Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)

Injection ratio of high-performance eco-friendly grouting materials

Ratio d'injection de matériaux de jointoiement écologiques de haute performance

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ABSTRACT: Cement-based materials are widely used as grout materials. The research on eco-friendly grout materials has attracted attention in recent years. However, the studies on the strength enhancement and economic evaluation of eco-friendly grout materials have mainly focused on ground improvement, and there is insufficient research on the injection characteristics of these materials. In this study, the injection characteristics of agar gum and sodium alginate (SA) were evaluated using the pore network model. Agar gum can improve the shear strength of the ground owing to its thermo-gelation properties, and SA can improve the shear modulus of the ground. The effect of the pore size distribution, injection pressure, viscosity, and capillarity on injection characteristics was examined. Numerical analysis showed that injection pressure had the strongest effect on injection characteristics. However, the injection pressure and pore size distribution used in field conditions are limited. Therefore, viscosity and capillarity are considered as the main factors to evaluate injection characteristics in field conditions.

RÉSUMÉ: Les matériaux à base de ciment sont largement utilisés comme matériaux de coulis. La recherche sur les matériaux de coulis écologiques a attiré l'attention ces dernières années. Cependant, les études sur l'amélioration de la résistance et l'évaluation économique des matériaux de coulis respectueux de l'environnement se sont principalement concentrées sur l'amélioration du sol et les recherches sur les caractéristiques d'injection de ces matériaux sont insuffisantes. Dans cette étude, les caractéristiques d'injection de gomme d'agar et d'alginate de sodium (SA) ont été évaluées à l'aide du modèle de réseau de pores. La gomme d'agar peut améliorer la résistance au cisaillement du sol grâce à ses propriétés de thermo-gélification, et l'AS peut améliorer le module de cisaillement du sol. L'effet de la distribution de la taille des pores, de la pression d'injection, de la viscosité et de la capillarité sur les caractéristiques d'injection a été examiné. L'analyse numérique a montré que la pression d'injection avait le plus fort effet sur les caractéristiques d'injection. Cependant, la pression d'injection et la distribution de la taille des pores utilisées dans les conditions de terrain sont limitées. Par conséquent, la viscosité et la capillarité sont considérées comme les principaux facteurs pour évaluer les caractéristiques d'injection dans des conditions de terrain.

KEYWORDS: eco-friendly grouting materials; injection ratio; pore network model; viscosity and capillarity

1 INTRODUCTION

Ground improvement has been studied for increasing the bearing capacity of the ground, reducing settlement, preventing liquefaction, controlling the groundwater level, improving the stability of excavation surfaces, and soil restoration (Moseley and Kirsch, 2004). Among ground improvement methods, grouting is used for reinforcement, improvement, and backfilling (Weaver 1991; Stille et al., 2012; Bezuijen et al., 2013). At present, grout materials are mainly cement based, clay based, and asphalt based. Among these, cement-based injection materials are the most widely used. However, in recent years, regulations on reducing carbon dioxide emissions are being applied worldwide in accordance with the Convention on Climate Change. Therefore, the use of eco-friendly construction materials is increasing (Hendriks et al., 1998; Van Oss et al., 2003). Biopolymers (e.g., xanthan gum, guar gum, and modified starch) are used as eco-friendly grout materials, and their strength and economics have been investigated. However, the research on their injection properties is insufficient (Khatami & O`Kelly, 2013; Chang et al., 2015(a); Ayeldeen et al., 2016; Jung et al., 2016; Chang et al., 2016; Lee et al., 2017; Jang 2020). Agar gum is a biopolymer with thermogelation characteristics, and it is expected to be used as a new construction material (Chang et al., 2015(b). In addition, sodium alginate (SA) increases the shear modulus of the ground (Ahn et al., 2020). Therefore, in this work, the ground injection characteristics of SA and agar gum (Jang, 2017) were investigated using a pore network model to improve the injection efficiency of these materials. Additionally, the effect of the pore size distribution, injection pressure, viscosity, and capillarity on the injection ratio was analyzed.

2 MATERIALS AND METHODOLOGY

2.1 *Grouting material preparation*

Distilled water and SA were weighed based on the calculated mixing ratio, and they were mixed using a magnetic stirrer for 24 h. After the prepared SA solution was stabilized, viscosity, surface tension, and the surface contact angle were measured at 25 °C. The viscosity, surface tension, and contact angle of agar (0.5%) were obtained from Jang (2017). Finally, the viscosity and capillarity characteristics of the polymer solution were used as input parameters for the pore network model.

2.2 *Viscosity*

Viscosity is an important factor because it is used to determine flow distribution patterns including capillary number and viscosity number(Lenormand et al., 1988; Lenormand, 1990). In this study, a viscometer (LV-DVE, Brookfield) was used to measure viscosity. The shear behavior of the grouting materials was analyzed using a power-law model. The viscosity of SA and agar gum at different shear rates is shown in Figure 1. SA and agar gum showed non-Newtonian shear thinning behavior, where viscosity decreased as the shear rate increased. The effective viscosity in porous media was determined using the consistency index (b) and flow behavior index (n), which are the indices of the power-law model (Eberhard et al., 2019).

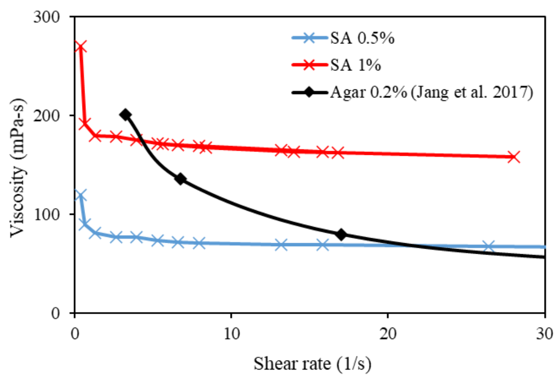

Figure 1. Shear behavior of grouting materials (SA and agar)

2.3 *Capillarity (surface tension and contact angle)*

Capillarity (surface tension and surface contact angle) is based on the capillary number, which determines the invading pattern of grouting materials. Surface tension was measured using a tensiometer (514-B2, Itoh) by employing the Du Nouy ring method, and the results are shown in Figure 2(a). The contact angle was measured by utilizing the sessile drop method under static conditions. Silica glass was used to simulate soil particles, and grout materials were dropped on the surface to measure the contact angle. The measured contact angle is shown in Figure 2(b).

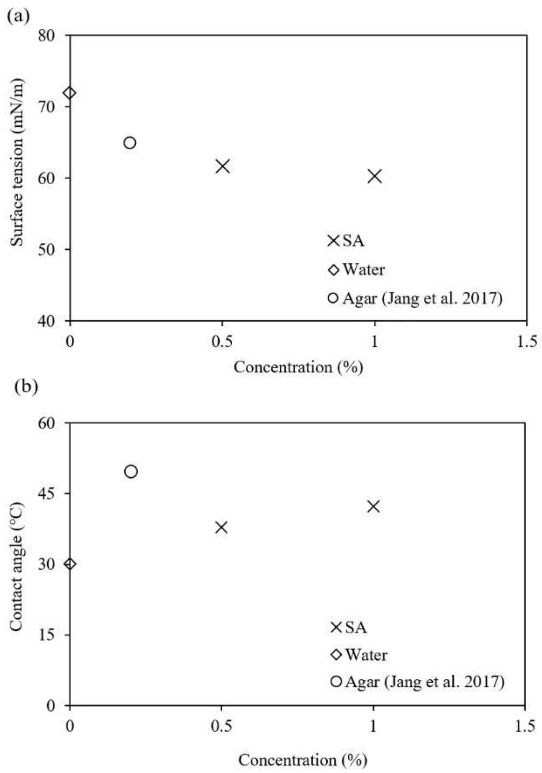

Figure 2. Capillarity of grout materials (a): Surface tension (b): Contact angle

2.4 *Pore network model*

The pore network model is based on the theory of Aker (1996), which is used for analyzing the flow of two immiscible fluids. The pore network model is mainly used for the analysis of multiphase fluid flow, such as in carbon dioxide storage and oil recovery (Blunt et al., 2013). In this study, the model was used to understand the injection characteristics of the grout materials by forming a virtual two-dimensional grid to realize a pore as a cylindrical tube. The pore network was composed of 50 × 50 nodes, and the total number of tubes was 4028. The mean pore size was selected as 1 μm with reference to Phadnis and Santamarina (2011), and this was used as the pore size of silty ground. In addition, the pore size distribution followed the log-normal distribution. The standard deviation(σ) was configured based on the numerical conditions. The average pore saturation value of 30 times was calculated for the running time to reduce the error of random distribution value. Figure 3 shows the results of low pore saturation and high pore saturation.

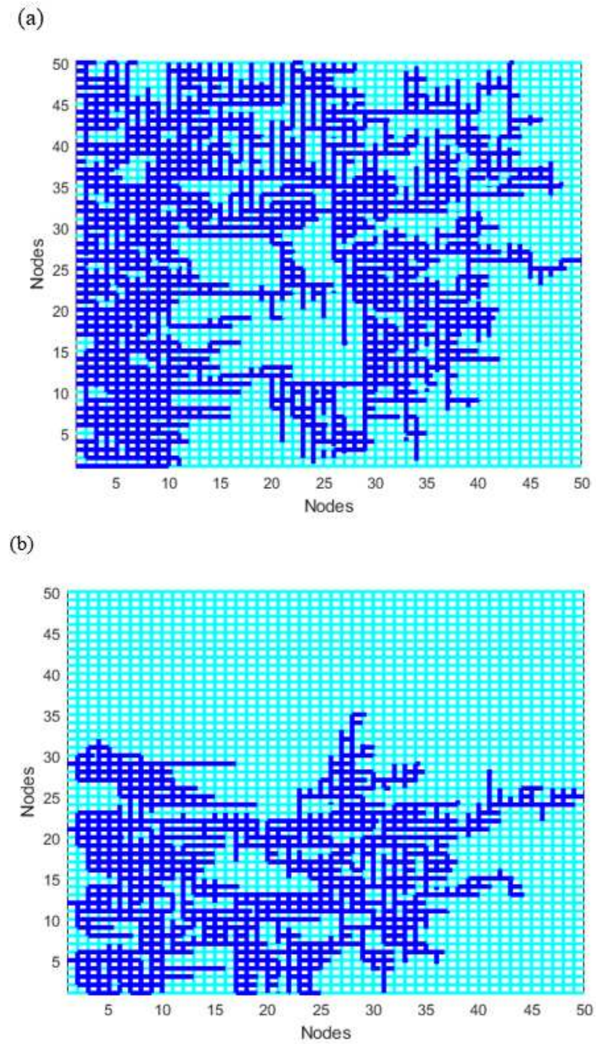

Figure 3. Results of pore network simulation (a): High pore saturation (b): Low pore saturation (blue line: invading fluid, bluish green line: defending fluid)

3 RESULTS

3.1 *Effect of pore size distribution*

Figure 4(a) shows the pore size distribution. The standard deviation of pore size was 0 to 2.5. Figure 4(b) shows the pore saturation at different standard deviations. At a standard deviation of 0 to 0.6, pore saturation was 52% to 54%, and only the error due to the random number occurred. Pore saturation rapidly decreased to 30% at a standard deviation of 1. In addition, pore saturation was less than 10% at a standard deviation of 1 to

1.8. Finally, pore saturation was 0 at a standard deviation of 2.5 or more. Thus, the injection ratio increased as the actual standard deviation of the pore size distribution decreased, and vice versa.

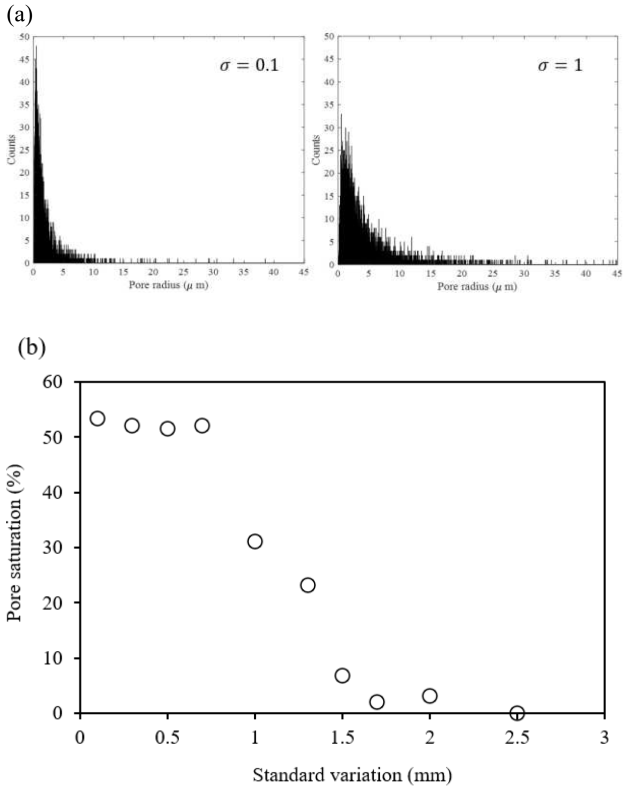

Figure 4. (a): Pore size distribution at σ = 0.1 and 1 (b): Pore saturation at different standard deviations

3.2 *Effect of injection pressure*

Figure 5 shows the pore saturation of agar (0.2%), SA (0.5%), and SA (1%) at different injection pressures.

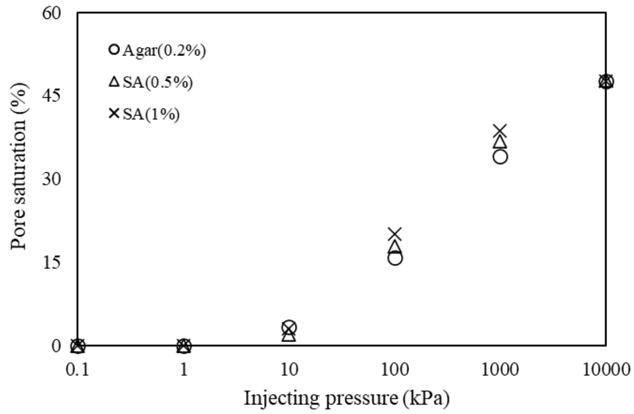

Figure 5. Effect of injection pressure on pore saturation

The injection pressure varied from 0.1 to 10000 kPa. The grout materials could not be injected at 0.1 and 1 kPa, and injection was possible at 10 kPa or more. Above 100 kPa, pore saturation increased with injection pressure. This was in agreement with the results of a previous study on cement-based grout materials (Gustafson, 1996). The difference between the pore saturation at 100 and 1000 kPa, which is the actual range of injection pressure used in field conditions, was approximately 20%.

3.3 *Effect of viscosity and capillarity*

Figure 6 shows the pore saturation of the grout materials at injection pressures of 100 and 1000 kPa. The pore saturation at 1000 kPa was the lowest in agar (0.2%) at 34.3% and the highest in SA (1%) at 38.6%. A similar trend was observed at 100 kPa. The surface tension and surface contact angle of agar (0.2%) were high. This resulted in a high capillary number. However, the viscosity number was low owing to low viscosity. Therefore, the pore saturation was the lowest.

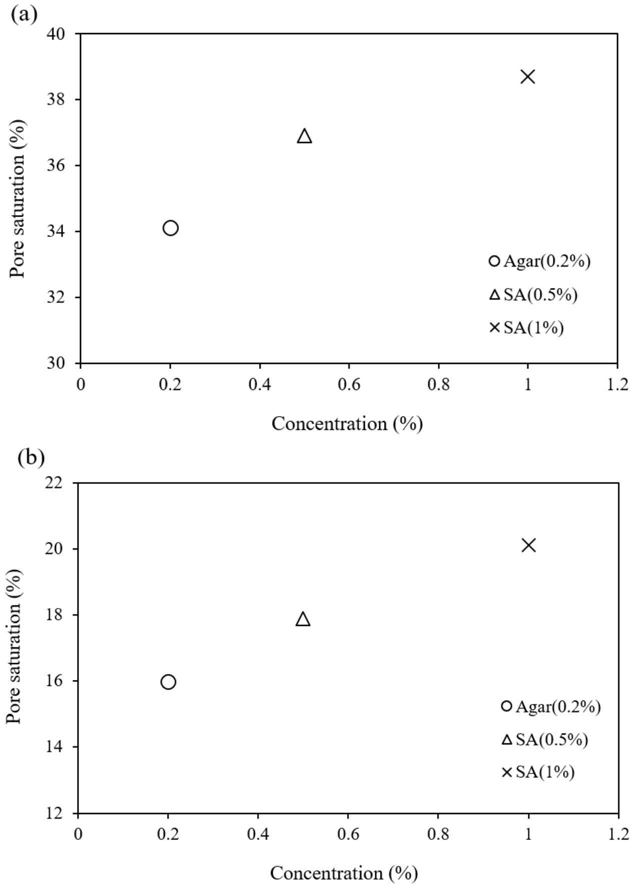

Figure 6. Pore saturation of grout materials (a): 1000 kPa (b): 100 kPa

4 CONCLUSIONS

The main purpose of this study was to evaluate the injection characteristics of grout materials. The injection characteristics of grout materials were examined using the pore network model, based on the pore size distribution, injection pressure, viscosity, and capillarity of the materials. The conclusions of this study are as follows:

- The variation in pore saturation with the standard deviation of the pore size distribution showed the following trends: Only an error due to a random effect occurred at a low standard deviation. However, pore saturation decreased rapidly when the standard deviation was higher than the average. As the standard deviation increased, the frequency of small pore sizes increased, and pore saturation was low owing to capillary force.
- The effect of injection pressure was not observed at 10 kPa or less, and the materials were injected at a pressure of 100 kPa or more. Pore saturation increased with injection pressure. It is considered that injection pressure has the

strongest influence on pore saturation because pore saturation does not change significantly with the pore size distribution and the concentration of the suspension.

- Among the three grout materials, agar (0.2%) had the highest capillary number but the lowest pore saturation. Pore saturation was influenced more by viscosity than by capillarity. It is believed that injection characteristics can be identified by considering the viscosity and capillarity of grout materials.

The results showed that injection pressure has the strongest effect on injection characteristics. However, viscosity and capillarity are the main factors that influence injection characteristics because the injection pressure used in field conditions is limited.

5 ACKNOWLEDGEMENTS

This work was supported by the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (Grant 21CTAP-C152100-03). This work was also supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (2020R1A2C101235211).

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