Experimental Study of Physical and Mechanical Properties of Chemically Grouted Sand and Gravel

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Abstract: Soil or rock mass with low strength or high permeability may not be appropriate for a dam foundation. Especially the faults are mainly composed by loose sand and gravel, so that they can cause severe damages to overlying structures, because of their considerable distress. Grouting is a suitable improvement technical method to solve this problem. Epoxy resins are commonly used in civil engineering because of their high strength and durability against mechanical or physical erosion. The chemical grouting materials is consisted of resin (component A) and hardener (component B). A comprehensive laboratory work was carried out to study the physical and mechanical properties of chemically grouted sand and gravel. Experimental test results show that, the formation of a dense polymer film-sand or film-gravel matrix is resulted in the significant reduction of water permeability and improvement of physical properties. A large number of voids are in filled with epoxy resins which act as adhesive ties to the sand or gravel grains forming a dense impermeable high strength structure. The mechanical properties of sand and gravel are improved by the epoxy resins. Copyright © 2014 IFSA Publishing, S. L.

Keywords: Chemical grouting, Sand and gravel, Epoxy resin, Experimental study, Physical and mechanical properties.

1. Introduction

Fault is always existed during the construction process of geotechnical engineering. The fault in a dam foundation indicates lower strength or a lack of durability [1]. Rock and soil materials in fault are commonly with low strength or high permeability and may not be appropriate for a foundation of high arch dam. In order to improve their properties, a suitable ground improvement technique is needed for dam foundation in order to confront these problems [2-4]. The increase in strength and reduction in compressibility are the main aims of a dam foundation improvement technique. Chemical grouting has been used by geotechnical engineers to solve foundation problems such as strengthening of weak soils or rock mass and infilling voids [5, 6]. Chemical grouting is a ground treatment method used to improve soil or rock mass behavior in terms of deformability, strength and permeability [7, 8].

A number of grouts have been developed over the last decades in order to extend the application range of ordinary cement grouts [9-12]. Particularly, epoxy resins are widely used in various engineering fields such as dam foundation and soil stabilization [13, 14]. Epoxy grouts is a polymer generally consist
of two components, one is amine components and another is a mixture of epoxy resins [15]. The epoxy grout is characterized by high compressive and tensile strength, lower permeability and long durability [16]. In this paper, an epoxy resin is used to improve the physical and mechanical properties of the sand and gravel in the F5 fault at the Jinping I Hydropower Station.

The F5 fault is mainly composed by loose sand and gravel, the mechanical properties is relatively in a low value and the permeability coefficient is relatively in a large value. The main purpose of this study is to experiment with the use of chemical grouting to loose sand and gravel by injection of epoxy compounds, emphasizing on the physical and mechanical properties of grouted sand and gravel. A comprehensive laboratory work was carried out in order to study the physical and mechanical properties of chemically grouted sand and gravel.

2. Experimental

2.1. Materials

The experimental use sand and gravel are retrieved from the F5 fault at the Jinping I Hydropower Station. Fig. 1(a) shows the site photo of the F5 fault at the dam foundation, the average width is about 0.5-2.0 m. A height of 305 m high arch dam is built in the Jinping Hydropower Station. There are several faults and shear zones existed in the dam foundation, and have significant impact on the security and stability of the high arch dam under large water pressure. Because of the F5 fault is mainly composed by loose sand and gravel (as shown in Fig. 1(b)), the mechanical properties is relatively in a low value and sensitivity to the water content.

Because of the fault length is very large, some part is hard to repair by excavation replacement by concrete or other anchor reinforcement measures. Chemical grouting is an effective measure to repair the F5 fault, to improve the physical and mechanical properties of the sand and gravel. Fig. 2 shows the particle size distribution characteristics of the sand and gravel in F5 fault.

As shown in Fig. 2, the sand is mainly composed by fine particles and the gravel is mainly composed by coarse rock blocks. The maximum particle diameter for sand is 1.0 mm, and 20.0 mm for gravel. The minimum particle diameter for sand is 0.01 mm, and 0.1 mm for gravel. Particle size distribution of sand and gravel is relatively uniform.

The chemical grouting materials is consisted of epoxy resin (component A) and amine-hardener (component B). Component B is added to component A and the two are then mixed with a paddle mixer at low speed. In order to obtain a longer workability of epoxy resin during grouting process, the mixed adhesive may be divided into portions. The components may be mixed together in the ratios specified by experimental test. Fig. 3 shows the chemical grouting materials for the experimental test.

The epoxy resin is yellow and the amine-hardener is brown, so that it is easy to see when the two components are homogeneously mixed. These two components were selected for optimization and several modifications were made to the original composition provided. The gravity ratio of component A and component B is 6:1.
Fig. 3. Chemical grouting materials for the experimental test: (a) epoxy resin (component A); (b) amine-hardener (component B) and (c) polymer (mixture of component A and component B).

2.2. Experimental Equipment

The equipment shown in Fig. 4 was used to obtain the shape of grouted sand, gravel and the injection pressure. Injection was stopped when the volume of the injected grout was equal to two void volumes of the sand or gravel in the mold. This has been a relatively common practice in previous investigations.

![Fig. 4. Equipment for grouting small-size specimens.](image)

As shown in Fig. 4, laboratory equipment was used to produce small-size grouted sand and gravel specimens, with a height of 200 mm and a diameter of 200 mm. There are three systems of the laboratory grouting equipment: the grouting system (two pipelines for component A and B); the model box; and, the detection system (injection pressure and velocity). The sands and gravels were at a dense and dry state and the grouted sand and gravel specimens were tested after curing for 28 days.

2.3. Laboratory Grouting Procedure

The laboratory grouting procedures are shown in as follow:

a) Experimental preparation. Prepare sand or gravel in the model box, and component A and B are imported into two buckets respectively.

b) Compact the loose sand or gravel to make it denser.

c) Initiation the injection pressure and velocity.

d) Chemical grouting. Keep a certain injection velocity and stopped if the pressure of the model box attains a determined value.

e) Curing after 28 days and then carry out the laboratory tests for the grouted sand and gravel.

Injection pressure is a comprehensive reflection of mechanical properties of loose sand and gravel, grouting material and a slurry-injection pump property. According to the characteristics of loose sand and gravel, grouting pressure should not be too high. Several experiments are carried out for determine the injection pressure to ensure the loose materials without significant displacement or erosion. In the grouting process, the injection pressure is about 0.5-2.0 MPa. A pressure pump providing the necessary constant very low injection rate (between 0.01 L/min and 0.05 L/min), was used in combination with a double chamber cylinder for the epoxy resins and amine-hardener. After polymerization and hardening of the resin after 28 days, the grouted sand or gravel cores were drilled and used for laboratory experiments. Fig. 5 shows the chemically grouted sand and gravel.

![Fig. 5. Chemically grouted loose materials: (a) grouted sand and (b) grouted gravel.](image)

As shown in Fig. 5, the chemical grouting and sand or gravel are well combined together, and the grouted sand and gravel can drilled by coring equipment. The physical and mechanical properties of the loose materials can be improved to meet the engineering requirements.
2.4. Laboratory Experiments

The laboratory experiments to evaluation the grouting effect is based on the borehole coring of the chemically grouted sand and gravel. The grouted sand or gravel core is a cylinder with the diameter of 46 mm. The grouted sand or gravel core is prepared to a cylinder with the height of 92 mm for uniaxial compression and water penetration tests (Fig. 6(a)). The grouted sand or gravel core is cut into a circle pie with the height of 5 mm and diameter of 46 mm for scanning electron microscopy (SEM) morphology tests (Fig. 6(b)).

![Fig. 6. Test samples of grouted sand or gravel: (a) cylinder for uniaxial compression and water penetration tests and (b) circle pie for SEM morphology tests.](image)

The uniaxial compressive tests are carried out by the MTS 815 rock and concrete test system (Fig. 7(a)). The scanning electron microscopy morphology tests are carried by the SEM test system (Fig. 7(b)). The density, porosity and uniaxial compressive strength are determined for the grouted sand or gravel. These parameters are the important indexes of the mechanical properties of grouted materials.

![Fig. 7. Test equipments for grouted sand or gravel: (a) MTS 815 rock and concrete test system and (b) Scanning electron microscopy (SEM) test system.](image)

3. Results and Discussions

Specimens of the same size as those used for the uniaxial compressive strength tests, aged 28 days, were used for the evaluation of mechanical properties of grouted materials. Porosity of grouted materials was calculated according to the method referred to by Anagnostopoulos [5]. Each of the reported values for physical and mechanical parameters represents the average value of three or six specimens.

3.1. Physical Properties

For each physical property, six test samples are used and the average value is adopted to evaluate the physical properties of grouted materials. Acoustic wave velocity is a typical parameter for solid materials, here we adopt acoustic test to determine the wave velocity of grouted sand and gravel. Fig. 8 shows the acoustic wave velocity characteristic of the grouted materials.

![Fig. 8. Acoustic wave velocity characteristic of the grouted materials.](image)

Experimental results show that, the average acoustic wave velocity is about 2613 m/s for grouted sand and 2152 m/s for grouted gravel. The wave velocity of grouted sand is larger than grouted gravel. The density is about 1.71-1.75 g/cm³ for grouted sand and 1.75-1.82 g/cm³ for grouted gravel. The
density of grouted gravel is larger than grouted sand, because of some rock block are existed in the grouted gravel. The average porosity is about 10.21% for grouted sand and 16.53% for grouted gravel. The porosity of grouted materials is influenced by the micro-structural of the particle and polymers. The existed of rock blocks for grouted gravel resulted in the larger porosity.

The average permeability coefficient is about $10^{-5}$ cm/s for grouted sand and $10^{-4}$ cm/s for grouted gravel. The permeability of grouted sand is less than the grouted gravel. As for the mechanical properties, the improvement of physical properties was also dependent directly on the content of epoxy resins. Permeability test results show that the formation of a dense polymer film-sand or film-gravel matrix by which a large number of pores are filled or sealed resulting in the significant reduction of water permeability.

### 3.2. Mechanical Properties

The compressive strength of test samples injected with epoxy resins exhibited an increasing tendency over time, and gradually stabilized after 28 days of curing. Fig. 9(a) shows the stress-strain relation of grouted sand and gravel specimens with epoxy resin grouts at 28 days of curing. Fig. 9(b) shows the failure mode of grouted gravel specimen under uniaxial compressive loading.

As shown in Fig. 9(a), the average uniaxial compressive strength is about 18.55 MPa for grouted sand and 19.78 MPa for grouted gravel. The peak strain is about 0.020 and 0.013 for grouted sand and gravel, respectively. The modulus of elasticity is about 2.694 GPa and 2.669 GPa for grouted sand and gravel, respectively. The Poisson’s ratio is about 0.385 and 0.356 for grouted sand and gravel, respectively. As shown in Fig. 9(b), the failure mode of grouted gravel is exhibited a compressive-shear characteristics. There is an obviously failure surface existed in the test sample.

There is an indication of the strong adhesion between the formed polymer and fine sand or gravel. The mechanical properties of grouted materials are determined by the elasto-plastic behavior of epoxy resin. These results illustrate the beneficial effect that epoxy grouts have on the strength and on the stiffness of the sand and gravel. The mechanical properties of sand and gravel are improved by the epoxy resins.

### 3.3. Micro-structural Properties

The observed improvement of physical and mechanical properties for the grouted sand and gravel can further be manifested by the experiments of scanning electron microscopy. Fig. 10 shows a micrograph of the view perpendicular to the failure surface of grouted sand and gravel specimens.

![Fig. 9](image9.png)

**Fig. 9.** Uniaxial compression test results: (a) stress-strain curve of grouted sand and gravel and (b) failure mode of grouted gravel.

![Fig. 10](image10.png)

**Fig. 10.** Scanning electron microscopy (SEM) morphology characteristics of grouted materials: (a) grouted sand and (b) grouted gravel.
As shown in Fig. 10, a large number of voids are in filled with epoxy resins which act as adhesive ties to the sand or gravel grains forming a dense impermeable high strength structure. The grain size of grouted gravel is larger than grouted sand. The failure surface of grouted sand is relatively smooth, because of the fine sand and uniform distribution of epoxy resins, but the failure surface of grouted gravel is coarse and failure of little rock blocks are happened.

4. Conclusions

In this paper, the F5 fault at the Jinping I Hydropower Station is taken as a case study example. Because of the fault is mainly composed by loose sand and gravel, the mechanical properties is relatively in a low value and the permeability coefficient is relatively in a large value. Chemical grouting is an effective measure to repair the F5 fault, to improve the physical and mechanical properties of the sand and gravel. The chemical grouting materials is consisted of epoxy resin (component A) and amine-hardener (component B). Laboratory grouting for sand and gravel are carried out to determine the physical and mechanical characteristics of grouted sand and gravel.

The laboratory experiments to evaluation the grouting effect is based on the borehole coring of the chemically grouted sand and gravel. The formation of a dense polymer film-sand or film-gravel matrix is resulted in the significant reduction of water permeability and improvement of physical properties. There is an indication of the strong adhesion between the formed polymer and fine sand or gravel. The mechanical properties of sand and gravel are improved by the epoxy resins. SEM morphology test results show that, a large number of voids are in filled with epoxy resins which act as adhesive ties to the sand or gravel grains forming a dense impermeable high strength structure.

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