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Research paper

Physical and strength development in lime treated gypseous soil with fly ash — Micro-analyses

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ABSTRACT

An attempt has been made to examine the role of fly ash content (0–30%) to control undesirable strength loss in lime–treated expansive soil containing gypsum (0–6%) after curing for different periods up to one year. Further, detailed experimental investigations have been performed to assess the plasticity, swell index and compaction behavior of soil treated with these additives. Results of the strength behavior revealed that a significant effect of higher fly ash content in the strength development of lime–treated soil is observed after longer curing periods. Presence of increasing amounts of gypsum accelerates early strength gain initially, but reduces long–term strength gain in soil–lime–fly ash mixes. Fly ash improves the strength of lime–treated gypseous soil. However, beneficial use of fly ash to improve the strength of lime treated gypseous soil depends on the amount of gypsum present in the soil and length of curing periods. Micro–analyses (XRD and SEM) revealed that the strength development is controlled by reaction products formed such as cementitious compounds and ettringite crystals.

1. Introduction

Physico–chemical mechanisms of the lime treatment of soils are well established (Herrin and Mitchell, 1961; Diamond and Kinter, 1965; Ingles and Metcalf, 1972; Little, 1995; Bell, 1996; Jha and Sivapullaiah, 2015b). Four mechanisms (cation exchange, flocculation, carbonation and pozzolanic reactions) are generally associated with the modification and stabilization of lime treated soils. Further, there has been an increase in the awareness of environmental and ecosystem degradation due to huge production and storage of waste materials such as fly ash, GGBS, rice husk etc. The utilization of these waste materials is also initiated to stabilize problematic soil, alone or, in combination with lime, effectively and economically (Maher et al., 1993; Smith, 1993; Jalali et al., 1997; Consoli et al., 1998; Bhanumathidas and Kalidas, 2005; Higgins, 2005; Muntohar, 2009; Pal and Ghosh, 2013). The utilization of fly ash in soil stabilization enhances hydration reactions by supplying additional pozzolans (siliceous and aluminous) with collections of adequate divalent and trivalent cations (Ca^{2+}, Al^{3+}, Fe^{3+}, etc.) (Indraratna et al., 1991; Kumar et al., 2007). Fly ash has a low specific gravity, high volume stability, low compressibility, high rate of consolidation, water insensitivity to compaction and pozzolanic reactivity (Prakash and Sridharan, 2009). Due to such valuable characteristics, fly ash is used to improve the properties of soil such as the consistency limit, compaction characteristics and swell potential (Sivapullaiah et al., 1996a, 1996b; Cokca, 2001; Sridharan et al., 2001). However, the long–term strength behavior of lime–treated soil with fly ash content and related mechanisms is still a topic of current research. Further, utilization of fly ash and lime for the stabilization of soil containing sulfate is challenging and needs extreme precautions (Mitchell, 1986; Solis and Zhang, 2008).

Gypseous soil (covering 20% of land in the world) poses several engineering problems such as settlement in dry conditions and ground subsidence with formation of pores, cracks and cavities by the dissolution of gypsum in wet conditions (Yamamoto and Kennedy, 1969; Azam et al., 1998; Solis and Zhang, 2008; Fattah et al., 2012; Jha and Sivapullaiah, 2014). Gypsum is the main source of sulfate (Abdi, 1992; Rajasekaran, 2005). Calcium–based stabilizers such as lime and cement have been used, traditionally, to stabilize sulfate–bearing soil (Hausmann, 1990). However, the formations of ettringite or thaumasite by soil–lime–sulfate reactions create several distresses to structures by heaving (Hunter, 1988; Mitchell and Dermatas, 1992; Petry, 1994; Puppala et al., 1999; Rollings et al., 1999; Little et al., 2005). Both ettringite and thaumasite are hydrous minerals, and therefore, an availability of water is the main controlling factor in their formation and growth instead of other factors (Hunter, 1988; Petry and Little, 2002; Jha and Sivapullaiah, 2016). Further, beneficial and detrimental effects on the properties of stabilized soil are controlled by the amount of sulfate (i.e. small amount of sulfate increase strength and higher sulfate content is detrimental) and types of soil (Ladd et al., 1960; Sherwood, 1962; Wild et al., 1993). The formation of ettringite and its

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needle–like or fibrous structure with a high aspect ratio develops an extensive crystal interlocking and reinforcing of the particles, leading to a sufficient gain in strength (Kujala and Nieminen, 1983; Mehta, 1983; Dermatas, 1995; Schoute, 1999). Kinuthia et al. (1999) state that the effect of sulfate depends on cation types because cations (Ca^{2+} and Mg^{2+}) improve lime treatment whereas the presence of Na^{+} and K^{+} has an adverse effect. Reduction in the strength of lime–treated soil with an addition of gypsum is due to a loss in the effective cohesion (Sivapullaiah et al., 2000) and cementation ability (Mehta, 1983). Recently, Jha and Sivapullaiah (2015a) have reported long–term strength deterioration of lime–treated soil in the presence of varying gypsum content.

Attempts have been carried out to control the adverse effect of sulfate in soil treated with calcium–based stabilizers by using Ground Granulated Blast Furnace Slag (GGBS), sulfate–resisting cement, barium chloride lithium salts and the application of double lime methods (Smolczyk, 1980; Raja, 1990; Ferris et al., 1991; Mitchell and Dermatas, 1992; Petry and Little, 2002; Gollop and Taylor, 1996; Wild et al., 1996; Tsatsos and Dermatas, 1998; Wild et al., 1998; Rollings et al., 1999). Comparatively few attempts have been made to explore the possible use of fly ash to suppress the heave in lime–treated gypseous soil (Kawamura et al., 1986; Berger et al., 2001; McCarthy et al., 2012a, 2012b; Talluri, 2013). Further, no relevant literature is available on the physical and long–term strength behavior of lime treated gypseous soil with fly ash content, and is the prime motive of present work.

In this paper, an attempt has been made to explore the effect of varying fly ash content on the physical and strength development in soil, lime–treated soil and lime–treated gypseous soil, in order to find whether it is suitable to use in the presence of sulfate (gypsum). Atterberg's limits, a modified free swell index, and compaction characteristics have been examined to address the physical behavior. Further, unconfined compressive strength tests have been performed to examine the strength development at different curing periods up to 365 days. Finally, pH and detailed micro–analyses (X–ray diffraction and scanning electron microscopy) have been carried out to elucidate the mechanism of strength variation through changes in alkalinity, mineralogy and microstructure, respectively.

2. Materials and methods

2.1. Materials

Soil used in the present study is obtained from Belgaum district of Karnataka in India. The soil is collected by open excavation from a depth of approximately 1.5 m below the natural ground level. The geotechnical properties of soil are presented in Table 1. An X-Ray Diffraction analysis (XRD) (Fig. 1(Aa)) confirms the presence of montmorillonite, aluminum oxide and quartz as dominant minerals in soil. A Scanning Electron Microscopy (SEM) image (Fig. 1(Ba)) illustrates several voids like honeycomb–networking patterns, and the ratio of Al:Si is found to be 1:2.1 from an Energy Dispersive Analysis of X-ray (EDAX) analysis (Fig. 1(Bb)) (Peethamparan et al., 2009), confirming the presence of montmorillonite in soil. Further, the presence of montmorillonite and aluminum oxide in the soil is confirmed by performing thermogravimetric analysis of soil (Jha and Sivapullaiah, 2015a, 2015b).

Table 1
Geotechnical properties of soil and fly ash.

Property	Soil	Fly ash
Specific gravity	2.67	2.14
Sand (4.75–0.075 mm), %	6	26
Silt (0.075–0.002 mm), %	31	70
Clay (< 0.002 mm), %	63	4
Liquid limit, %	72.1	31.3
Plastic limit, %	31.7	–
Plasticity index, %	40.4	–
Shrinkage limit, %	13.6	–
Free swell index, %	72.7	–
Modified free swell index, ml/g	1.9	–
Optimum moisture content, %	32.5	21
Max. dry unit weight, kN/m^3	13.4	12.6
Classification as per IS plasticity chart	CH	–
Degree of expansion	Very high	–

Fly ash used in the present study is collected from the Raichur thermal power plant (RTPS) in Raichur district, Karnataka, India. The geotechnical properties of fly ash are presented in Table 1. Based on the chemical composition [SiO_2 (57%), Al_2O_3 (26%), CaO (0.97%), MgO (0.48%), K_2O (1.83%), Fe_2O_3 (8.70%), TiO_2 (1.55%) and loss of ignition (5.39%)], fly ash classifies as Class F (ASTM C618, 2008). Fly ash contains mullite (aluminum silicon oxide) and quartz as the dominant minerals as shown by an XRD analysis (Fig. 1(Ab)). The microstructural examination of fly ash (Fig. 1(Bc)) shows rounded particles. EDAX (Fig. 1(Bd)) confirms the presence of higher amounts of alumina and silica than soil.

Hydrated lime [$Ca(OH)_2$] and calcium sulfate dihydrate [$CaSO_4{\cdot}2(H_2O)$] are used as chemical additives. An XRD analysis is performed to ensure the purity of both additives [Fig. 1A(c & d)]. The XRD analysis of hydrated lime powder showed the presence of calcium hydroxide [$Ca(OH)_2$] in all major peaks of lime and peak of calcium carbonate ($CaCO_3$) as a small impurity [Fig. 1(Ac)]. The XRD analysis of gypsum only showed the peaks of calcium sulfate dihydrate [$CaSO_4{\cdot}2(H_2O)$] [Fig. 1(Ad)]

2.2. Methodologies followed

Amounts of additives used to prepare mixtures of different combinations are taken on the basis of percentage by dry weight of the soil. Primarily, a desired amount of oven–dried fly ash is mixed thoroughly with the soil to get a uniform soil–fly ash mixture. A predetermined quantity of chemical additives is added to the soil–fly ash and mixed thoroughly in dry state until the mixture appears uniform in color and texture. After that, a desired amount of distilled water is added and it is remixed again thoroughly. The untreated and treated samples are kept for mellowing up to 24 h and 1.5 h, respectively, to ensure a uniform distribution of moisture throughout the soil mass and further experimental procedures have been performed after completion of mellowing period. Similar procedures for sample preparation have been followed by several researchers (Little, 1995; Al-Mukhtar et al., 2010; Al-Mukhtar et al., 2012; Aldaood et al., 2014).

Atterberg's limits of all combinations have been determined as per Indian standards of IS 2720 (Part 5) (1985) and IS 2720 (Part 6) (1972). A modified free swell index of all the combinations has been carried out as per the procedure developed by Sridharan et al. (1985).

Optimum Lime Content (OLC) used for the experimental purpose is obtained by a pH test as per Eades and Grim (1966). The pH result of the soil–lime mixes confirmed a lime content of 6% as OLC. A similar procedure has been followed to obtain the pH value for specimens collected after an unconfined compressive strength test.

Maximum dry density and Optimum Water Content (OWC) values of untreated and treated soil are determined by carrying out a mini compaction test procedure developed by Sridharan and Sivapullaiah (2005). Unconfined Compressive Strength (UCS) tests are performed as per IS 2720 (Part 10) (1973). The cylindrical static compacted specimens (size of 76 mm height and 38 mm in diameter) are prepared at maximum dry unit weight (γ_{dmax}) and OWC for all combinations. The samples are kept in air–tight desiccators by proper wrapping in polyethylene bags and cured up to desired periods. Samples are checked for loss in water content by measuring the weight after each curing period and are rejected when the difference obtained is > 0.5%. Two and three identical specimens for curing periods up to 28 days and longer curing periods of 90, 180 and 365 days are tested, respectively.