



Composite alkaline activator on cemented soil: Multiple tests and mechanism analyses



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HIGHLIGHTS

- Composite activator of aluminate and sulfate was feasible to enhance UCS of cemented soil.
- Reaction rate of hydration strongly depended on activator dosage.
- Two types of pozzolanic reaction products were formed competitively at different activator dosage.
- The dominant factor affecting the reaction progress in cemented soil was proposed.
- UCS of cemented soil mainly depended on types and amounts of reaction products.

ARTICLE INFO

Article history:

Received 23 May 2018

Received in revised form 17 August 2018

Accepted 17 August 2018

Keywords:

Cemented soil

Composite alkaline activator

Hydration

Pozzolanic reaction

Reaction products

ABSTRACT

Adding cement in to reinforce soft soil has been a widely used technique in engineering projects. However, there exist great concerns over the issues of low early strength and massive resources consumption. This study tested a composite alkaline activator of sulfate and alkali aluminate in cemented soil by Unconfined Compressive Strength (UCS) test. Multiple analyses of X-ray Diffraction (XRD), Fourier Transform infrared spectroscopy (FT-IR), Thermo Gravity Analysis (TGA), Scanning Electron Microscopy-Energy Dispersive Spectroscopy (SEM-EDS) and Mercury Intrusion Porosimetry (MIP) were carried out to explore the activation mechanisms of the activator under different additions over curing periods. Test results revealed that UCS of stabilized soil was greatly improved in especially early periods with proper activator dosages. Hydration and pozzolanic reaction extents were accelerated with proper additions, while significant retardation for products of hydration and pozzolanic products was observed with excessive dosages.

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1. Introduction

Cement treatment is a widely used method for improving soil properties in many engineering aspects. However, its application is greatly limited by the slow development of early strength and massive consumption in certain soft soil [1,2]. Furthermore, the manufacture of cement consumes massive resources, emits enormous carbon dioxide, posing a great threat to environment [3,4]. As cement is still an economic and easy-attainable material for chemical soil stabilization, research concerns have been drawn by the use of chemical additions, capable of improving early strength and reducing cement content.

References for the present study suggested that most of the published work regarding inorganic additions focused on sulfate additions, alkali hydroxides and sodium silicate [5–7].

Calcium sulfates and sodium sulfates are two most common sulfate additions. It is known to all that various reactions take place in cemented soil with sulfates. Such reactions result in physical properties changes like grain size, water content, and dry unit weight, which are regarded as temporary alternation, while the formation of hydration products is regarded as permanent improvement [6]. Rica et al. and Zhang et al. [8,9] found that the addition of sulfates promoted the hardening process of cemented soil. The presence of sulfates in cemented soil might induce significant heaving, which can result in strength loss or structural damage [10]. It was reported that volume swelling started at the sulfate ion concentration of 0.03 g/kg [11,12], while the strength loss starts around 7 g/kg [13]. This phenomenon is caused mainly by

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the formation of ettringite (Aft), increasing the potential by 250% [14]. Either in cement mortar or in treated soil, the reaction between sulfates, tricalcium and calcium hydroxide leads to the generation of weak products like thaumasite during the curing period. Such reactions not only weaken the matrix strength, but also lower the alkalinity, inducing instability for calcium silicate hydrates [15,16].

Extensive researches have reported the applications of alkaline activators with natural pozzolanic materials or industrial by-products instead of cement in soil stabilization. With respect to activator types, highly soluble alkaline hydroxides, sodium silicate or their composites are most commonly used activation materials. Literatures reported that [17–19] the addition of sodium provides enormous HSiO_3^- , which polymerizes with positive ions to form Zeolitic phase and Calcium Silicate Hydrated (i.e. C(A)SH, (N,K)ASH).

As to alkaline hydroxides, the dissolved OH^- are capable of breaking the covalent bonds of alumina-silicate (Al-O-Si, Si-O-Si, Al-O-Al) of soil particles, then polymerize with positive ions to amorphous alumina-silicate gel of 3D-structure, consolidating (either concrete or treated soil) the binders [7,20]. Regarding positive ions variations, KOH usage results in faster cementitious materials hardening, NaOH utilization leads to higher binder strength, while $\text{Ca}(\text{OH})_2$ addition further promotes the system strength [18,21,22]. Notably, mechanical properties of activated cement binder exhibit sensitive response to activator dosage. According to Palomo's research [23], alkali-activated cement showed higher strength than normal cement, whereas excessive addition of OH^- led to significant strength decrease. Meanwhile, research results of Yang et al. [24] turned out that cemented soil with appropriate alkali degree exhibited satisfactory mechanical properties. As to the extent of geopolymer, excessive alkaline addition might promote no more strength increase after reaching certain concentration, and strength loss in long-term curing might happen due to the high alkali in product [18]. According to Sargent's investigation [25], either transport or binder cost of using cement for soil stabilization was a lot lower than that of using geo-polymer. In addition, it has been proven that adopting alkaline activation to reduce cement usage appears to be the most economical [26]. Yet, limited was the research focused on the particular application to cemented soil, let alone the proper dosages for alkaline addition.

The present work aimed at examining the feasibility of a novel composite activator of sulfate and alkali aluminate for cement-treated soil, understanding its mechanism of activation, based on previous studies of sulfates and alkaline additions. The changes in mechanical properties were evaluated by compressive strength test. And, the reaction mechanisms are explored by multiple methods of X-ray diffraction (XRD), thermo-gravity analysis (TGA), Fourier Transform infrared spectroscopy (FT-IR), Scanning Electron Microscopy-Energy Dispersive Spectroscopy (SEM-EDS) and Mercury Intrusion Porosimetry (MIP) test.

2. Materials and methodology

2.1. Materials and mixture design

The cement used in this study was commercial ordinary Portland cement 42.5#, and the soil was collected from a construction site in the suburb of Nanjing. Before conducting relevant tests, the undisturbed soil was dried under 105 °C, then was passed through 2 mm sieve after grinding. Basic properties of the soils including optimum water content (OWC) and maximum dry density (MDD), Atterberg limits, soil classification, specific gravity and particle size distribution (PSD) were controlled according to relative standards. Results of basic properties were given in Table 1, with PSD curve presenting in Fig. 1. Chemical compositions of the soil and cement were obtained by X-ray fluorescence analysis (XRF), given in Table 2. The composite activator was consisted of sodium aluminate, calcium aluminate and sodium sulfate, the chemical compositions were given in the forms of oxide, listed in Table 2 as well. The composite activator used in this study has already been authorized as a patent of the authors' research group in China [27].

The soil and cement were mixed with a relative low cement addition ratio of 9:1 for all cemented soil samples. The OWC and the MDD of cemented soil without the activator was also provided in Table 1, and the specific procedure for compaction test would be demonstrated below. The activator dosages were maintained as 0.4%, 0.6%, 0.8%, 1.0% and 1.2% of total dry mass, written as J40, J60, J80, J100 and J120 in context, of the cemented soil. The cemented soil with activator was written as ACS, and control samples of untreated soil and cemented soil without activator were written as US and CS, respectively.

2.2. Compaction test

The MDD and OWC for sample preparation were conducted according to JTG E51-2009 (Test methods of materials stabilized with inorganic binders for highway engineering, Chinese standard). In which, the soil were mixed with the distilled water, then the soil-water matrix were wrapped with plastic bags and cured in chamber thereafter. After 24 h' curing, the cement and the activator (if needed) were added to the matrix for compaction test. The compaction energy was 2698 kJ/m^3 , equivalent to that of ASTM D1557. The compaction results of treated soil samples were given in Fig. 2, which showed that the MDD and OWC of treated soil samples were around 1.58 g/cm^3 and 35.2%, respectively.

2.3. Sample preparation and curing conditions

To prepare samples, the water content for all samples was controlled to 35% of the total dry weight, within $\pm 0.5\%$ of OWC. And all samples were compacted to within $\pm 0.5 \text{ g/cm}^3$ of MDD. The soil

Table 1
Basic properties of the soil and cemented soil.

| Basic soil properties | | Value | Reference standard |
|---|--------------------------------------|---------------|--------------------|
| Liquid limit (%) | | 60.6 | ASTM D4318 |
| Plastic limit (%) | | 38.7 | |
| Plasticity index PI | | 21.9 | |
| Soil classification | | CH (Fat clay) | ASTM D2487 |
| Optimum water content (%) | Untreated soil | 34.8 | ASTM D1557 |
| | Cemented soil | 35.2 | JTG E51-2009 |
| Maximum dry density (g/cm^3) | Untreated soil | 1.65 | ASTM D1557 |
| | Cemented soil | 1.58 | JTG E51-2009 |
| Specific gravity | | 2.72 | ASTM D854 |
| Particle size distribution (%) | <5 μm | 32.2 | ASTM D422 |
| | 5 μm –75 μm | 48.9 | |
| | 75 μm –2000 μm | 18.9 | |

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