingly, leaching is expected to become a serious problem in the near future. Meanwhile, owing to the numerous harbor activities, enormous volumes of MDS are also dredged. These waste sources can cause unpredictable difficulties in their management. For this reason, these materials need to be recycled for geotechnical applications. Therefore, this study focused on the development of a new cementless binder to utilize the combination of various by-products, such as fly ash, gypsum, and red mud, for the stabilization of MDS. The stabilized MDS can then be used as a material to benefit coastal engineering works (breakwaters or shorelines). Fly ash, which is an unburned residue from

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an electrical generating station (i.e., as a by-product of burning pulverized coal), is collected in the boiler using the flue gases. In general, fly ash consists of spherical particles and is extensively used in controlled, low-strength materials, for many benefits, including good flowability, low segregation, bleeding, thus contributing to the characteristics of a cost-effective material [9,13]. In addition, fly ash is also introduced in concrete by lowering of the heat of hydration, improvement of durability, and by the reduction of the cost of concrete [24,30].

Red mud is the by-product of the Bayer process for manufacturing alumina from bauxite. In Korea, approximately 200,000 tons are discharged annually [17,7]. The chemical and mineralogical compositions of red mud are different from other types of red mud or from by-products of Bayer processing methodologies. However, six main components (Fe_2O_3, $A1_2O_3$, SiO_2, TiO_2, Na_2O, and CaO) are typically found in red mud. Furthermore, a well-known problem of red mud waste is its very high pH value (highly alkaline slurry) [33]. Gypsum is a by-product originating from the production of phosphoric acid based on a wet process. In Korea, 30 million tons of Gypsum accumulates as waste [22]. With the increased content of $CaSO_4$ (i.e., larger than 95%) in Gypsum, it is possible to make binders [32]. With regard to MDS stabilization, there have been a number of studies addressing this problem with various approaches [19,6,20,18,35,31,11]. In the study by Dermatas et al. [6], laboratory tests were performed on MDS to explore the possible uses of treated MDS as a backfill material. Portland cement was employed as the main binder in their study. The treated MDS was stabilized by adding cement (9%, 11%, and 13%) and water (90%, 130%, and 170%). The authors reported an improvement in the compressive strength up to 70 psi in the case when 11% cement and 90% water was used. In addition, the void ratio of stabilized MDS decreased at high-cement and low-water contents in the consolidation test. The same authors also reported an improvement in hydraulic conductivity after treatment. It was concluded was that it is feasible to reuse the cement-treated dredged material for transportation projects. Zentar et al. [35] performed a large-scale field test using marine MDS. Their work focused on evaluating the compatibility of these dredged soils, and the mechanical behavior and environmental impacts were considered in the long-term (periods over one year). Maher et al. [20] investigated the feasible use of dredged material in both laboratory and field tests. All geotechnical properties of the stabilized dredged materials were first explored in the laboratory test. In the field, the construction process was monitored when the material was used as a filling material. According to their results, the stabilized dredged material conformed to most geotechnical criteria for fill constructions. More recently, the utilization of fly ash (i.e., partial cement replacement) was also investigated for the stabilization of MDS. In the study by Silitonga et al. [31], the by-product of fly ash was partially used for the stabilization of MDS in road pavement work. The study's authors also concluded that it is possible to recycle MDS for the purpose of road pavement work as the stabilized MDS using fly ash performed well from the aspects of mechanical properties and cost-effectiveness. More recently, Kang et al. [11] discussed the applicability of cement-treated MDS (clay) for various applications of reclamation, or for use as construction materials. They focused on an evaluation of strength and stiffness of marine dredged clay with respect to the curing stages. However, the common point of these studies is that cement was employed fully or partially as the representative binder in MDS stabilization. It should be noted that the production of cement is connected with the emission of greenhouse gases, such as CO_2, SO_x, and NO_x. Meanwhile, South Korea ranks in the top 10 in the list of countries that produce carbon dioxide emissions from the combustion of fossil fuels and cement manufacturing (https://en.wikipedia.org/wiki/List lists countries based on their carbon dioxide emissions). For this reason, the development of a cementless binder using by-products is necessary and encouraged. Using industrial by-products in a cementless binder could not only reduce the natural raw materials (coal, limestone, and clay) and energy (electricity) consumption but also eliminate the emission of greenhouse gases and other toxic pollutants.

Correspondingly, the present study focuses on the development of a new cementless binder from various by-products (fly ash, gypsum, and red mud) as a potential replacement for Portland cement in MDS stabilization. The new cementless binder (Fa-RmLG) was made with a cementitious mixture composed of fly ash (Fa), red mud (Rm), lime (L), and gypsum (G). Subsequent to its synthesis, various stabilization MDS mixtures were produced with MDS and with different proportions of the newly proposed cementless binder. The reactions of pozzolanic materials, such as fly ash, activated by lime and red mud, would be effective factors in hardening and enhancing strength and other MDS properties. In addition, the presence of gypsum, which reacts with Al_2O_3 in the fly ash, red mud, and calcium oxide in lime, is believed to produce ettringites. This study evaluates the engineering properties and environmental impacts of MDS mixtures synthesized with the new cementless binder (Fa-RmLG) for possible use as a complete replacement for cement.

2. Experimental program

2.1. Materials

The soil used in the present study was fine MDS that originated from the Jeollabuk-do harbor in Jeolla province (South Korea). MDS is classified as silty sand. All physical MDS properties, such as its maximum dry density, optimum moisture content, liquid limit, plastic limit, and specific gravity, are tabulated in Table 1.

In this study, to develop the new cementless binder (Fa-RmLG), fly ash, red mud, lime, and gypsum were employed. The fly ash used herein was generated in a thermal power plant in Jeolla province. The red mud was obtained from a Bayer processing plant also in Jeolla province. It was passed through sieve number 200 to be used in the experimental program. During the production of phosphoric acid based on the wet process, gypsum wastes were first ground to powder, and then subjected to the temperatures of 110–120 °C to remove the water of crystallization and finally produce calcium sulfate hemihydrate ($CaSO_4{\cdot}1/2H_2O$). The specific gravity of gypsum used in this study was 2.32. The particle size distributions of raw materials are listed in Fig. 1. The chemical compositions of all raw materials shown in Table 2 were obtained by the X-ray fluorescence (XRF) MiniPal 2/PANanalytical (Netherlands).

SEM images depicting the particle surfaces of raw materials are shown in Fig. 2. The X-ray diffractometer of both raw materials (MDS, fly ash, gypsum, and red mud) and stabilized MDS are shown in Fig. 3. From the results obtained using the X-ray diffraction (XRD) patterns, it was found that MDS contained mostly quartz, a little Calcite, Halite (NaCl), and Pyrite. In addition, well-known components of quartz and mullite were found in fly ash. While some mineral components (quartz, gibbsite, hedenbergite, and hematite) were observed in red mud, gypsum mainly consisted of Anhydrite ($CaSO_4$) and Bassanite ($CaSO_4{\cdot}0.5H_2O$).

2.2. Test procedures and mixture proportions

A comprehensive experimental program was planned to evaluate the strength behavior, hydraulic resistance capacity, microstructure, and environmental impacts of MDS mixtures made with the new cementless binder. Table 3 shows the mix