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Research paper

Effect of optimum compaction moisture content formulations on the strength and durability of sustainable stabilised materials

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ABSTRACT

The achievement of Optimum Compaction Moisture Content (OCMC) of clay soil plays an important role in compaction as well as the durability and strength of compacted soil. This is due to its effect on the structure and orientation of the clay soil particles. Most researchers on stabilised systems involving soils and/or industrial waste by-product additives for applications in roads and buildings are faced with the problem of how to approach the establishment of OCMC, when the complex mixtures involved. This paper reports on the laboratory investigation of theoretical methods of two different approaches to establish the OCMC in the stabilisation of clay soil involving multi-binary binder in cementitious binder system. Furthermore, this research also explores the use of an industrial by-product, Pulverized Fuel Ash (PFA) as partial target material and ground granulated blastfurnace slag (GGBS), with a view to reducing the reliance on the traditional cementitious binders, such as lime and/or Portland Cement (PC), in stabilising Lower Oxford Clay (LOC) soil combining with PFA at 50:50 ratio. LOC + PFA was stabilised both in conventional manner using Lime and PC as control and using sustainable binders incorporating GGBS. The results show that there was no one particular approach to the establishment of the optimal compaction moisture content for best strength development and durability. The best approach being dependent on the period of curing, stabiliser content and whether GGBS was blended with Lime or with PC. Of the various stabilisers studied, the highest strength magnitudes were however recorded with LOC-PFA stabilised using the blended binders incorporating GGBS. For all 7, 28 and 56 days of curing periods, the PC-based stabilisers were observed to be less sensitive to the different approaches to compaction moisture content, relative to the lime-based systems.

1. Introduction

Soil stabilisation is an alteration of the properties of an existing soil to meet the specified engineering requirements. The main properties that may require to be altered by stabilisation are strength, volume stability, durability and permeability. Soil stabilisation is widely used in road construction to improve sub-bases and sub-grades. Several methods are available for stabilising clay soil in order to increase the strength properties and to reduce swelling or expansion behaviour. These can be achieved by the use of chemical additives, soil replacement, compaction control, moisture control and surcharge loading. Chemical stabilisation involves the formation of strong bonds between the clay minerals and other soil particles. Lime and PC are common among earlier chemical stabilisation. Regardless of the stabilisation method, the ultimate goal is to ensure adequate strength of stabilised soil (Jagendan et al., 2010; Malhotra and Sanjeev, 2013; Kartik et al., 2014). The achievement of the optimum moisture content (OMC) and maximum dry density (MDD) of a soil plays an important role in compaction as well as in strength and durability of the compacted soil, where the properties of the soil and its performance are influenced by the molding moisture content due to its effect on the structure and orientation of clay particles. For all stabilisation work, the extent to which air can be removed depends on the strength of the soil or the friction between soil particles which in turn be subject to the moisture content of the soil during compaction. The moisture content of a soil has a major impact on how well the soil will compact and stabilised. When a soil is completely dry it will not compact to its greatest possible density because of friction between the soil particles. As the moisture content increases, the water lubricates the soil, allowing it to move more easily into a compact state and the density increases. The effect of water content on the compaction of soil can also be explained with the help of electrical double layer theory of clay particles. At low water content, the forces of attraction in the adsorbed water layer are large, and there is more resistance to movement of the particles. Stabilised material are usually compacted at the optimum moisture content when the dry density at its maximum or at the wetter side nearly saturation

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line (Whitlow, 2001). For a given compactive effort, higher strength can be achieved by compacting the raw material at its optimum moisture content to ensure that the maximum dry density is achieved. The complex interaction between stabilising agent and water makes the relationship between water, strength and durability much harder to predict (Beckett and Ciancio, 2014).

On the other hand, in recent years much research has been directed to the identification and investigation of wide range of new pozzolanic materials from industrial and agricultural source such as metakaolin, fly ash, red mud, rice husk ash, wheat straw ash or by latently hydraulic materials. The partial replacement of cementitious material, lime and cement by pozzolanic materials results in the effective reduction in cost of production. Therefore there are significant numbers of research projects on the application of lime or cement blended binders in soil stabilisation, which offer sustainability advantages. Researchers now believe that with the addition of small amount Lime or PC, the calcium present causes an ionic exchange, which results in flocculation that has dramatic effect on modification of soil's workability and strength. Stabilisation transpire as the reaction between silica and alumina within the clay structure, lime and water to form calcium silicate hydrates, calcium-aluminate-hydrates and calcium-alumino-silicate-hydrates (C-S-H, C-A-H and C-A-S-H) to bind the structure together. Regardless of stabilisation method, the ultimate goal is to ensure adequate final density and strength of the soil. The point of achieving optimum moisture content and maximum dry density of the soil plays an important role in compaction. For nearly all soil, the extent to which air can be removed depends on the strength of the clay lumps or friction between the granular particles which in turn depend on the moisture content of the soil during compaction (Barnes, 2000).

The potential of using by-products such as fly ash and blastfurnace slag (GGBS) is promising, well establish, and has been investigated by several researchers. These by-products can incorporated in cementitious material to modify and improve certain properties and also to conserve non-renewable natural resources (Seco et al., 2011; Oti et al., 2014; Adam and Maria, 2015; Marcelino-Sadaba et al., 2017; Shalabi et al., 2017). GGBS is commonly activated by PC. Water hydration of PC produces mainly calcium hydroxide ($Ca(OH)_2$) and C-S-H gel. In the hydration of blended PC-GGBS system, although minor amount of alkalis released, GGBS is mainly activated by the hydration products $Ca(OH)_2$ (Bijen, 1996). PC-GGBS hydration produces slightly different hydrates from those formed by hydration of standard PC, as the main reaction products of GGBS hydration are C-S-H gel, C-A-H gel and small amount of calcium hydroxide (Higgins et al., 1998). Therefore PC-GGBS system is not significantly different from either the PC or activated GGBS system.

It is believed that there is a gap of published work directly referring to the effect of optimum compaction water content on the strength and durability of stabilised material. Therefore this paper aims to address this vagueness by determining the effect of optimum compaction moisture content using two different formulations.

2. Experimental procedures

2.1. Materials

2.1.1. Lower Oxford Clay (LOC)

LOC used in this study is currently used in the manufacture of fired clays. The characteristics and mineralogy of LOC is well established. It was supplied by Hanson Bricks Ltd., from their clay-mine at Stewartby, Bedfordshire. The clay is grey in colour and is known to have high sulfate and sulfide contents. Mineralogy studies by Hanson Brick Ltd. has established that LOC contains illite (23%), kaolinite (10%), chlorite (7%), calcite (10%), quartz (29%), gypsum (2%), pyrite (4%), feldspar (8%) and organics (7%).

Table 1
Oxide composition of LOC, PFA, PC, Lime and GGBS.

Oxide	LOC[a] (%)	PFA[b] (%)	PC[c] (%)	Lime[d] (%)	GGBS[e] (%)
SiO_2	46.73	47.6	20	≤0.9	35.34
Al_2O_3	18.51	26.2	6	≤0.15	11.59
CaO	6.15	2.4	63	95.9	41.99
Fe_2O_3	6.21	9.4	3	≤0.07	0.35
MgO	1.13	1.42	4.21	≤0.46	8.04
SO_4	1.29	0.86	2.3	–	0.23
K_2O	4.06	3.02	–	–	–
Mn_2O	0.07	–	1.11	–	0.45
Na_2O_3	≤0.52	1.1	–	–	–
TiO_2	1.13	–	–	–	–
FeO	≤0.80	–	–	–	–
P_2O_5	≤0.17	–	–	–	–
$CaCO_3$	–	–	–	2.2	–
Loss on Ignition	15.79	–	–	–	–

[a] Hanson Brick Ltd.
[b] Ash Resources.
[c] Lafarge Cement Ltd.
[d] Calch Ty Mawr lime.
[e] Civil and Marine Slag Cement Ltd.

2.1.2. Pulverized fuel ash

Pulverized fuel ash (PFA) is a by-product of thermal power plants resulting from the combustion of pulverized coal in the coal-fired furnaces. It is commonly available in the United Kingdom. The PFA used in this research was supplied by the United Kingdom Quality Ash Association (UKQAA).

2.1.3. Stabilisers

Portland Cement (PC) was supplied by Lafarge Cement Ltd. UK. The PC was used as an alternative to lime and as the activator to Ground Granulated Blastfurnace Slag (GGBS) in order to stabilised the target materials. Quicklime (CaO) was supplied by Breacon Calch Tý Mawr Lime, Wales, UK. CaO is denser, less dusty and more effective as a stabiliser having a higher available lime content per unit mass where 3% CaO is normally equivalent of 4% hydrated lime. GGBS which is readily available throughout UK was supplied by Civil and Marine Slag Cement Ltd. at Llanwern, Newport, Wales. It has a latently hydraulic material that occurs as by-products of steel industry when molten slag is rapidly cooled and granulated. The use of GGBS as a cementitious material blended with PC or CaO are based on its activation with alkalis (mainly $Ca(OH)_2$) released from hydration of PC. Table 1 shows the oxide composition of target materials and stabilisers used in this research.

2.2. Preparation of specimens and testing procedures

Prior to sample preparation, target values of maximum dry density (MDD) and optimum moisture content (OMC) were established using Proctor compaction test in accordance with BS 1377 (1990) Part 2. In all systems, LOC-PFA + Lime, LOC-PFA + PC, LOC-PFA + Lime:GGBS and LOC-PFA + PC:GGBS, the MDD ranges from 1.42–1.48 Mg/m^3 and OMC ranges from 19 to 24%. Therefore, for the test, the MDD of 1.42 Mg/m^3 and OMC value of 24% were adopted for all specimen mixes. All specimens were expected, within experimental error, to be of approximately comparable bulk-density, since the volume was maintained as 50 mm diameter and 100 mm height was established to be about 380 g. Two approaches for establishing the compaction water content were used as presented in Table 2. Using these parameters, two formulations (F1 and F2 at OMC and 1.2OMC) were used to calculate the amount of water. Mix Design Composition are summarised in Table 3.

The dry materials were mixed thoroughly before adding the pre-calculated amount of water. A steel mould fitted with collar, was used to compact the material into a cylinder using hydraulic jack. After

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