Construction and Building Materials xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Construction and Building Materials

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

On the viscous behavior of cement mixtures with clay, sand, lime and bottom ash for jet grouting

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HIGHLIGHTS

- Different stabilizers have been investigated for viscous behavior of jet grouting.
- Flow capability of mixture is primarily dependent upon the dosage rate of stabilizer.
- The rates that insignificantly affect the native cement could be applicable ($p > 0.05$).
- Shear stress–shear rate curves dominantly indicate a thixotropy property.
- Herschel–Bulkley simulates the yield-pseudoplastic behavior better than Casson.

ARTICLE INFO

Article history:
Received 15 December 2014
Received in revised form 1 April 2015
Accepted 1 May 2015
Available online xxxx

Keywords:
Jet grouting
Viscous behavior
Shear stress–shear rate
Cement
Bottom ash
Control chart
Multiple comparisons

ABSTRACT

Jet grouting is one of the newest technologies being popular in the improvement of the marginal soils (i.e., soft fine-grained or loose coarse grained) mostly available at the construction sites of engineering structures. The performance of soil improvement due to this technique is primarily dependent on the flow abilities of the fresh grout mixtures. Without satisfactory flow properties, it is unlikely that the hardened material of jet grout column could be achieved with desirable results. This paper investigates the viscous properties of cement based grout mixtures with different stabilizers comparatively, for jet grouting, in the point of rheological characteristics (viscosity, yield stress) and rheological behaviors (the flow curve of shear stress–shear rate). The stabilizer inclusions are clay, sand, lime and bottom ash in various proportions at the dosage rates from 0% to 100%, by dry weight of binder. An extensive experimental study was carried out by conducting the rheometer tests with ten replicates for each stabilizer rate. Using statistical analysis of quality control charts, satisfactory tests within the ten replicates have been determined and employed throughout their investigations in the study. The effect of stabilizer versus dosage rates on native cement was determined using the statistical significance analysis of multiple comparisons (Dunnett test). It is observed from the results of study that the employed stabilizers relatively have the potential of contributions to flow capability of the mixtures primarily dependent upon their dosage rates. The proportions up to the dosages rates of 30%, 40% and 50% respectively for the separate additions of sand, lime and bottom ash, which do not show statistically significant changes on the rheological characteristics of native cement, due to the multiple comparisons ($p > 0.05$), could be potentially offered for practice. Similar benefits on the native cement have also been obtained from the attempts of stabilizer combinations. The rheological behavior of shear stress–shear rate curves due to the stabilizer inclusions generate a non-Newtonian motion with various nonlinear responses, which dominantly result in pseudo-plastic behavior followed by the one of yield-pseudoplastic. The potential dosage rates of stabilizers that provide insignificant effects on the rheological characteristics are also produce same rheological behaviors with the native cement (except lime inclusions) representing a good consistency to support their usage. From the model comparisons (i.e., Casson, Herschel–Bulkley) with the measured shear stress–shear rate curves resulted in yield-pseudoplastic behavior, it is found that the Herschel–Bulkley model describes the rheological behavior more properly as compared with the Casson model. The satisfactory model could be helpful for querying the complex relations in the mixture compositions. The attempt presented in this work reflects the influences of the employed stabilizers on native cement with the promising findings for jet grouting in the linkage of rheology. The findings on the usage of bottom ash could also contribute to its disposal problem in the environmental point of view.

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http://dx.doi.org/10.1016/j.conbuildmat.2015.05.072
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Please cite this article in press as: Güllü H. On the viscous behavior of cement mixtures with clay, sand, lime and bottom ash for jet grouting. Constr Build Mater (2015), http://dx.doi.org/10.1016/j.conbuildmat.2015.05.072

1. Introduction

In order to improve the engineering properties of marginal soils (soft fine-grained soils or loose coarse-grained soils) that cause considerable engineering problems (settlement, bearing capacity, hydraulic conductivity) for construction sites, the jet grouting method could be employed as one of the newest technologies being popular due to its ability of great versatility within the history of grouting techniques (i.e., intrusion, permeation, compaction, jet-grouting) [7,9,38,50,51]. The advantage of versatility incorporating with the injection of high pressure by means of the jet grouting technique allows engineers to improve a wide range of soil types from coarse-to-fine-grained soil, and to produce different geometric shapes of soil columns or panels. Thus, this facility of improvement provides the preference of jet grouting with the intensively employment in practice [9,38,48]. Due to the several parameters (soil type, grout flow rate, exiting jet energy from nozzle, rotating and lifting speed, mixture influx between soil and grout, etc.) that control the design of the jet-grouting system and jet-grout columns [39], the composition of grout has a particular concern, since its fluidity properties directly affects the injection, which is the main role during the jet-grouting cooperating with the other variables. The grout should possess sufficiently high fluidity and suspended materials in the point of groutability, since the fluidity characteristic controls the velocity of the grout and the soil/grout mixing capability for obtaining the soil columns with a desirable stability. Stability is the capacity of grout to remain in a sufficient fluidity until reaching to the desired location in the soil mass without segregating into separate components of grout. Regarding the variation of time of flow as a function of strength, it is appeared that an increase in both fluidity and strength is not possible, since fluidity can be increased with increased water. This in turn reduces alkali concentration in the grout mixture and consequently its strength, and indicates to the fluidity being of significance importance for a desirable jet grout column. Such knowledge is also essential to effectively design the injection of grout in order to obtain a higher structural matrix for effectively filling the soil voids. It is reported that an increase in the injection pressure correlates well with an increase on the diameter of the jet grout columns, which clearly enhance bearing capacity of foundation [11]. The composition of jet-grout is partially dependent on the soil being treated. The analytical calculation of the composition could not be possible in practice due to the jet-grouting parameters and the complex process of erosion, mixing, replacement, filling of pore space [12].

On the consideration of grout composition, viscosity of a grout mixture clearly displays a particular importance through the production of jet-grouting columns, since it is the rheology of the grout that will determine how well the grout can be properly injected and flow through the soil [10,12,22]. If a high viscosity of grout is used, the jet-grouting columns could be constructed in the level of weak homogenization between the soil and the grout. This is of special concern when dealing particularly with low permeability soils (fine-grained soils). In the reverse, a low viscosity adversely affects the injection through the nozzles to produce a solid mass of the soil columns. In the principle, the viscosity resistance of deformation is obtained against the shear stress of grout. It is caused by the cohesive forces between the molecules in liquids as well as the internal molecular friction within the liquid producing the frictional drag effect [11]. The viscosity characteristics of the jet-grout mixtures are primarily dependent on the physico-chemical characteristics of the stabilizers in the compositions (e.g., grain size, mineralogy, soil type). For the mixtures consisting primarily of clay-sized particles, a viscoplastic description is considered appropriate. A significant change in viscosity may be obtained under the same testing conditions [10]. It is reported that as soon as internal friction appears in the grout mixture, the grouting is no longer possible. In very dense grout, cement grains come into contact and develop friction that can arrest the grouting process [14].

To the relevance of practical applications in jet grouting, the rheological investigations on grout composition are increasing [16,28,53,35]. The grout could be defined as the cementitious slurry (i.e., a mixture of liquid and solid particles retaining some fluidity) that is normally composed of the mixture of cement + water. The cement mixture is in a fluid state within the soil injected due to the large amount of injected water. It could require several hours or days to attain strength for this admixture [48]. In accordance with [2], the grout specimens are allowed to leave in the molds when they are to be tested within about 16 h. After 16 h, they may be removed from the mold provided that they have sufficiently cured to be undamaged by handling. On the basis of past works [43], the specimens could be tested at 1, 2, 3, 7, 14, 28 and 96 days of curing time dependent upon the desirable strength development. The grout could also contain the other materials such as clay, bentonite, sand, fly ash, pozzolans, etc., besides cement and water. Some amount of clay could be added to lean Portland cement mixture of clay as filler material in order to obtain some benefits on pumpability, injectivity, bleeding and economy. Two principal types of clay mostly employed in grouting work are montmorillonite and kaolinite [52,31]. Since clay minerals are insoluble, a protective environment around cement particles could be formed, thus preventing dissolution by aggressive waters. Therefore, the grouts including clay particles may be relatively stable [6]. Sand may be used when a considerable volume of void space with a relatively open structure is to be filled. Generally, the sand used in the grout is finer than the one used to make conventional concrete [31]. The fine sands are added to neat cement as filler material sometimes for the reasons of economy as well. In general, uniform graded sand with high sphericity (i.e., rounded as opposite to flat or angular) is preferable when it is desired the pumpability better. Other benefits of fine sand in the grout include lower water-cement ratios, less heat of hydration and less shrinkage. It is suggested that the maximum diameter of sand should be reduced to 0.5 mm for long pumping distances to avoid segregation [27]. Some admixtures of stabilizers including fly ash and bentonite are often used to help good fluid properties, without occurring segregation during injection. It is reported that fly ash provides an additional cementitious action, but results in high permeability due to its absorption capability of large amount with a concomitant large increase in volume [31]. As a replacement material of the cement, the maximum amount of fly ash should not exceed 30% of the cement by weight to maintain the strength levels approximately at the ones of 28-days age [52]. The pozzolans (other than fly ash) could be used in the grouts through chemical reaction with calcium hydroxide of Portland cement to form compounds embodying cementitious properties when they are in finely divided forms [52]. Due to this suggestion, bottom ash is likely to be an alternative candidate for replacement of cement in the grout mixtures. Here, it can be noted that several types of cement blended with mineral admixtures are available rather than ordinary Portland cement (i.e., rapid hardening, low-heat, modified cement, sulfate resisting, Portland blast-furnace, high-slag blast-furnace, Portland-pozzolan, etc.) in relation to the required physical and chemical characteristics of jet grout mixtures. They influences to the mixtures for the specific characteristics such as hardening rate, heat development during hydration, aeration, resistance to sulfates, organic matters, salts, etc [31]. Even though the grout mixtures in the jet-grouting technology have been investigated to some extent, there is still insufficient research about the

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