Applied Clay Science 161 (2018) 64–69

Contents lists available at ScienceDirect

Applied Clay Science

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

Research paper

Experimental study on fluid properties of slurry and its influence on slurry infiltration in sand stratum

Fanlu Min[a,b], Hangbiao Song[b,*], Nan Zhang[c,*]

[a] Key Laboratory of Geomechanics and Embankment Engineering, Hohai University, Ministry of Education, Nanjing 210098, China
[b] College of Civil and Transportation Engineering, Hohai University, Nanjing 210098, China
[c] Department of Civil Engineering, The University of Texas at Arlington, Arlington, TX 76019, USA

ARTICLE INFO

Keywords:
Slurry
Infiltration
Darcy's law
Initial hydraulic gradient
Fluid property

ABSTRACT

In construction of slurry engineering, especially in sand stratum of high permeability, small size fine particles in slurry are likely to flow through the stratum and washed away. In this study, nine groups of slurry fluid property tests were performed using a NXS-11A rotary viscometer in order to investigate infiltration of slurry in sand stratum. Additionally, a series of penetration tests were also conducted by a self-designed infiltration device. Experimental results show the test slurry meet characteristics of Bingham fluid at a medium to high shear rate, while it conforms to the Herschel-Bulkley model at a low shear rate. Darcy's law is no longer applicable to infiltration of slurry in sand stratum, because of the initial hydraulic gradient. The infiltration rate (v_s) is not strictly linearly related to the hydraulic gradient at small hydraulic gradient (i). It is also indicated that the yield stress of slurry is the fundamental cause of initial hydraulic gradient during the infiltration process of slurry in sand stratum. The yield stress has a positive correlation with the initial hydraulic gradient. Ideally, initial hydraulic gradient is proportional to the dynamic shear force of slurry.

1. Introduction

The slurry is easily available, and widely used in oil drilling, diaphragm wall, drill shaft, slurry shield and other projects since it has a strong ability of wall protection and slagging removal (Nasiri et al., 2017; Lei et al., 2017; Zhou and Chen, 2007; Li et al., 2009). The wall protection is achieved by the fact that the slurry penetrates to strata with fine particles clogging the pore space in stratum, and forming the filter cake on the surface of stratum. However, when the slurry is applied to a sand stratum with a relatively high permeability, fine particles may flow through the stratum where filter cake cannot be formed. In this scenario, the slurry is considered as a Newtonian fluid like water that infiltrates in sand stratum (Min et al., 2013), and the wall protection of slurry can not be achieved, which may lead to stratum collapse and other destruction. In addition, slurry (or cementitious slurry) infiltrating into sand formation is also considered in grouting reinforcement technique for a controlled grouting distance. Under these circumstances, the fluid properties of slurry and its infiltration rule in sand are the main factors which affect grouting distance and reinforcement effect (Axelsson et al., 2009). It is reported that the infiltration of water in sand strata conforms to Darcy's Law when laminar flows occur (Darcy, 1856; Holden, 2005; Marle, 2006), but the slurry contains some fine soil particles with a certain grain size distribution, and a density of around 1.05–1.3 g/cm^3, thereby the fluid properties are different from those of water. Therefore, it is not well understood whether Darcy's Law can be applied, and how infiltration law works in the process of slurry infiltration.

The slurry is generally defined as Bingham fluid in order to simplify calculation for engineering purpose (Frigaard et al., 2017; Merrill et al., 2017). Its infiltration behavior is studied and applied under this assumption as well. Actually, the fluid characteristics are more complex with different slurry properties. Fig. 1 shows several rheological models for typical fluids (Ariaratnam et al., 2007). Newtonian model rheological curve passes through the origin point, and the shear stress is linearly correlated with shear rate. Compared with Newtonian model, Bingham model has an initial shear stress. In contrast, for power model and Herschel-Bulkley model (Barnes, 1999), the rheological curves show a nonlinear relationship, and the Herschel-Bulkley model has an initial shear stress.

Wu et al. (2015) found that with the increase of solid content, the fluid properties of slurry (solid content lies between 46.7% and 71.3%) were transited from power law fluid to approximate Newtonian fluid by adding petroleum coke and lignite to drilling slurry. Hong et al. (2016) carried out rheological tests in kaolin slurry (solid content lies between

---

* Corresponding authors.
E-mail address: nan.zhang@mavs.uta.edu (N. Zhang).

https://doi.org/10.1016/j.clay.2018.03.028
Received 5 December 2017; Received in revised form 20 March 2018; Accepted 21 March 2018

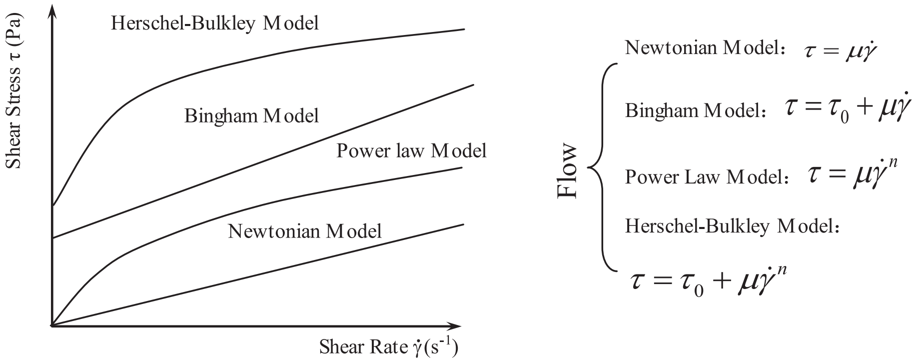

Fig. 1. Typical rheological models and flow equations.

10% and 80%), and indicated that the slurry viscosity coefficient and shear stress increased with the increase of the content of solid particles, especially when the solid concentration was > 50%. Assefa and Kaushal (2015) also obtained the same conclusion, and indicated that the viscosity coefficient of slurry was closely related to non-uniform coefficient *Cu* and average grain size d_{50} of solid particle.

Xu et al. (2017) found that dredged clay slurry ($w > 200\%$) behaved more like Newtonian fluid as water content of slurry increased, whereas its behavior was close to Bingham fluid at low water content. Lv et al. (2017) also drew similar conclusion, and indicated that the slurry property approached the power law fluid with a yield value when moisture content was < 150%, and it can be described by the Herschel-Bulkley model. Wang et al. (2012) studied rheological properties of petroleum drilling fluids ($\rho = 1.5\,g/cm^3$, $2.2\,g/cm^3$) under high temperature, pressure, and density conditions. They found that the drilling fluid approached the power law fluid with a yield value, and its rheological properties were consistent with Herschel-Bulkley model. Heinz (2006) found that the addition of polymer changed the fluid properties of bentonite slurry, but did not affect the formation of slurry film. Silt, sand and other additives can effectively reduce the infiltration distance in sand layer. Min et al. (2013) stated that the slurry used in slurry shield belongs to Bingham fluid. He also proposed a ratio of the average pore diameter D_0 to the effective particle size d_{85} to divide the infiltration phenomenon into three categories: a filter cake, a filter cake with an infiltrated zone, and infiltrated zone without filter cake.

Thus, there is still a lack of research about the influence of slurry fluid properties on its infiltration behavior in stratum. Related studies may refer to the infiltration behaviors of fluids with large viscous coefficients (such as polymer solutions, oils, etc.) in the formation. Prada and Civan (1999) found that permeation of saturated brine was not consistent with Darcy's law in eight typical sandstones and Brown sandstones, and there was an initial pressure gradient, which is the function of the permeability of pore medium and the viscosity coefficient of the fluid. Wang et al. (2006) found that the crude oil flow, in the Zaoyuan Oilfield in Cangzhou, Hebei Province, needed to overcome a fixed initial pressure gradient that essentially met the power law fluid with a yield value. The initial pressure gradient was proportional to the yield strength of the fluid and the porosity of the formation, and was inversely proportional to the permeability of the formation. Based on the fractal theory, Yun et al. (2008) established a fractal model of initial pressure gradient of flow of Bingham fluid in porous medium, and the conclusion was consistent with Wang et al.'s study.

The key objective of this study is to identify the rheological model of slurry based on multiple sets of different properties (density and viscosity) of slurry of fine particle size. The infiltration behavior of slurry in high permeability sand strata is also studied. The relationship between the rheological properties of slurry and the infiltration behavior is analyzed, and the applicability of Darcy's law in slurry permeation is discussed as well.

2. Laboratory experiments

2.1. Materials

In this study, a pure Na-bentonite slurry with a concentration of 9.1%, and a density of 1.06 g/cm^3 was selected as the test material. The mineralogical composition of the Na-bentonite includes montmorillonite of 63.65%, illite-kaolinite of 23.46%, quartz of 10.35%, and plagioclase of 2.54%, and it was manufactured from Tangshan of Nanjing city in China. Additionally, it has an expansion index of 21 ml and a pH value of 10.09. The clay was used to adjust the density of slurry, and Carboxymethyl Cellulose (CMC) (note: the commonly used tackifier in slurry engineering at present) with a concentration of 2% was also used to adjust the viscosity of the slurry (Menezes et al., 2010). Meanwhile, the slurry need to be sieved to remove soil particles retaining on No. 200 sieve in order to avoid the change of permeability of stratum and affecting infiltration behavior of slurry in stratum due to the clogging during infiltration process. Nine slurry samples with different densities and viscosities were measured. Laser particle sizer, slurry density meter and Marsh funnel viscometer were used to measure gradation, density and viscosity of the slurry samples. Physical properties of slurry are summarized in Table 1.

The fluid properties of the slurry were measured by a NXS-11A rotational viscometer produced by Chengdu Instrument Factory as depicted in Fig. 2a. The instrument has five sets of measurement systems with different ratios of inner diameter to outer diameter of cylinder as presented in Table 2. The instrument has fifteen different speed levels, which corresponds to 5 × 15 sets of measurement options. The largest measurable particle size is about 2.5 mm. NXS-11A rotational viscometer is a universal coaxial cylinder on the rotary viscometer. Schematic diagram of the working principle is shown in Fig. 2b. By choosing different upper rotors, outer cylinders and speed levels, the measured viscosity coefficient ranges from 2.8 to 1.78×10^7 mPa s, the shear stress ranges from 27.67 to 21,970 Pa, the shear rate ranges from 5.6 to

Table 1
Physical properties of test slurries.

Identity of slurry	d_{85}/μm	ρ/(g/cm^3)	Marsh time/s
NJ1	58	1.05	47
NJ2	59	1.1	47
NJ3	62	1.15	48
NJ4	64	1.19	47
NJ5	64	1.24	47
NJ6	60	1.15	31
NJ7	61	1.15	67
NJ8	64	1.15	80
NJ9	63	1.15	102

Note: d_{85} = particle size for which 85% by weight of particles in the slurries are smaller.
The Marsh time of water at 20 °C is 25 ± 0.5 s.