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Chemical stabilization of rammed earth using calcium carbide residue and fly ash

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HIGHLIGHTS

- Use of calcium carbide and fly ash type F for stabilization of a clayey sand for earth construction.
- Strength increase from 0.2 MPa to over 5 MPa after 60 days of curing.
- CCR:FA ratio of 40:60 with 12% binder content showed a significant growth of strength of the tested soil.
- SEM images were used to analyze the effect of binders on the microstructure of soil.

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ABSTRACT

Rammed earth has been considered as a sustainable construction technique that uses local soil to build structural walls. However, some natural soil do not have adequate strength and must be treated in order to improve their engineering properties. Chemical stabilization is a recent technique for this purpose and Portland cement is the most commonly used binder material. In the current study, industrial by products such as calcium carbide residue (CCR) and fly ash (FA) are investigated as binders instead of hauling them to landfills. Two different ratios of binders (CCR:FA = 40:60 & CCR:FA = 60:40) at five different binder contents (3%, 6%, 9%, 12% & 15%) were utilized to investigate strength properties of a model soil. Based on the CCR and FA ratios, soil specimens were grouped as A and B. The unconfined compressive strength (UCS) for both groups was tested after four different curing times (3, 7, 28 & 60 days). The UCS values of Group A specimens showed better performance at 12% binder content, whereas, Group B specimens showed an improved strength behavior at 15% binder content for all curing conditions. Also, results of SEM images for Group A specimens at 12% binder content indicated formation of a more integrated soil matrix with reduced soil voids and therefore, significant improvement of the soil strength.

1. Introduction

Rapid growth of the world's population is constantly pressing demands of new infrastructure such as buildings, roads, pipelines, bridges etc. Conventional construction methods using cement releases substantial amounts of greenhouse gases into Earth's atmosphere, which is harmful for the global environment. In addition, according to Pacheco-Torgal and Jalali [1], the consumption of raw materials in construction industry is approximately 50% which adds pressure on the industry to find alternative and sustainable materials for their use. Natural and locally available materials are one of the potential approaches that can minimize the cost of construction and reduce energy consumptions [2,3].

The technique of using soil as construction material has been successfully used for years [1,4–8]. Earth bricks dating back to 7500 BCE have been found in the Tigris River basin [9]. It was estimated that in 2014, 30–40% of the world population lived or worked in structures that have soil as construction material [10]. There are multiple techniques for using soil in construction, including rammed earth walls, earth bricks, and compressed earth blocks [1,4,11,12]. Among them, Rammed earth walls are constructed by compacting soil layers between formworks on-site. Pacheco-Torgal and Jalali [1] discussed the economic aspects of earth construction; which is determined based on the technique used, stabilization process, labor cost, and how often rehabilitation is needed.

Studies showed that a suitable soil for rammed earth technique should contain fines (i.e. clay) at certain ranges, since clay acts as a natural binder between soil grains [8,12,13]. Bui et al. [13] and Maniatidis and Walker [8] specified that the range of fines for cement-stabilized soil should be between 20% and 35% and the

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sand content should be greater than 50%. According to Burroughs ([5,6], samples with sand content higher than 64% did not show satisfactory results. In terms of compressive strengths, the New Mexico Earthen Building Materials Code [14] specifies that the ultimate compressive strength of soil used in rammed earth construction should be greater than 2 MPa. The low compressive strength of rammed earth construction lead to structural limitations, as a result, structures are usually shorter and thicker to comply with the material limitations [4,12]. If specifications are not met, binders must be added to stabilize the soil and to improve its strength properties [1,2,12,15].Ordinary Portland cement is the most prevalent chemical stabilizer used in geotechnical and pavement applications [16]; however, due to Portland cement's elevated unit price and high energy consumption in production, alternative cementitious stabilizers should be adopted [17,18].

Calcium carbide residue has become promising as soil binder due to its smaller particle size, larger specific area, and elevated pH values [19–21]. Calcium carbide is used in the manufacturing of polyvinyl chloride (PVC), polyvinyl alcohol, and acetylene. As a byproduct of these manufacturing practices, large amounts of calcium carbide residue (CCR) are being generated and stock piled around the world [15,17,19,20,22,23]. In recent studies presented by several researchers [15,17,20,22–25] had used CCR and fly ash/biomass ash at different ratios to examine their effects on soil strength or durability.

Fly ash (FA), another widely used binder material, is a residue produced by coal fired power plants [15,17,20,24,26]. The permeability, specific gravity, consolidation characteristics, and internal friction angle of fly ash increases the bearing capacity of the soil and reduces its settlement [26]. Moreover, fly ash also increases the surface area of the clay by dispersing large soil clusters and increasing the reactive surface for pozzolanic reaction [15,20]. Horpibulsuk et al. [17,20] and Kampala et al. [25] showed in their works that the incorporation of type F fly ash provides more alumino-silicates to react with any calcium hydroxide that does not previously reacted with the clay. As previously mentioned, researchers analyzed the combination of CCR and FA at different rations as binders. For example, Horpibulsuk et al. [20] identified CCR:FA ratio of 90:10 as an optimum ratio to improve engineering properties of problematic silty clay. Horpibulsuk et al. [24] then found another CCR:FA ratio of 40:60 that provided the best results for a stone dust material.

The research project was designed and implemented to develop techniques to be used in rammed earth construction. As part of the tasks, a model soil was prepared using poorly graded sand and low swelling bentonite clay. In addition, two binders CCR and FA at two different ratios were mixed at five different percentages to identify the most efficient combinations that can be used in the improvement of soil's strength. Compaction and unconfined compressive strength (UCS) tests were performed for each testing conditions. In addition, UCS tests were also completed for four different curing times. Finally, scanning electron microscope (SEM) images with dispersive X-ray spectroscopy (SEM/EDS) were taken to analyze the morphology and anatomic changes in elemental composition of the soil-binder mixtures that provided optimal strengths at different curing times.

2. Materials and methods

2.1. Soil properties

The natural soil used in this study, classified as a poorly graded sand (SP) according to USCS classification system. The soil was collected locally from a construction site in Kelowna, British Columbia. Fig. 1 shows the particle size distribution (PSD) of the natural soil. This soil was then used to develop a model soil in the laboratory using three steps. (i) Particles size greater than 2 mm were first removed from the natural sand; (ii) the remaining sand was then separated using a 300 μm sieve; (iii) a new composition of soil was prepared with 30% retained and 35% passing soil through the 300 μm sieve as well as with an addition of 35% low swelling bentonite clay (swell index of 12 ml/2g). Bentonite clay was added to increase the percentage of fines in the soil. As Maniatidis and Walker [8] suggested that a suitable material to be used in rammed earth construction stabilized with cement should have a fines between 20 and 35%. The bentonite clay, consisting of 35% montmorillonite, was obtained locally from the Hat Creek Valley, BC, Décor mine operated by Pacific Bentonite Ltd. The cation exchange capacity of the bentonite clay was 51 meq/100 g and its plastic and liquid limits were 21% and 209%, respectively. Fig. 1 also shows the PSD of the model soil. The plastic and liquid limits of the model soil were found to be 16.5% and 64%, respectively. According to the USCS classification system, the model soil was classified as clayey sand (SC). The Standard Proctor Maximum Dry Density (MDD) was found to be 1880 kg/m^3 and Optimal Moisture Content (OMC) was found to be 13%. The chemical compositions of the bentonite clay and the model soil are presented in Table 1.

2.2. Binder materials

Two binder materials such as calcium carbide residue (CCR) and fly ash (FA) were selected for this study. The CCR had a density of 2220 kg/m^3 and it was prepared by passing the material through a 600 μm sieve. A local construction company supplied the fly ash for this experimental study. The chemical analysis of the fly ash was completed in accordance to ASTM C618 [27] and the results were summarized in Table 2. Results indicated that the sum of SiO_2, Al_2O_3, and Fe_2O_3 accounted for 93.7% of the total composition, therefore, this fly ash is classified as class F. The selection of class F fly ash was necessary to ensure that enough pozzolanic material is available for chemical reactions.

The model soil was tested at two different CCR and FA ratios. The first group is named as Group A with a CCR:FA ratio of 40:60 and the other one is Group B with CCR:FA ratio of 60:40. These ratios were selected to examine the behavior of the model soil under circumstances where higher CCR is available or vice versa.

After completing several combinations of trials, five binder contents of 3%, 6%, 9%, 12%, and 15% by dry weight of model soil were selected. A maximum binder content of 15% was chosen as previous studies found that beyond 15% the soil-binder mixtures are in either an inert zone or a deterioration zone where the soil shows no increase, or even a decrease, in strength [15,17,20,23].

2.3. Sample preparation

Standard Proctor compaction tests were performed for each soil mixture in accordance with ASTM D698 [28] and a minimum of five compaction points were obtained for each of the five soil-binder mixtures. The specimens for unconfined compression strength (UCS) tests were prepared by compacting the soil-binder mixtures in cylindrical molds (40 mm diameter and 80 mm height). The specimens were compacted in three layers until they attained their MDD at moisture contents 3% greater than their OMC. This approach was considered as earlier study by Muhmed and Wanatowski (2013) and Horpibulsuk et al. [17,29] suggested that the optimal strength and durability are achieved when specimens were compacted at their OMC. An addition of 3% in the OMC was kept to allow the transformation of calcium carbide into calcium carbide residue. Calcium carbide (CaC_2) when react with water produce acetylene gas (C_2H_2) and CCR in terms of $Ca(OH)_2$.