Construction and Building Materials 36 (2012) 727–735

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Soil stabilisation using alkaline activation of fly ash for self compacting rammed earth construction

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HIGHLIGHTS

- Low calcium fly ash activated with a sodium-based solution to enhance soil properties for earth construction.
- No significant improvement with sodium chloride or superplasticiser.
- There are optimum liquid:solid and alkali:ash ratios and alkali concentration in terms of maximum strength.
- Microstructure is significantly affected which can be related to strength increase.
- Mixture consistency allows dispensing any compaction energy, only vibration is necessary.

ARTICLE INFO

Article history:
Received 31 January 2012
Received in revised form 16 May 2012
Accepted 4 June 2012
Available online 15 July 2012

Keywords:
Soil stabilisation
Alkaline activation
Fly ash
Rammed earth

ABSTRACT

This paper studies the effectiveness of alkaline activation of low-calcium fly ash on the improvement of residual granitic soils to be used on rammed-earth construction. Different liquid:solid ratios, alkali concentrations and Na_2O:ash ratios were tested. Effect of calcium hydroxide, sodium chloride and concrete superplasticiser is also reported. Compressive strength up to 7 days at 60 °C was determined. Results show that there is an optimum value for the activator:solids ratio and the alkali concentration, and that a decrease in the Na_2O:ash ratio results in a strength increase. No improvement was observed with the sodium chloride or the superplasticiser, while the calcium produced only a short term increase in strength. SEM/EDS analysis were used to analyse microstructural development, showing that strength is fairly related to the Si:Al and Na:Si ratios.

1. Introduction

Soil is certainly one of the most ancient building materials. The most common earth construction techniques are rammed-earth and adobe masonry [1]. Adobes are bricks prepared with moist earth (to which straw is added sometimes) by simply moulding it in a wooden frame and drying it out in the sun. Then the masonry is prepared by 'gluing' the adobes with earth mortar. A rammed earth wall is made by compacting thin layers of packed earth using a rammer. The development of modern construction materials gradually made the application of earth as a construction material less and less attractive, which had more to do with social than with technical disadvantages. Inclusively, this trend had a significant influence on the lack of production of specific regulation codes. However, the recent growing concern with a meaningful and sustainable development is a serious motivation for seeking environmentally friendly construction materials. Also, a curious change of mentality occurred, since what was until recently a social embarrassment is now seen as a very modern material, capable of producing comfortable and visually impressive buildings. Therefore, earth construction is now a valid option, which sparked off the research in this field, mainly concerning the materials used. Rammed earth walls are relatively thick (0.5–0.9 m), and the dwellings are usually one or two stories high, in order to limit the compression stresses. That is because these walls have a lower compressive strength than other building materials, which causes serious limitations in terms of architectural and structural design. During the construction of these walls the soil is placed inside the moulds and compacted up to a certain level, depending on the mould support. However, in the research here presented, the

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0950-0618/$ - see front matter
http://dx.doi.org/10.1016/j.conbuildmat.2012.06.037

soil-stabiliser mixture had a slurry consistency, meaning that compaction was not necessary, only some form of vibration, which can easily be achieved in a live scale wall, using a concrete vibrator.

Traditionally, the soils used for rammed earth have a distinctive clayey behaviour, since the cohesion plays an important role in the structural stability of the walls, and it also helps preventing disaggregation of the wall surface. However, the strength of the soil often needs to be improved if it is going to be used for earth construction [1–3]. One of the major techniques to overcome problems created by under-performing soils is the mixing with a cementitious binder. Usually these binders are cement and/or lime based, and glues the soil particles together through chemical reactions. In the case of cement, the reactions are mainly hydraulic, while with lime they are pozzolanic. This means that cement needs only water to react and increase in strength; while lime needs water and a pozzolanic material, like soil. Both binders share the fact that their reactions with water depend largely on their specific surface. Moreover, although the type of reaction is different for lime and cement, the final product is very much alike, based on calcium and siliceous compounds. In terms of mechanical strength, cement-based binders usually deliver significantly better and more consistent results when compared to lime-based binders. However, if the clay fraction is significant, as is usually the case in soils used for earth construction [1,2], chemical improvement with lime is very effective, due to the significant and permanent reactions between the calcium compound and the pozzolanic soil [4–6]. Also, although the compressive strength achieved is lower than with cement, it is usually enough for the purpose of current earth construction designs. However, since the aim of this research is to study the possibility of using soils from northern Portugal in earth construction, and these are mostly granitic, with a small clay fraction of less than 10% composed mainly by kaolinite [7,8], more appropriate binders need to be used. This conclusion is based on previous research [4–6,9], that concluded that a clay fraction of at least 10% is needed for a soil to be properly stabilised with lime. One obvious choice would be cement, however, environmental and durability concerns with cement production and application are increasing rapidly and can no longer be ignored. Therefore, the environmental issue related with cement production was – together with strength and durability concerns – the main motivation to study the application of a geopolymeric binder (also known as alkaline activation) in this research project, which deals with the improvement of residual granitic soil used in rammed earth construction. This technology – alkaline activation of fly ash – was already tested for soil improvement in geotechnical applications [10,11]. As in the case of most of other geopolymer applications, the binder was obtained using a waste material. Its application is rapidly increasing in the construction industry, not only as a technically sound construction material, but also as an important contribution for the reduction in cement consumption, since it allows its substitution in significant percentages, while at the same time uses an industrial by-product, namely fly ash.

In general terms [10–15], alkaline activation is a reaction between alumina-silicate materials and alkali or alkali earth substances, namely: ROH, R(OH)2, R_2CO_3, R_2S, Na_2SO_4, $CaSO_4{\cdot}2H_2O$, $R_2{\cdot}(n)SiO_2$, in which R represents an alkaline ion like sodium (Na^+) or potassium (K^+), or an alkaline earth ion like calcium (Ca^{2+}). It can be described as a polycondensation process, in which the silica (SiO_2) and alumina (AlO_4) tetrahedra interconnect and share the oxygen ions. The process starts when the high hydroxyl (OH^-) concentration of the alkaline medium causes the breaking of the covalent bonds Si–O–Si, Al–O–Al and Al–O–Si from the vitreous phase of the raw material, transforming the silica and alumina ions into colloids and releasing them in the solution. The extent of dissolution depends upon the quantities and nature of the alumina and silica sources and the pH levels. In general, minerals with a higher extent of dissolution will result in higher compressive strength after the process is complete. At the same time, the alkaline cations Na^+, K^+ or Ca^{2+} act like building blocks of the structure, compensating the excess negative charges associated with the modification of the aluminium coordination during the dissolution phase. The resulting products accumulate for a period of time, forming a ion "soup" of high mobility. If calcium is present in the mixture in significant amounts the dissolved Al–Si complex will diffuse from the solid surface and produce a dominant C–S–H gel phase. Otherwise there is poly-condensation of the dissolved gel with the Si and Al ions precipitating around nuclei points, sharing all oxygen ions and forming a Si–O–Al and Si–O–Si three-dimensional structure (the formation of Al–O–Al is not favoured), which is more stable than those existing in the original aluminosilicate source. The resulting polymeric structure of Al–O–Si bonds is the main structure of the new material. Materials formed using reactions between silica and alumina and alkali cations like sodium or potassium are very similar, at a molecular level, to natural rocks, sharing their stiffness, durability and strength.

The aim of this paper is to determine, through a parametric analysis using laboratory tests, the optimum fly ash – based alkaline activated binder for the improvement of soil to be used in rammed earth construction. This evaluation was made in terms of mechanical strength of each mixture after specific curing periods. Different compositions were considered, all of them with a slurry-type consistency, with the objective of determining the following:

- Effect of maximum particle size.
- Influence of hydrated lime, sodium chloride and concrete superplasticisers.
- Effect of liquid:solid ratio.
- Effect of activator concentration.
- Effect of Na_2O:ash ratio.
- Relationship between strength and microstructure.

2. Methodology

2.1. Material characterisation

Laboratory tests were performed with granitic residual soil recovered near University of Minho, in Guimarães, Portugal. It can be considered as representative of the typical soils from the north of Portugal. After being submitted to characterisation

Table 1
Soil properties.

Plastic limit (%)	NP
Liquid limit (%)	33.8
Optimum water content (%)	12.2
Maximum dry density (kN/m^3)	19.2
Clay content (%) [ϕ < 0.002 mm]	5.7
Silt content (%) [0.002 < ϕ < 0.06 mm]	14.0
Sand content (%) [0.06 < ϕ < 2 mm]	45.6
Gravel content (%) [2 < ϕ < 20 mm]	34.8
D_{10} (mm)	0.007
D_{30} (mm)	0.179
D_{60} (mm)	1.482
Cu	201.9
Cc	2.9