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Comparison of rheological models for jet grout cement mixtures with various stabilizers

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HIGHLIGHTS

- The rheological models (B, MB, C, HB, DK, RS) have been compared for jet grouting.
- The shear stress-shear rate curves mostly result in pseudoplastic or yield-pseudoplastic.
- The RS and derived models are most acceptable with the fitting of high ranking.
- The Casson model is unacceptable with an inadequate fitting.

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ABSTRACT

The use of jet grouting technique for ground improvement has become very popular approach for civil engineering projects. Despite the availability of large number research related to development of this technique, the rheological models of grout flow have still become in concern for jet grout applications. Thus, an investigation on the performances of the most common rheological models (Bingham, Modified Bingham, Casson, Herschel-Bulkley, Robertson-Stiff, De Kee) for prediction of flow behavior in terms of the shear stresses due to the cement grout mixtures incorporating with the stabilizers of clay, sand, lime, bottom ash in various proportions (0–100%) has been addressed in this article for jet grouting. For this purpose, a thorough comparison of the rheological models has been performed using the flow curves of the shear stress-shear rate data collected from previous study. On the basis of the comparisons, the performances have been presented in a ranking scheme that represents the favorable models within the low to high ranking. It is found from the performances that all rheological models, except the Casson, at most of the stabilizer inclusions have been adequately fitted to the shear stress-shear rate data, resulting in the lower errors (MAE, RMSE) and the strong correlations ($R > 0.8$) with a significant evidence ($p < 0.05$). It is proposed from the ranking scheme that the Robertson-Stiff model and derived formulas in this study are most acceptable (high ranking), the De Kee model is moderate acceptable (moderate ranking), the Herschel-Bulkley and Modified Bingham models are less to moderate acceptable (low to moderate ranking), the Bingham model is least acceptable (low ranking), and the Casson model is unacceptable. Applicability of the ranking performances is relatively promising for jet grouting when compared with the measured shear stress-shear rate data.

1. Introduction

Jet grouting is one of the newest technologies of ground improvement that has been used to enhance the engineering characteristics (i.e., bearing capacity, settlement and permeability) of marginal soils (i.e., soft fine-grained, loose coarse-grained) for building foundations, slope stabilization, underpinning, block stabilization of contaminated soils, barrier formation for the migration control of contaminant in the environmental field, etc [1–3]. Due to being its extremely versatile ability on a wide range of soils types (because of its existence of high-pressure technology) and economically attractive facilities when compared with other methods, the jet grout technology has become a worldwide technique extensively applied for soil improvement [4–5]. In this technique, a slurry grout is injected into the subsoil at high pressure and velocity to destroy the soil structure. Consequently, the injected grout slurry (normally cement) and the fragmented soil together produce an improved soil mass (i.e., jet grouting columns usually known as soilcrete) with the favorable characteristics in strength, deformability and permeability [2,5]. However, it is essential that

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the properties of grout slurry when its fresh state is very complex task in the point of rheology that controls the soil-grout mix after the hardening process of jet-grout column takes place [1,6]. As well as the hardened material in desired property, the grout mixtures should have sufficient fluidity with the fresh properties in order to facilitate the process through the pumping [7], to perform the service for the nozzles conveniently and to provide full penetration into soil voids [6], particularly associated with rheological behavior [8–10]. Sufficient fluidity and stability of grout mixture with adequate mechanical properties are the main requirements for the ground treatment due to jet grouting [1,6–7,9]. Thus, the issue of rheological behavior specifically through the comparison of possible rheological models of cement-based slurries for the jet grouting relatively deserves to be researched in order to obtain the improvement well in the quality and economy. Moreover, the investigation of rheological models for grout mixtures could be beneficial for understanding the effects of different parameters (flow rate of grout, soil types, mixture influx between soil and grout, rotating and lifting speed of driven road, etc.) involved in jet grouting process [2–3,6]. This could also be helpful especially for designing, planning and managing of construction projects due to jet grouting. Hence, this paper compares the possible rheological models for the cement-based slurry grouts included with various stabilizers (i.e., clay, sand, lime and bottom ash) for jet-grouting purpose. Even though there are some past works on the rheological models of cement based slurry grout, the research regarding the cement slurry with various stabilizers has still been limited. Moreover, the attempt for the jet-grouting purpose is not sufficiently available in current literature.

The deformation characteristics of cement-based grout mixtures on the flow capability are generally explored by the flow curve (i.e., the shear stress versus shear rate curve) experimentally obtained from the flow test (i.e., the rheometer or viscometer test). A fundamental concern of using grout associated with rheological behavior due to the flow curve is represented by rheological model (flow model) that can be constructed by a mathematical formula in various approximations developed from the flow curve of fresh grout mixture [8–9,11–14]. The rheological models are able to predict the deformation of cement paste with reasonable accuracy when they have a successful model capability to describe the viscous behavior. This occurs in a very broad intermediate range between elastic solid and viscous fluid states. Hence, they could relatively be beneficial for understanding the rheological behavior of fresh grout mixture [15–16]. The shear stress-shear rate curve has a special interest of the knowledge with the rheological flow parameters of viscosity (plastic viscosity) and yield stress (i.e., shear stress corresponding to zero shear rate). The possible developed formula of rheological model of grout mixture primarily contains the variables of the flow parameters that include shear stress, shear rate, viscosity and yield stress. However, depending on the nonlinearity of the shear stress-shear rate curve, the rheological parameters of viscosity (plastic viscosity) and yield stress could sometimes be excluded in the rheological models [9–10,16–20].

Various investigations have been carried out on the rheological behavior of cement-based slurry of grout mixtures. They show that the grout mixtures exhibit a non-Newtonian flow characteristics, which indicates a nonlinear behavior of the flow curves, markedly different from a single Newtonian fluids [7,11,18,21]. The nonlinear behavior of grout mixtures could result in the responses of pseudoplastic type (i.e., shear thinning as the decrease in viscosity (apparent viscosity) with the increased shear rate) or dilatant type (i.e., shear thickening as the increase in viscosity (apparent viscosity) with the increased shear rate) [7,16,22]. In the case of a pumped grout mixture due to these responses above, the pumping pressure (shear stress) will be affected by the pumping rate (shear rate) dependent upon the mix inclusions [16,23]. Relevance to this viewpoint, it is reported that the nonlinear rheological behavior of grout mixtures depends on many parameters of physical and chemical factors, which mainly include the solid concentration (water/binder ratio), composition of binder (i.e., cement+stabilizer), particle interactions, grain shape, grain size distribution, etc [7,18,24–28]. It is also reported that high-performance structural grouts are shown to exhibit shear-thickening behavior at low water/cement ratios and shear-thinning behavior at relatively higher water/cement ratios [25]. Many works on the rheological behavior of cement-based grouts have shown that the nonlinear response of the grout mixtures behaves as a viscoplastic fluid usually having a yield stress that must be overcome by the shear stress in order to initiate flow [7]. In the existence of yield stress, the nonlinear behavior of grout mixtures could be called as yield-pseudoplastic or yield-dilatant [21–22,29]. The yield stress in the cement-based mixtures for jet grouting is an important property affecting the flow behavior. The flow rate could be dramatically influenced by the presence of yield stress [17]. The rheological model of the grout mixture is the mathematical approximation of the nonlinear response of the shear stress-shear rate curve as stated above. It is reported that the estimation of the rheological parameters from the flow curves (i.e., the shear stress-shear rate curves) could be based on the empirical models that take the shear history, time-dependent behavior and test procedure into consideration [8–9,16–19].

Relevance to the performance of cement-based grout mixtures to ensure the sufficient fluidity and stability [7], the various stabilizers (clay, sand, pozzolans, lime, mineral fillers, admixtures, etc.) could be added separately or together to the cement slurry for the aim to obtain desired property. The addition of various stabilizers to the grout mixture could enable the experimenter not only to develop a wide range of physical properties in the grout but also to make adjustments in the field to meet project specific conditions. The various proportions of stabilizers with a finer particle-size distribution when incorporating with the cement slurry could highlight on the improvement of packing of solid particles, enhancement of rheological properties and improvement of grout consistency. Using the stabilizers in the cement slurry could also provide a contribution to the grout, mainly for reasons of economy when replaced with various amount of cement [10,12–13,24,30–33]. This replacement could also environmentally be beneficial, since high level of CO_2 is released during cement production estimated at 7% of the total anthropogenic CO_2 [6]. It is reported that clay is found useful as a stabilizer in native cement due to their improved pumpability, injectivity and economy. Small dosages of clay additions have also been demonstrated to improve the cohesiveness of cement-based mixtures. The grouts including clay particles may be relatively stable because a protective environment around cement particles could be formed due to clay additions [30,34]. Sand particles (fine sand) in cement-based grouts could be useful for providing less heat of hydration and less shrinkage with a desired pumpability [30]. Some admixtures of mineral additions (superplasticizer) could act by presenting a viscosity that increases with the shear rate [12,22,35–37]. Pozzolanic materials (siliceous and aluminous materials) in finely divided forms could be used in grout mixtures to obtain the compounds embodying cementitious properties by the chemical reaction with calcium hydroxide of cement [6,30]. One of the pozzolanic materials recently being popular [38], bottom ash (a waste material of industrial by product), could be alternately attempted as a stabilizer with a special concern when dealing with buried structures like jet-grout columns. The pozzolanic activation of bottom ash has been recently offered for clay treatment for soil stabilization purposes [38]. However, up to now its application has not been sufficiently observed to ground improvement via jet grouting. Similar to fly ash usage due to the advantage of alkali-based product over