



Performance Evaluation of Chlor-Alkali Process Waste in Marl Soil Stabilization with Emphasis on Unconfined Compressive Strength

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ABSTRACT

The growth of the petrochemical industry in Iran has resulted in the generation of substantial quantities of chemical waste, posing a significant environmental challenge in terms of waste management. Chlor-alkali process waste predominantly contains calcium carbonate and magnesium hydroxide, and its composition provides potential for beneficial reuse in various applications, including as a filler in construction materials, a neutralizing agent, and a stabilizing material for problematic soils. Marl soils are also highly sensitive to moisture variations and may experience substantial reductions in strength, with strength losses of up to 80% reported with increasing moisture content. Conventional soil stabilization methods, particularly the use of cement and lime, have limited environmental sustainability due to their high energy consumption and associated greenhouse gas emissions. Therefore, this study investigates the feasibility of utilizing chlor-alkali waste from Bandar Imam Khomeini as a low-cost stabilizing agent to improve the mechanical properties of marl soil. In this laboratory study, marl soil specimens were mixed with 30% chlor-alkali waste by dry weight, both with and without alkaline activators. The specimens were subsequently cured for 7 days and subjected to unconfined compressive strength (UCS) testing. The results showed that the addition of chlor-alkali waste increased the compressive strength from 90 kPa for the untreated control specimen to 123 kPa for the stabilized specimen, corresponding to a 35.66% improvement in strength. This enhancement in strength is attributed to the formation of hydrated calcium silicate and magnesium silicate phases resulting from pozzolanic reactions between the calcium and magnesium ions present in the waste and the silicate and aluminate components of the marl soil. In contrast, specimens containing alkaline activators exhibited a substantial reduction in strength, reaching 48.49 kPa, indicating the adverse effect of excessive alkalinity on the stabilization process. Based on the findings of this study, chlor-alkali process waste can provide a practical approach for the management and beneficial reuse of industrial waste while serving as an effective stabilizing material for marl soils.

Introduction

The rapid expansion of the oil, petrochemical, and chemical industries has contributed substantially to economic development and industrial growth but has also resulted in the generation of considerable quantities of industrial waste. The chlor-alkali process is one of the important industrial processes in which brine is electrolyzed to produce chlorine, sodium hydroxide, and hydrogen. These products are widely used in the production of pharmaceuticals, detergents, disinfectants, pesticides, plastics, and many other industrial products. However, the purification and demineralization of brine before electrolysis generates solid waste containing considerable amounts of calcium carbonate, magnesium hydroxide, sodium chloride, and other mineral constituents. Improper disposal of this waste can cause environmental problems and increase the burden on industrial waste-management systems. Marl is also considered a problematic soil because of its complex mineralogical composition and sensitivity to moisture variations. The simultaneous presence of clay minerals and calcium carbonate can significantly affect its mechanical behavior under wetting, drying, and loading conditions. Although marl may exhibit relatively high strength in a dry state, its strength can decrease considerably under saturated conditions, limiting its use in infrastructure projects. Chemical stabilization is widely used to improve the engineering properties of problematic soils because of its effectiveness, flexibility, and relatively low cost. Cement is one of the most common stabilizing materials; however, its production is energy-intensive and associated with considerable carbon dioxide emissions. Therefore, the reuse of industrial wastes as alternative stabilizing materials can provide both environmental and geotechnical benefits. Accordingly, this study investigated the feasibility of using chlor-alkali process waste generated in Bandar Imam Khomeini as a stabilizing agent for marl soil. The main objective was to evaluate the effect of the waste on the unconfined compressive strength (UCS) of marl and to determine whether this industrial by-product could serve as a more sustainable alternative to conventional stabilizing materials. The effect of an alkaline activator consisting of sodium hydroxide and sodium silicate was also examined.

Method

A laboratory-based experimental approach was adopted. Based on previous studies and the chemical composition of the chlor-alkali waste, particularly the presence of calcium carbonate and magnesium hydroxide, the waste was considered potentially suitable for marl stabilization. A waste content of 30% by dry weight was selected as an initial level for evaluating its stabilization performance. Three mixtures were prepared: untreated marl as the control specimen, marl containing 30% chlor-alkali waste, and marl containing 30% chlor-alkali waste with an alkaline activator. The dry materials were thoroughly mixed, after which water was added until a homogeneous mixture was obtained. The initial moisture content was set at 8%, corresponding to the dry side of the optimum moisture content obtained from compaction tests. The specimens were compacted to a dry density of 1.5 g/cm³, equivalent to approximately 84% of the maximum dry density. For the activated mixture, a 14 M sodium hydroxide solution was prepared and mixed with sodium silicate at an equal mass ratio. The resulting activator was added at a dosage corresponding to 50% of the mass of the chlor-alkali waste. The mixtures were compacted in cylindrical PVC molds measuring 5 cm in diameter and 10 cm in height in accordance with the requirements of ASTM D2166. Petroleum jelly was applied to the internal surfaces of the molds to facilitate demolding. After preparation, the specimens were placed in sealed plastic chambers to minimize moisture loss and cured for seven days at an ambient laboratory temperature of approximately 25 °C. Following curing, the specimens were removed from the molds and tested for unconfined compressive strength. Mean UCS values and standard deviations were subsequently determined.

Results

The results showed that adding 30% chlor-alkali process waste increased the mean UCS of marl from 90 to 123 kPa after seven days of curing, corresponding to a 35.66% improvement. This increase may be attributed to interactions between the calcium- and magnesium-bearing constituents of the waste and reactive mineral phases in the marl, potentially enhancing interparticle bonding and soil cohesion. However, the formation of C–S–H and M–S–H phases could not be experimentally verified because XRD and SEM analyses were not performed. In contrast, the addition of the alkaline activator reduced the UCS to 48.49 kPa. This reduction may be related to the high alkalinity and increased salinity resulting from the combined use of 14 M NaOH, sodium silicate, and the NaCl-rich waste (40.9% NaCl). Overall, direct application of chlor-alkali waste produced the most favorable mechanical performance, whereas alkaline activation had an adverse effect on strength development.

Conclusions

The findings demonstrate the potential of chlor-alkali process waste as a stabilizing material for marl soil. Incorporation of 30% waste by dry weight increased the seven-day UCS from 90 to 123 kPa, representing an improvement of approximately 35.66%. This improvement may be associated with interactions between calcium- and magnesium-bearing constituents of the waste and reactive mineral phases in the marl, potentially promoting the development of cementitious binding products. However, further mineralogical and microstructural analyses are required to confirm these mechanisms. In contrast, the alkaline activator composed of sodium hydroxide and sodium silicate reduced the UCS to 48.49 kPa, indicating that activation was not beneficial under the conditions investigated. Therefore, direct utilization of chlor-alkali waste, without alkaline activation, appears to be a more promising approach for marl stabilization. The reuse of this industrial waste can potentially reduce the volume of waste requiring disposal while decreasing dependence on conventional cementitious stabilizers. Considering the availability of chlor-alkali waste in southern Iran, particularly around Bandar Imam Khomeini, this approach may have practical potential for construction applications in the region. Nevertheless, further studies should investigate different waste contents, longer curing periods, durability under repeated wetting–drying cycles, and the leaching behavior of stabilized materials. XRD and SEM analyses are also recommended to identify reaction products and clarify the mechanisms governing strength development. Overall, the beneficial reuse of chlor-alkali process waste represents a potentially sustainable strategy for problematic-soil stabilization while simultaneously contributing to industrial waste management and more environmentally sustainable construction practices.

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