Laboratory study of Uniaxial compressive strength for mixed soil specimens of jet-grout simulation

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ABSTRACT: Jet-grouting is a ground improvement method, in which liquid solidifying agent is injected into soft-ground with water and air-pressure to mix or replace the soil with the agent. The uniaxial compressive strengths of improved soil by Jet-grouting have uncertainties depending on the factors of the grout materials and the mixing conditions. In this study, the laboratory mixed strength tests are performed to analyze the sensitivity of the uniaxial compressive strength depending on the influence factors, e.g. mixing time and speed, water-cement ratio (W/C), and cement quantities.
The uniaxial compressive strengths of specimens increase significantly as the mixing time and the mixing speed increase. When the soil and solidification agent are mixed more than a speed of 180rpm or mixed more than 3min, variation of the uniaxial strength of the samples are decreased. Water-cement ratio (W/C), influences on the workability of field construction. When W/C ratio is less than 1.0, the uniaxial compressive strengths of the specimens decrease, as W/C increases. Variations of uniaxial compressive strength of the specimens are increased when W/C is greater than 1.0. The uniaxial compressive strength of the field grouted specimens turned out to be about 64% of the uniaxial compressive strength of laboratory mixed specimens.

Keyword: Jet-grouting, uniaxial compressive strength, laboratory mixed specimen, mixing speed, mixing time, water cement ratio (W/C).

1 INTRODUCTION

Jet-grouting (JG) is one of the ground improvement methods performed by mixing or replacing the soil with the liquid solidifying agents after cutting the ground by air or water force (Burke and Koelling, 1995; Burke et al., 2001; FDOT, 2004; KGS, 2008). Jet grouting plays a key role as the reinforcement method to support the superstructure. Jet grouting is classified into the single, double, and triple fluid systems by the injecting mechanism, equipment, injecting pressure, and construction method. Depending on the number of fluids injected into the subsoil, the single and double fluid systems are called as the mixing system, and the triple fluid system is called as the replacement system.

The uniaxial compressive strength (UCS) of JG improved soil is the most important factor for the design of JG method, and is effected by the soil characteristics in the field (Adaska et al., 1992; Choi, 2003). Therefore, it is important to estimate the compressive strength of the improved soil (q_{uf}) using the soils collected in the field where the jet-grouting is applied. Since the compressive strength of JG improved soil could not be measured directly due to the economic problem, it has been predicted by the two types of method. One is to use the strength ranges proposed from the literatures, and the other is to conduct the laboratory test using the soil collected in site. In the two methods, the latter is a good alternative which can be substituted for the direct measurement of the field compressive strength (q_{uf}).

Currently, design standards are not prepared to perform laboratory tests to predict the compressive strength of JG improved soil. Most designers predict the field compressive strength (q_{uf}) through the empirical judgement. As a result, the design of JG method is too conservative, and could not reflect the soil characteristics of the site accurately, where the jet-grouting method was applied.

In this paper, the compressive strength (q_{ul}) is measured by performing the laboratory tests to be able to apply q_{ul} as the field compressive strength (q_{uf}) in the design. Tests were performed to analyze the sensitivity of the influence factors, e.g. mixing-speed, mixing-time, water-cement ratio (W/C), and cement quantity on the laboratory compressive strength (q_{ul}), The compressive strength of specimens by the laboratory test (q_{ul}) was compared with the compressive strength of core samples (q_{uf}) collected in the field, in which JG method of the triple fluid system was applied.

2 PRIDICTION METHOD OF COMPRESSIVE STRENGTH OF JG IMPROVED SOIL

2.1 *Empirical method*

Through the geotechnical investigation, the types of soils, N value, cohesive strength, water content, particle composition, hydraulic conductivity, and the content of organic matter are determined. Geotechnical engineers predicts the field compressive strength (q_{uf}) by using the empirical strength range proposed by the soil types determined from the results of geotechnical investigation. This method could lead to the difference between actual and predicted q_{uf}, since the engineers decide the compressive strength arbitrary based on the data of geotechnical investigation and the solidification agents of JG applied to the field. Thus, this method has large uncertainties.

2.2 *Laboratory method*

The field compressive strength (q_{uf}) can be predicted by performing the laboratory tests, of which soil characteristics and site conditions are considered. In order to apply the site conditions accurately, the optimal mixture ratio and water-cement ratio (W/C) reflecting the original soil characteristics should be determined after the strength characteristics of JG improved soil is checked depending on the cement quantity. Detailed procedure is explained in the next section.

3 LABORATORY TEST TO PREDICT THE COMPRESSIVE STRENGTH OF JG IMPROVED SOIL

Laboratory tests are carried out through a series of processes, i.e. making and curing specimens, and testing unconfined compressive strength (UCS) after the cement slurries and the soils are mixed (Fig. 1). In this study, pre-mixing tests are performed to analyze the sensitivity of the influence factor, e.g. mixing-speed, mixing-time, cement quantity, and water-cement ratio (W/C), for laboratory compressive strength (q_{ul}). This way of preliminary tests can minimize the uncertainties of the laboratory test before the laboratory test is conducted according to the parameters determined. The laboratory compressive strength (q_{ul}) can be compared with the field compressive strength (q_{uf}) of core samples collected in the field.

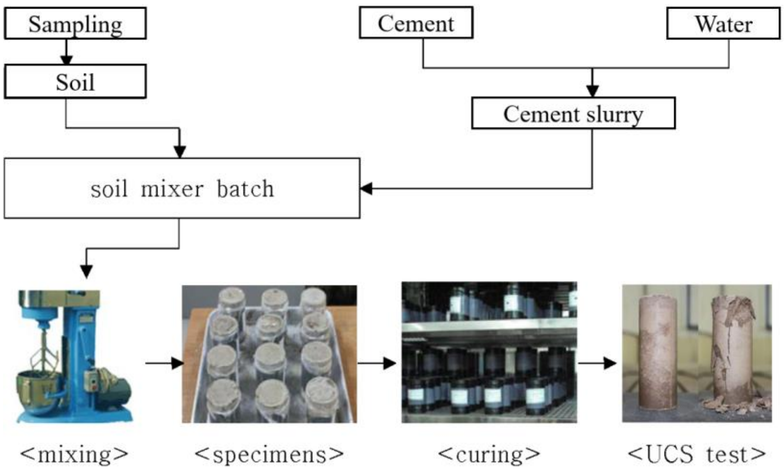


Figure 1. Laboratory test procedures to measure the compressive strength of JG improved soil

3.1 *Material*

The soil used in the laboratory test was collected at the JG site of Daegu, located in southeastern province of Korea. Triple fluid system was applied and the Portland cement was used for the solidification agent at the site. The properties and particle size distribution of the collected soil are shown in Table 1 and Figure 2.

Table 1. Soil properties where JG method was applied

Unit weight (kN/m^3)	Specific Gravity (G_s)	Water Content (%)	USCS	Fine grain Content (%)
18.1	2.6	13.0	GW	9.0

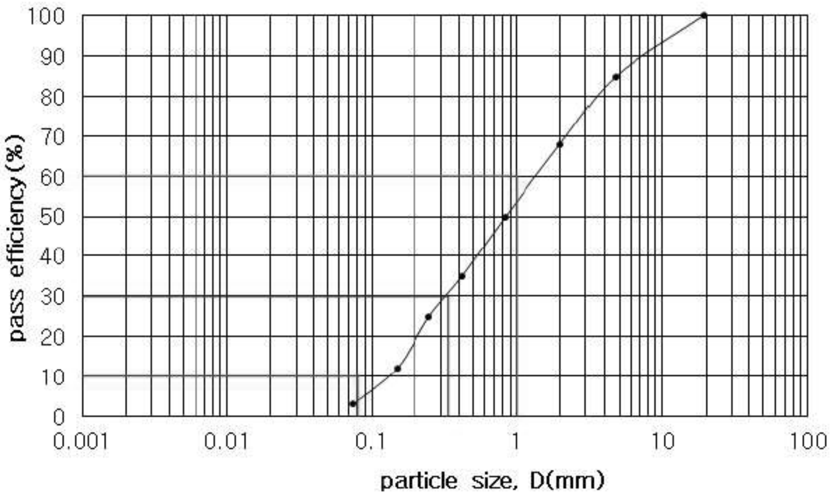


Figure 2. Particle size distribution of soil sample

3.2 *Pre-mixing test to check the sensitivity of influence factors*

3.2.1 *Compressive strength by mixing-speed*

Mixing-speed has large effect on the uniform mixing of soil, solidification agent, e.g. cement and water. Proper mixing-speed is necessary to mix cement and soil, uniformly. In the test, mixing-speed increased at the rate of 60, 120, 180, 240 and 300 rpm, and the selected mixing-time was 10 minutes. The experiments were carried out three times for each mixing-speed.

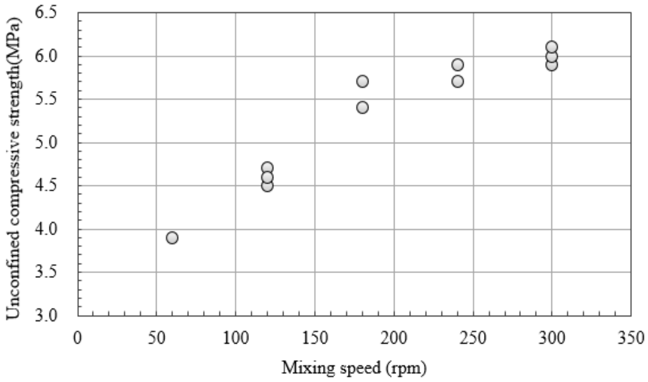
The results showed that the cement was mixed more uniformly with the soil as the mixing-speed increases and the laboratory compressive strength (q_{ul}) tended to increase. The compressive strength was increased steeply up to 180 rpm, and was increased gradually after that. Variation of the strength was decreased (Fig. 3a).

When the water-cement ratio (W/C) of the material was high, the materials can be flown out from the mixer as the mixing-speed was increased. Therefore, the appropriate mixing-speed, in this study, was as 180 rpm at which the curvature of the compressive strength curve is high.

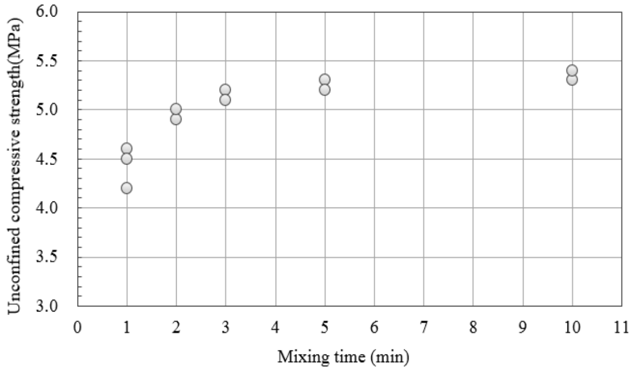
3.2.2 *Compressive strength by mixing-time*

Mixing-time is an important factor that can affect to the degree of mixing for the mixture of cement and soil in the specimen. In KSF 2329 (2012), it stated that the mixing-time should not exceed 30 minutes until the mixing and the compacting operations are completed. In this study, mixing-time was allotted as 1, 2, 3, 4, 5 and 10 min and the changes of the compressive strength of the specimens were analyzed (Fig. 3b).

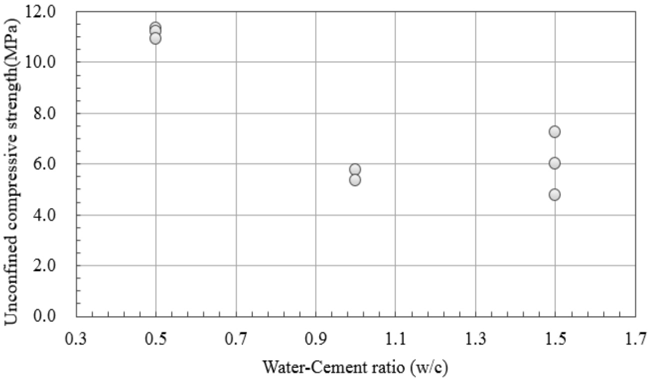
From the results, when mixing-time is 1 min, the deviation of the laboratory compressive strength (q_{ul}) is large since the cement, soil, and water were not mixed sufficiently. Contrary, when the mixing-time goes more than 3 minutes, the increase of compressive strength was less than 0.25 MPa and the deviation of compressive strength becomes narrow. It was decided that mixing time for the standard mixing laboratory test is about ten minutes in this study.



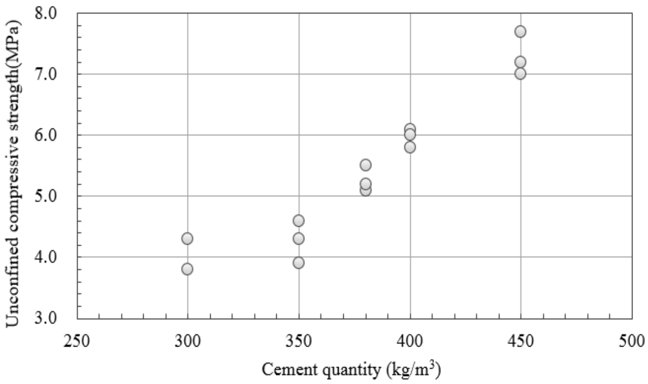
a) UCS versus mixing-speed



b) UCS versus mixing-time



c) UCS versus W/C



d) UCS versus cement quantity

Figure 3. Results of unconfined compressive strength (UCS) test to analyze the influence factors, i.e. mixing-speed, mixing-time, water-cement ratio (W/C), and cement quantity, for the laboratory test

3.2.3 *Compressive strength by water-cement ratio (W/C)*

Water-cement ratio (W/C) is an influence factor which is related to the efficiency of mixing work. When W/C decreases, the compressive strength of improved soil by JG method increases, because the cement ratio increases in the injected material, i.e. soil-cement-water mixture. However, it is difficult to inject the material into the ground due to the high viscosity of mixture during the construction. In contrast, the strength of the mixed specimens become low when the water-cement ratio (W/C) increases more than a certain limit. It needs to find out a proper W/C for the field construction of Jet grouting.

In the experiment, W/C was increased at the rates of 0.5, 1.0, and 1.5 with the fixed cement quantity. The results showed that the laboratory compressive strength (q_{ul}) was decreased depending on the incrase of W/C until W/C equals to 1.0. When the water-cement ratio (W/C) became 1.5, three problems were occurred as follows; (1) Non-uniform injection of material in the specimen, (2) Separation of the materials, and (3) the deviation of compressive strength down to 4 MPa (Fig. 3c).

EN (2001) has proposed a range of W/C from 0.5 to 1.0 for the mixture work. Water-cement ratio (W/C) range of domestic sites where JG method was applied, have been analyzed from 0.65 to 1.0 (Kim, 2014). In this study, the optimum water-cement ratio (W/C) for the laboratory tests was decided as 1.0.

3.2.4 *Compressive strength by cement quantity*

Cement quantity is the most important factor for the compressive strength of JG improved soil. In the experiment, the water-cement ratio (W/C) was fixed as 1.0. The cement quantity was allotted as 300, 350, 380, 400, 450 kg/m^3. From the results, it was found that the laboratory compressive strength (q_{ul}) was increased depending on the increase of cement quantity. When the cement quantity is less than 380 kg/m^3, mixture material was separated into the specimen since the hydration didn't occur sufficiently. It made a large deviation of the compressive strength. Deviation of compressive strength was decreased from the cement quantity of 380 kg/m^3 (Fig. 3d).

3.3 *Comparison of the compressive strength of specimens (q_{ul}) and core samples (q_{uf})*

3.3.1 *Laboratory test*

Soil characteristics used in the laboratory test are the same as the soil used in the pre-mixing test (Table 1, Fig. 2). The test-conditions, i.e. mixing-speed, mixing-time and water-cement ratio (W/C), are determined as the values selected in the pre-mixing tests. The cement quantity was changed as 300, 350, 380, 400, and 450 kg/m^3. The curing time was fixed as 28 days. The test results were compared with the field compressive strength (q_{uf}) collected by core-sample type from the site of Jet grouting Daegu in the Gyeongsang Province (Table 2).

3.3.2 *Compressive strength of core samples (q_{uf}) collected in the site*

Field compressive strength (q_{uf}) collected at the site in Daegu was measured by unconfined compressive strength (UCS) test after the core samples were collected. At the site, JG method of triple-fluid system was applied and the samples were cured for 28 days in the laboratory. The construction condition, e.g cement quantity and the water cement ratio (W/C), of the 15 samples are shown in Table 2.

Table 2. Test conditions of UCS test

Item	Condition	
	Laboratory test	Core samples in Daegu site
Cement quantity (kg/m^3)	300, 350, 380, 400, 450	380
Water-Cement ratio (W/C)	1.0	1.0
Mixing-speed (rpm)	180	-
Mixing-time (min)	10	-
Curing time (days)	28	28

3.3.3 *Strength ratio between q_{ul} and q_{uf}*

The compressive strength (q_{ul}) determined by the laboratory test tended to increase as the cement quantity increases. The field compressive strength (q_{uf}) showed the deviation from 2.5 MPa to 4.2 MPa. The mean laboratory compressive strength (q_{ul}) was measured as 5.1 MPa, and the mean field compressive strength (q_{uf}) was estimated as 3.4 MPa. By comparing q_{ul} with q_{uf}, the compressive strength (q_{uf}) of the field samples was about 64% of the compressive strength (q_{ul}) of laboratory samples (Fig. 5).

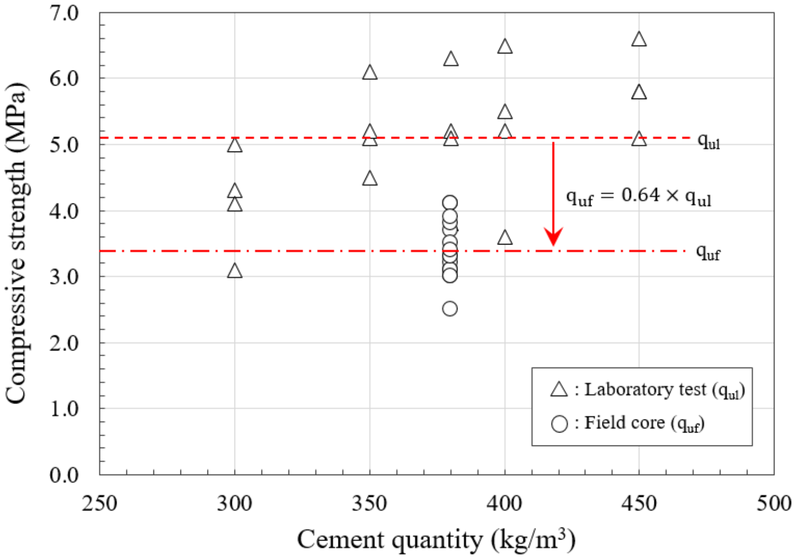


Figure 5. Comparison of field and laboratory compressive strength of JG mixture samples changing the cement quantities

4 CONCLUSIONS

In this study, laboratory test are conducted to predict the field compressive strength (q_{uf}) of Jet grouted specimens. To decrease the uncertainties of test results, the sensitivity of influence factors for the compressive strength was analyzed using the pre-mixing tests before the laboratory tests of the defined conditions. Finally, the authors proposed the strength ratio comparing the laboratory compressive strength (q_{ul}) and field compressive strength (q_{uf}). The main findings of the study are summarized as the following.

1. Compressive strength of the specimen was increased as the mixing-speed was increased. When the material was mixed over 180 rpm, the increment of the compressive strength was slow down, while the deviation of the measured compressive strength was decreased.
2. Compressive strength of the specimen was increased significantly up to 3 minutes of mixing-time. When the material was mixed more than 3 minutes, the compressive strength did not increase significantly and the deviation of compressive strength was decreased.
3. Water-cement ratio (W/C) affected the workability of the field construction. When W/C was less than 1.0, the compressive strength of specimens was decreased as W/C was increased. When W/C was over than 1.0, the deviation of the compressive strength become large. It was found that W/C applicable in the field should not exceed 1.0.
4. The mean laboratory compressive strength (q_{ul}) of the specimen was estimated as 5.1 MPa and the mean field compressive strength (q_{uf}) was measured as 3.4 MPa. The ratio of field (q_{uf}) versus laboratory (q_{ul}) compressive strength of the Jet grouted specimens can be proposed as 64%.

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