



Collapsibility potential of gypseous soil stabilized with fly ash geopolymer; characterization and assessment



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HIGHLIGHTS

- Geopolymer fly ash showed higher sulfate resistance than Portland cement.
- Higher sulfate resistance was recorded in geopolymer fly ash class F activated with KOH.
- Collapsibility potential of gypseous soil decreased when stabilized with fly ash geopolymer.
- Leachate and permeability decreased in gypseous soil stabilized with geopolymer fly ash.

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ABSTRACT

This study focused on effects of intrinsic sulfate in gypseous soil on its collapsibility potential when stabilized with fly ash geopolymer binder. Accordingly, compression and collapsibility tests were performed on the binder and the stabilized soil, respectively. XRD, TGA, and SEM/EDX tests were also conducted to trace changes due to geopolymerization and sulfate attack before and after exposure at different ages of up to 90 days. The results showed the formation of geopolymer gel (A-S-H) with higher strength and more sulfate resistance than Portland cement paste in binder. Furthermore, incorporation of KOH (12 M) activated fly ash in gypseous soil recorded the lowest collapsible potential and coefficient of permeability at 90 days of exposure.

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1. Introduction

Gypseous soil demonstrates sudden volumetric changes in wetting state due to dissolution of gypsum which causes uneven settlement or collapsing [1–4]. Consequently, engineering construction upon the gypseous soil is extremely risky as several problems such as crack induction, tilting or differential settlement and composition failure may occur [3,4]. Gypseous soils are widely distributed in arid and semi-arid areas of the world such as the Arabians peninsula, Russia, Armenia, the United States, Iraq, Iran and Spain [5,6]. So far, soil stabilization with cement is a comprehensively researched treatment technique and has been widely used to reduce collapsibility of gypseous soils under engineering constructions, such as foundations and pavements [2,7–10].

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Nevertheless, the utilization of cement to treat the soils with large gypsum contents is prone to sulfate attack [10].

In general, collapsible soils have porous texture with high void ratio and relatively low densities. During a dry state, they possess high recorded strength, but they are susceptible to large reductions in void ratio upon wetting which leads to failure [11]. The Collapse mechanism can be explained by initial collapse of metastable texture of soil due to dissolution of gypsum when the soil is subjected to the wetting condition by which bonds between grains are broken down [12]. Then, the soil particles rearrange into a denser state of packing accompanied with collapsing as the dissolved gypsum leaches out [13].

One of the practical techniques used to immobilize gypsum from leaching out is to stabilize it with cement. However, the major problem with stabilization of soil using cement is the internal sulfate attack [14–17]. Degradation of cement paste as a result of chemical reactions between hydrated Portland cement and sulfate ions from an outside source is known from crack propagation

and expansion in the cement matrix. Sulfate attack can cause a significant reduction in the strength and mass due to disintegration of C-S-H [16,18–20]. Production of gypsum from the reaction of Ca^{+2} in C-S-H and calcium hydroxide with SO_4^{-2} is one of the major deteriorating mechanisms in sulfate attack [19]. Furthermore, exposure of alumina containing hydrates to aggressive water would form ettringite which can also cause expansion and disintegration of the cement matrix [21–23]. As in cement stabilized gypseous soil, the sulfate attack is induced in wetting state of the soil due to availability of high content of sulfate ions in gypsum, which leads to disintegration of the stabilizing binder. The low integrity of the matrix, as a result, increases permeability of the binder and facilitates infiltration of water and accelerates the gypsum leach out. Increased porosity of the soil along with disintegration of stabilizers increases the collapsibility potential of the soil [23].

Recently, geopolymer binders are introduced as good replacements to cement due to their comparable mechanical properties, resistance to chemical attacks as well as their low carbon footprint [24]. The term ‘geopolymer’ was initially coined by Davidovits in the 1970s, and was later utilized to a class of solid materials synthesised through the reaction of silica- and alumina-rich materials with an alkaline solution [24–28]. The aluminosilicate materials are generally industrial by-products or other economical materials supplied in a powder form activated with an alkaline activator which is usually a concentrated aqueous solution of alkali hydroxide, silicate, carbonate or sulfate [26]. So far, several materials are used as precursors in geopolymer binders such as Metakaolin [29], Fly ash class F and Palm oil Fuel ash [30]. The strength gain in the geopolymer binder is related to the formation of geopolymer gel which depends on rapid dissolution of the aluminosilicates and release of the tetrahedral units of $[\text{SiO}_4]^-$ and $[\text{AlO}_4]^-$ in the solution. The dissolution can be related to the breakdown of the Si-O-Si and Si-O-Al bonds by reaction with the OH⁻ ions in the alkaline activator. The Si-O-Si bonds can be further weakened and get more susceptible to rupture by redistribution of ions and increase of their electronic density around the silicon atoms. These tetrahedral units are later joined in a process called as coagulation-condensation by sharing oxygen atoms instead of a polymeric precursor to form aluminosilicate hydrate (A-S-H) [31]. The alkaline metal which catalyzes the reaction in the dissolution stage, in the condensation stage acts as a structural component [32].

Due to the energy efficiency and the environmental friendly nature of the process, and excellent engineering properties, geopolymer binders are fast emerging as materials of choice for high demanding civil engineering applications. However, limited research has been conducted on particular applications in soil stabilization. Few published papers on the subject [16,33–45] addressed the effectiveness of geopolymer binders for soil stabilization. Based mostly on the microstructural analysis, these authors demonstrated that a binding gel (N-A-S-H) was developed inside the soil voids, helping to form more compact microstructures and improved compressive strength [44].

The overarching purpose of this study is to employ low calcium fly ash geopolymer to stabilize gypseous soil in order to reduce its collapsibility upon wetting. Fly ash is a finely divided mineral residue resulting from the combustion of coal in electric generating plants. It consists of inorganic, incombustible matter present in the coal that has been fused during combustion into a glassy, amorphous structure. Previous studies discussed usage of fly ash as stabilizing agent in soil stabilization [45]. The fly ash can be used as a stabilizer agent in bases or subgrades, or it can reduce lateral earth pressures through the stabilize backfill. It was also used to improve slope stability in embankments [46,47]. Erdal Cokca (2001) found that the compressive strength of expansive soil was improved by using 25% of fly ash class C. [48]. Some recent studies used alkali activation method instead of partial cement replace-

ment to exploit more amounts of fly ash especially Class F that has less reactivity due to low amounts of calcium. Davies (2011) used 20, 30 and 40% of the geopolymer binder to grout soil [36]. Also Nuno Cristelo (2013) found that the appropriate dosage of activated fly ash for soft soil stabilization was 20, 30 and 40% [37]. However, they reported that the effectiveness of alkali activation of low calcium fly ash on improvement of residual granitic soils was highest when the dosage ranged from 15% to 30% in [38].

In this study, geopolymerized fly ash was used as a binder to immobilize the gypsum in soil matrix by covering the gypsum particles in soil and to prevent any contact between the gypsum particles and water. Furthermore, the calcium free structure of the gel binder can provide sulfate resistant properties by which the vulnerability of the soil to collapsibility potential (C_p) may be reduced. As mentioned earlier, the low availability of Ca ions in the geopolymer matrix can prevent the formation of gypsum and ettringite as main causes of crack propagation in the hardened matrix. The fly ash class F geopolymer binder can be a suitable yet sustainable alternative for cement as it is more resistant to sulfate attack. The findings of this study help to understand the underlying mechanism by which low calcium geopolymer controls the internal sulfate attack caused by high quantity of gypsum in the soil matrix and to assess the collapse behavior of gypseous soil stabilized with fly ash geopolymer. Besides, estimation of C_p can be used in order to evaluate the settlement that may occur in a soil layer at a particular site. Settlement of a soil layer for the applied vertical stress is determined by multiplying C_p by $H/100$, where H is the thickness of the soil layer [49].

2. Materials and methods

2.1. Materials

2.1.1. Natural soil

The gypseous soil was collected from a highway construction site (1–1.5 m under the natural ground surface) in Babylon, Iraq. Iraqi soil has (3–80) % gypsum, which covers almost 31% of Iraq land. The geotechnical index property tests were conducted according to the BS (1377-2) [50] and the results are illustrated in Table 1. The grain size distribution is illustrated in Fig. 1. Also, X-ray fluorescence analysis (XRF) and X-ray Diffraction (XRD) test were conducted to assess the chemical components and mineralogy of gypseous soil, as shown in Table 2 and Fig. 2, respectively. XRD Test results revealed the presence of gypsum in the soil.

2.1.2. Fly ash

In this study, fly ash class F (low calcium) was collected from a thermal power station, Kapar, Selangor, Malaysia, as a residue of coal burning process. The main oxide composition of fly ash is reported in Table 2 according to X-ray fluorescence analysis (XRF). The particles size of fly ash ranged from 0.6 to 27.8 μm with surface area of 0.72 m^2/g based on Brunauer–Emmett–Teller (BET) analysis. Fig. 2 shows the XRD patterns of fly ash with a dominant

Table 1
Geotechnical characteristics of natural soil.

Properties	Value
Liquid limit	32.2%
Plastic limit	19.1%
Specific gravity	2.66
Dry density	1901 Mg/m^3
In situ water content	17.3%
Bulk density	1980 Mg/m^3
Optimum Moisture content	13.5%
Gypsum content	13.2%

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