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Strength characteristics of fly ash stabilized with lime and modified with phosphogypsum

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ABSTRACT

The paper presents the strength characteristics of fly ash stabilized with lime and phosphogypsum. A series of unconfined compression strength test and unconsolidated undrained triaxial tests were conducted on the reference mix composed of fly ash, 8% lime and 2% phosphogypsum. The specimens for these tests were prepared and cured for 7, 28, 56 and 90 days with three different curing methods termed as method M1, M2 and M3. The results of this study indicated that the unconfined compressive strength, deviator stress, cohesion, friction angle, initial tangent modulus and secant modulus increased with the increase in curing period. The increase in these parameters was highest for M3 method of curing followed by M1 and M2 respectively. Further to predict these parameters an empirical relationship is proposed which was found to predict the given parameters within acceptable error. It is anticipated that the results of present study will be useful in utilizing the waste materials (fly ash, phosphogypsum) for various geotechnical applications.

1. Introduction

Waste transformation is the powerful term used in effective solid waste management technique. Under this preview the ultimate goal should be to convert entire waste material produced into useful engineering material. By doing so, the growing concern of solid waste and related disposal problems will be minimized. Fly ash which is a by-product of thermal power plant and industrial waste phosphogypsum are two such materials which create disposal problems and further their utilization is very less in India in comparison to other developed countries due to lack of research on this topic. Further, in an effort to address the ever increasing waste disposal problem and to conserve our depleting landfills, there has been a growing interest in recent years to study the strength characteristics of waste materials for geotechnical application. The use of fly ash either solely or with activator like lime and gypsum for geotechnical applications is studied widely in the literature [1–6]. At present it is well established in literature that the addition of lime leads to an enhancement in strength of fly ash due to cation exchange whereas the addition of gypsum further helps in gaining early strength in the same. For instance, [2] carried out the investigation on the low calcium fly ash, lime and gypsum mix and concluded that the unconfined compressive strength of fly ash mixes substantially improved with the inclusion of additives like lime and gypsum. The shear strength characteristics of a low lime fly ash (class F) modified with lime alone or in combination with gypsum were studied by [3]. In their study, the unconsolidated undrained triaxial tests were conducted for 7 and 28 days cured specimens. The study reported that the addition of a small percentage of gypsum (0.5% and 1.0%) along with lime (4–10%) enhanced the shear strength of modified fly ash within short curing periods (7 and 28 days). It was also reported that the unconfined compression strength (U.C.S.) of fly ash increased from 172 kPa to 5902 kPa at 90 days curing period with the addition of 10% lime. Further with the addition of 1% gypsum to this mix U.C.S. observed was about 6308 kPa. It was also concluded that the contribution of gypsum in increasing the strength of fly ash, lime and gypsum composite is substantial only up to a curing period of 45 days. Based on the results of study, the deviator stress at failure (q_f) and cohesion (c) of composite mix was related to unconfined compressive strength (q_u) and confining pressure (σ_3) as $q_f = 0.9\, q_u + 3\sigma_3$ and $c = 0.2\, q_u$ respectively. An increase in the unconfined compressive strength from 7.83 to 10.55 MPa of air cured fly ash–lime–gypsum mixes with three alternate cycles of heating- cooling was reported by [4]. Steam curing and addition of superplasticiser to fly ash-lime-gypsum mixes were useful for the strength enhancement as reported by [7]. It was also mentioned by Sivapullaiah and Moghal [5] that the strength of low calcium fly ash increases significantly up to a lime content of 5% and thereafter the increase in strength is gradual. Further the addition of gypsum to lime-fly ash mix lead to an enhancement in strength at any lime content. It

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was also reported that the addition of gypsum to lime stabilized fly ash increases the durability of the mix. The relationship between initial tangent modulus ($E_{i,ucs}$) and unconfined compressive strength (q_u), secant modulus ($E_{s\text{-}50,ucs}$) and initial tangent modulus ($E_{i,ucs}$) from U.C.S. test and secant modulus ($E_{s\text{-}50,triaxial}$) and initial tangent modulus ($E_{i,triaxial}$) from unconsolidated undrained triaxial test for the fly ash-lime-gypsum mix were reported by [6] as: i) $E_{i,ucs} = 58.6\, q_u{}^{0.85}$ ii) $E_{s\text{-}50,ucs} = 0.97E_{i,ucs}$ and iii) $E_{s\text{-}50,triaxial} = 0.97E_{i,triaxial}$. It is quite noteworthy that the strength enhancement of fly ash with lime and gypsum received a greater attention in recent period. However, a very limited attention has been received to study the strength characteristics fly ash with the addition of lime and phosphogypsum (an industrial waste which contains gypsum about 90% along with other impurities such as P_2O_5 as monocalcium phosphate, dicalcium phosphate and tricalcium phosphate, fluoride as sodium fluoride, sodium silico fluoride or calcium fluoride, organic matter and small quantity of soluble alkalies). The impurities present in phosphogypsum impair the strength development in the matrix.

In the present study an attempt is made to examine the strength characteristics of fly ash–lime–phosphogypsum composite. A series of laboratory unconfined compressive strength and unconsolidated undrained triaxial tests were carried out by varying the curing method and curing period. Further on similar lines with [3,6], empirical correlations to predict deviatoric stress, cohesion, friction angle and deformation modulus were developed.

2. Material used

The fly ash used in this investigation was brought from Ropar Thermal Power Plant, Punjab, India. It had a specific gravity of 2.04. The maximum dry unit weight and optimum water content as obtained by Standard Proctor test was found to be 11.36 kN/m^3 and 26% respectively. The *XRD* and *SEM* of fly ash are shown in Fig. 1(a) and Fig. 1(d) respectively. In the XRD of fly ash, prominent peaks of Quartz, Mullite are noted along with occasional Magnetite (Mt) peaks. The chemical composition of the fly ash is shown in Table 1. From this Table it can be seen that the fly ash had CaO content of 1.6% (less than 20%) hence can be considered as low calcium or Class F fly ash in accordance with [8,9]. Hence the use of activator like lime to trigger the pozzolanic reaction will be necessary for it's strength improvement. Commercially available dry lime procured from the local market was used in the present study. The specific gravity of the lime was 2.37. The *XRD* and *SEM* of lime are shown in Fig. 1(b) and Fig. 1(e) respectively. Fig. 1(b) indicates prominent Portlandite (CH) peaks along with a few Quartz and Calcite peaks. The phosphogypsum used in the present study was collected as industrial waste from Ludhiana, Punjab, India. The specific gravity of the phosphogypsum was 2.20. The chemical analysis of the phosphogypsum provided by the supplier indicates that it contains 92–95% $CaSo_4$. The X–ray diffraction and SEM of phosphogypsum is shown in Fig. 1(c) and Fig. 1(f) respectively. Fig. 1(c) indicates prominent gypsum peaks.

2.1. Experimental procedure

In the present study the optimum mix of fly ash (FA)-lime (L)-phosphogypsum (PG) was arrived by trial. On the basis of literature study, the content of lime and phosphogypsum was varied from 2% to 10% and 0.5–4% respectively and further the optimum mix was arrived from the results of Standard Proctor compaction test. The results of this tests indicated that the maximum dry unit weight is observed for a mix FA + 8% L + 2% PG. Hence this mix is considered as reference mix and further tests like unconfined compression strength (U.C.S.) tests and unconsolidated undrained (U.U.) triaxial tests were carried out on the same. To prepare the specimen, the fly ash was grounded lightly by hand with a pestle to separate the individual particles. A metallic mould having size 38 mm inner diameter and 76 mm long with additional detachable collars at both ends were used to prepare cylindrical specimens for the U.C.S. tests and U.U. triaxial tests. The required quantity of lime (8%) and phosphogypsum (2%) corresponding to dry weight of fly ash was then mixed thoroughly and the water (corresponding to optimum moisture content) was added to the mix. To ensure uniform compaction, the specimen was compressed statically from both ends till the specimen just reached the dimensions of the mould. Then the specimen was extracted with the hydraulic jack and was allowed to dry at room temperature. The specimens prepared were then cured for 7, 28, 56 and 90 days using three different curing methods. In the first method, the specimens extruded from the mould were wrapped closely and individually in the polyethylene bag to prevent moisture loss and was placed in a desiccator having a small quantity of water at the bottom to maintain humidity within the desiccator with a closed lid and was kept at the room temperature. This method of curing is akin to that suggested by Electric Power Research Institute and was designated as M1 in the paper. In the second method of curing, the specimen was first cured with method M1. The specimen was then removed from the polyethylene and was kept in distilled water for 8 h at a room temperature before carrying out the unconfined compressive strength tests and the unconsolidated undrained triaxial tests. The durability of the specimens is investigated in this method, as the specimen becomes nearly saturated before the tests. This method of curing was designated as M2 in the paper. Similar method of curing was adopted by [10] while studying the factors influencing the fly ash-cement mixtures. In the third method of curing, the specimen was not wrapped in polyethylene bag as in case of curing method M1, but was exposed to the humidity within the desiccator during curing. This method is akin to that of reported by [11] and it is designated as M3 in the paper. The unit weight of the different specimens were maintained at 11.63 ± 0.22 kN/m^3. The UCS and UU triaxial tests were performed in accordance with [9,11] respectively but with a deformation rate of 0.24 mm/min. A similar deformation rate was adopted by [12] while assessing the suitability of fly ash-lime-phosphogypsum composite. Proving rings of capacity 2 kN, 10 kN, 25 kN, 50 kN were used for testing specimens cured for 7 days and 28, 56, 90 days respectively.

3. Results

3.1. Compaction

The standard proctor compaction tests were conducted as per [13] by varying the content of lime from 2% to 10% in fly ash. The results of this study are shown in Fig. 2. The study of Fig. 2(a) reveals that the maximum dry unit weight and optimum moisture content of the fly ash was 11.36 kN/m^3 and 26% respectively. With the addition of 2% lime, the dry unit weight and optimum moisture content increased to 11.38 kN/m^3 and 27.78%. The dry unit weight and optimum moisture further increased to 11.79 kN/m^3 and 29.10% as the lime content in fly ash is increased to 8%. However as the lime content in fly ash raised to 10%, the dry unit weight of mix decreased to 11.28 kN/m^3 and the optimum moisture content is increased to 30.12%. The decrease in dry unit weight can be attributed to the excess of coarse fraction generated by flocculation/agglomeration of fly ash- lime mixture. From the above study the FA + 8% L mix was chosen for further compaction study. To this mix, phosphogypsum (PG) was added in the range of 0.5–4% as a percentage of dry mass of fly ash. The variation of maximum dry unit weight and optimum moisture content of FA + 8% L with phosphogypsum (PG) is indicated in Figs. 2(c) and 2(d) respectively. From this graph it can be seen that the maximum dry unit weight is observed as 12.09 kN/m^3 at 2% phosphogypsum (PG) that is for FA + 8% L + 2% PG mix. The corresponding optimum water content of mix was 24.9%. Hence it can be concluded that the addition of phosphogypsum to fly ash-lime mix leads to slight increase in unit weight and a decrease in optimum moisture content. This observation with regard to FA + 8% L + 2% PG mix is similar to the findings of [14] with regard to