Geomechanics and Engineering, *Vol. 12, No. 5 (2017) 739-752*
DOI: https://doi.org/10.12989/gae.2017.12.5.739

Evaluation of the grouting in the sandy ground using bio injection material

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(*Received October 03, 2016, Revised December 17, 2016, Accepted February 16, 2017*)

Abstract. This study was intended to evaluate the improved strength of the ground by applying the bio grouting method to a loose sandy ground. The injection material was prepared in the form of cement-like powder, with the bio injection material produced by microbial reactions. The grouting test was conducted under the conditions similar to the field where the bio injection material can be applied. In addition, the injection materials (cement and sodium silicate No. 3) used for Labile Waterglass (LW) method and the conventional grouting methodwere prepared through a two-solution one-step process. The injection into the specimens was done at a pressure of 150 kPa and then, with a bender element, their moduliof elasticity were measured on the 7th, 14th, 21st and 28th curingdays to analyze their strengths according to the duration of curing. It was confirmed that in all injection materials the moduli of elasticity increased over time. In particular, when 30% of the bio injection material was added to 100% cement, the modulus of elasticity tended to increase by about 15%. This confirmed that the applicability became higher when the bio injection material was used in place of the conventional sodium silicate.

Keywords: grouting; bio injection material; loose sandy ground; modulus of elasticity; microbial reactions

1. Introduction

1.1 Background and objective

According to the Korea Cement Association (2011), the domestic cement production in 2006 is approximately 48 million tons, ranking Korea 7th in the world cement production. CO_2 generated, when one ton of cement is produced, is approximately 0.9 tons. Therefore, if a material can replace 1% of the 48 million tons, about 480 thousand tons of cement could be reduced, resulting in the cost reduction of approximately 13 billion won/year (\$22 per ton of CO_2 for carbon credits) (Chang and Cho 2012, Chang *et al*. 2016). In addition, Korea has become one of the countries participating in CO_2 emission regulation since 2015 in accordance with Kyoto Protocol. If a country emits more CO_2 than the permitted level, they will have to pay CO_2 emission charge. Therefore, it is necessary to develop environmentally-friendly materials that can replace or reduce the amount of cement used in the field of soil improvement, where cement is used mostly. It is imperative to develop new materials that can contribute to the green growth policy including low

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http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

carbon and prevention of global warming and address such problems as rise of raw material costs and shortage of construction materials.

Upon this, efforts have been made to develop new eco-friendly materials that can cement soils by substituting and/or injecting cementing materials (hereinafter referred to as "bio injection materials") produced through microbial and biochemical reactions to soft-clay ground or loose-sand ground, which are problems from the geotechnical engineering perspective.

In particular, the study of geotechnical engineering using bio injecting material has been actively conducted by Kim *et al*. (2012b, 2013, 2014); Dejong *et al*. (2006, 2010); Chang and Cho (2014), Sidik *et al*. (2014), Park (2015), Cheng *et al*. (2016) in geotechnical engineering. In addition, ground improvement methods using biopolymer, an eco-friendly material that can reduce cement, organic materials, and plant extracts are studied.

Overseas, mostly in the USA and the Netherlands, researchers like Dejong *et al*. (2010) and Paassen *et al*. (2009) have developed eco-friendly materials through soil cementing and bio grouting. However, there is still much to be improved and supplemented in order for bio injecting materials and bio grouting to the field, such as economic costs and application to the limited types of grounds they should be improved and supplemented. In particular, there are problems of complex microbial treatment and supernatant treatment due to repeated injection. In order to solve these problems, it is necessary to develop bio injection materials like cement and use them for grouting.

In this study, bio injection material was developed in cement-like powder form and used as an admixture that can reduce and replace the cement. In order to evaluate the applicability to the ground, the ground conditions were selected by applying the bio grouting to the SP specimens of relative compaction (RC) 70%, 80%, 85%, 90% and 95%. The sand was classified as "well-graded and poorly-graded sands" based on the Unified Soil Classification System (USCS), and its classification symbol is denoted as "SW and SP". In addition, through the two-liquid one-step grouting test on the SP specimens, the strengths of the conventional injection material and the bio injection materials were analyzed.

1.2 Previous studies

Recently, studies to develop materials that can fundamentally reduce the use of cement have been conducted in various ways. In particular, a small number of domestic and foreign researchers have performed research to cement soft ground using bio injection material ($CaCO_3$), a cementing material produced by bio-chemical reactions of *SporosarcinaPasteurii* (KCTC 3558) among various microorganisms in the soil (Kim *et al*. (2012a, b, 2013, 2014); Park and Kim (2012, 2013), Mitchell and Santamarina (2005); Dejong *et al*. (2006, 2010), Kim and Park (2013), Martinez *et al*. (2013), Park *et al*. (2014), Feng and Montoya (2015), Montoya and Dejong (2015), Lin *et al*. (2015), Cheng *et al*. (2016)).

With regards to the cementation of soil using microorganisms, various domestic and overseas studies have been underway over the last decade. The microorganism cementation technique utilizes Microbial Calcite Precipitation (MCP) technology in various fields including microbiology, architectural engineering and environmental studies, not to mention geotechnical engineering. Previous studies of each field are as follows.

In the geotechnical engineering field in Korea, Kim *et al*. (2012a) carried out the test for cementation of soft ground by pure microbial action for the first time. In other countries, a number of researchers including Dejong *et al*. (2006, 2010), Martinez *et al*. (2013), Feng and Montoya

(2015), Montoya and Dejong (2015), Lin *et al*. (2015) have conducted the study of cementation by microorganisms. Most of the researchers performed triaxial tests on Ottawa Sand, measured theamount of calcite produced by the repeated injection of the microbial solution, and investigated the shear behavior of the specimen treated with MCP. Based on the test results, it was observed that as the calcite precipitation increased, the shear modulus and shear strength generally increased. However, the repeated injection of the microbial solutions to the ground is not very practical in the field. In addition, Whiffin *et al*. (2007) and Paassen *et al*. (2009) conducted research on the biogrouting technology. Whiffin *et al*. (2007) obtained a strength value of 10 MPa from specimen but the strength was an estimate, not a result of quantitative analyses. Paassen *et al*. (2009) carried out their experiment on artificial soil. In their experiment, it was shown that the strength increased only on the outer surface to which bio injection material penetrated but the increase of strength at the center was insignificant.

These studies intended to improve the strength of soft ground using aqueous solution of calcium carbonate. However, due to the fact that the strength was calculated by estimates, their reliability was low. Also, the aqueous solutions, there are such problems as strength degradation and supernatant buildup when a large amount of bio injection material is applied.

In this study, a bio injection material produced by the reaction of microbial solution and aqueous solution of calcium chloride was developed in a powder form like cement which is widely used as a construction material. The uniaxial compression strength of the injection material was measured and analyzed and, through 2-liquid one-process grouting, its strength was compared with that of the conventional injection materials (Ordinary Portland Cement, hereinafter referred to as “OPC”; Micro Cement, “Micro”; Bio Injection Material, “Bio”; and sodium silicate No. 3), which makes this study differ from those previous studies.

2. Prepartion of bio injection material specimens

2.1 Making of the bio injection material

For the preparation of the microbial solution, in this study, the *Sporosarcina Pasteurii* microbes of KCTC 3558 were cultivated for 24 h in a shaking incubator of 180 rpm at 30°C. Under the microbe cultivation environment, the concentration level of microbe was approximately 10^7colony forming units per milliliter (CFU/mL).

Separately, 1 L of culture fluid was made by mixing 8 g of nutrient broth (which consists of 5 g enzymatic digest of gelatin and 3 g of beef extract) with 20 g urea (H_2NCONH_2) and by adding purified water until the total solution volume became 1 L. Urease is an enzyme catalyzing the reaction for hydrolyzing urea to create ammonia and carbon dioxide. In other words, Urea is hydrolyzed into a carbonate (CO_3^{2-}) and two ammonium ions (NH_4^+), as follows

$$CO(NH_2)_2 + 2H_2O \xrightarrow{\text{Urease reaction}} CO_3^{2-} + 2NH_4^+ \tag{1}$$

The carbonate (CO_3^{2-}) is combined with the calcium ion (Ca^{2+}) dissolved in the aquatic solution of calcium chloride ($CaCl_2$) to result in a bio injection material [calcium carbonate ($CaCO_3$)] depositions

$$Ca^{2+} + HCO_3^- + OH^- \longrightarrow CaCO_3 \downarrow + H_2O \tag{2}$$

(a) Mix the microbial solution and the sodium chloride solution

(b) Make it into powder on a bowl plate

Fig. 1 Making of the bio injection material

The bio injection material used for this study was made by the same method as microbial solution used for typical concentration treatment as shown in Fig. 1(a). The microbial solution and the calcium chloride solution (0.75 M) were mixed at 1:1 ratio (Park 2015). When white precipitate was formed, only the sediment, which was bio injection material, was extracted through a filter. The extracted bio injection material was dried for 24 hours at 40°C and made as powder using a bowl plate as shown in Fig. 1(b).

2.2 Mixing ratios for evaluation of the bio grouting range

The sample used in this study was Poorly-graded Sand (SP specimens) of 0.42 mm - 0.84 mm size. Its specific gravity (KS F 2308), particle size (KSF 2302) and compaction (KS F 2308) were measured and the sieve analysis (KS F 2309) was conducted, in accordance with the Korean industrial standards, to determine their physical characteristics. The specific gravity was measured as 2.68, and the rate of particles going through #200 sieve was 2.14%, and the liquid limit and plastic limit were found to be non-plastic.

In order to determine the grouting efficiency and range according to the relative compaction (RC), the following test was conducted. The SP specimens sample was made into specimens with the relative compaction (RC) of 70%, 80%, 85%, 90% and 95%.

The RC refers to a value of the dry unit weight of the field divided by the maximum dry weight obtained at the laboratory through KS F 2308 test. Eq. (3) is an equation for obtaining the RC. Therefore, the weight of the specimen for the RC was determined by obtaining the dry unit weight of the field.

$$RC = \frac{\gamma_{d(field)}}{\gamma_{d(\max, laboratory)}} \tag{3}$$

With the air compressor pressure at 150 kPa, microbial solution and calcium chloride solution were mixed at the ratio of 1:1 (weight) through the two-solution one-step process, and 2,000 ml of the mixed solution was injected once for the test. The specimen used for this study was collected from the banks of Seomjin River, and molded into a case with the diameter (D) of 150 mm and the heights (Hs) 300 mm to 150 mm to prevent overflowing. The lower 50 mm of the case was filled

Table 1 Mixing ratio for evaluating the bio-grouting injection range

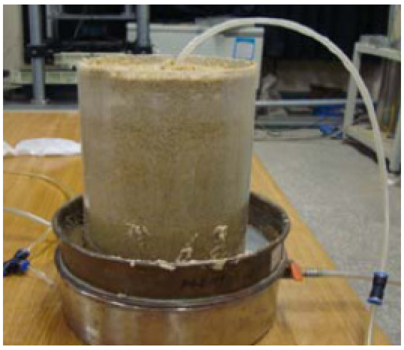
Condition	Soil(g)	$CaCl_2$(ml)	Microorganism (ml)
SP-RC-95%	5,389	2,000	2,000
SP-RC-90%	5,105	2,000	2,000
SP-RC-85%	4,822	2,000	2,000
SP-RC-80%	4,538	2,000	2,000
SP-RC-70%	3,971	2,000	2,000

with standard sand to have the drainage condition, and the top 100 mm was filled with Well-graded Sand (SW specimens). The mixing ratios of the specimens are shown in Table 1.

2.3 Mixing ratios for grouting test for the injection material

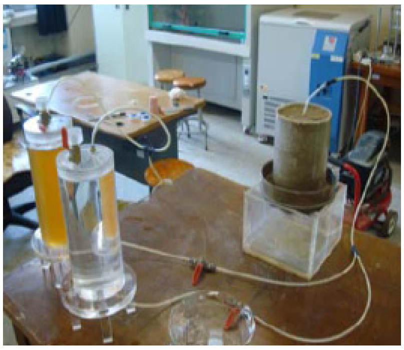
Fig. 2 is a view of bio grouting. The white solution on the left in Fig. 2(a) is a calcium chloride solution with the concentration of 0.75 M, and the yellow solution on the right is a microbial solution with general concentration. The grouting specimen in Fig. 2(b) was molded into the case through free fall with the relative density (Dr) of 40% applied. Fig. 2(c) is an injection nozzle with

(a) Reaction solution and microbial solution



(b) Molding of specimen

(c) Injection nozzle



(d) Injection equipment

Fig. 2 View of bio grouting during the laboratory test

Table 2 Mixing ratio for grouting test for the injection materials

Classification	Solution A			Solution B			
	Sodium silicate No. 3 (ml)	Bio injection material (g)	Water (ml)	OPC (g)	Micro cement (g)	Bio injection material (g)	Water (ml)
OS	200	-	200	200	-	-	400
MS	200	-	200	-	200	-	400
BS	200	-	200	-	-	200	400
OB-1	-	65	200	200	-	-	400
OB-2	-	65	200	135	-	-	400
MB-1	-	65	200	-	200	-	400
MB-2	-	65	200	-	135	-	400

<Note> OS = OPC 100% + Sodium silicate No. 3
MS = Micro 100% + Sodium silicate No. 3
BS = Bio 100% + Sodium silicate No. 3
OB-1 = OPC 100% + Bio 30%
OB-2 = OPC 70% + Bio 30%
MB-1 = Micro 100% + Bio 30%
MB-2 = Micro 70% + Bio 30%

8-mm diameter tube, and Fig. 2(d) is a view of injecting to the specimen made with the injection equipment.

Uniform pressure of 150 kPa gauge indicated on the pressure gauge display panel of the air compressor was applied through the nozzle nose on the top. Usually, about 500 kPa -1,000 kPa pressure is applied when the injection material for Labile Waterglass (LW) method is used at the field. In this study, however, the injection test was carried out at the maximum injection pressure of 150 kPa due to the experimental limitations. The specimens were made in such a way that the cementing material produced through eco-friendly microbial reactions was to be evenly injected to the specimens through the injection nozzle as the cementing material was mixed at Y-shaped discharge nozzle at the bottom.

Standard mixing ratio conditions of the conventional LW method was scaled down for the laboratory test, and the mixing ratios for grout injection were selected as shown in Table 2. Here, O refers to OPC; M, micro cement; B, bio injection material; and S, sodium silicate No. 3. The particle size of micro cement is smaller than that of OPC. Bio injection material is the bio mineral power ($CaCO_3$) that is produced by the chemical reaction in this study.

2.4 Measurement of modulus of elasticity of the injectin materials

Strength of the specimens was measured by calculating the shear wave velocity at which the specimens went through the bender element. In a previous study (Cho and Lee 2002), the shear wave velocity of 150 m/s – 500 m/s was measured for dry pebbles and 150 m/s ~ 200 m/s was measured for dry sand.

In order to do the same measurements on the 7th, 14th, 21st and 28th day after the injection test, four points were marked around the injection nozzle as shown in Fig. 3(a) and then the shear wave velocity was measured for each injection material specimen and expressed as an average. Dry

(a) Measurement points

(b) Specimen molding

Fig. 3 View of the shear wave velocity test

density was calculated by measuring the weights of specimens over time after the soil in the drainage layer and the top layer was removed in three days after the injection with only 10 cm around the injection nozzle being left, as shown in Fig. 3(b).

3. Results of laboratory tests

3.1 Results of the bio grouting injection

(1) Evaluation of cementation of the specimens after bio-grouting

Measurement of the injection rate and the injection range was to evaluate the range of cementation formed around the injection nozzle. At a pressure of 150 kPa from the air compressor, the mixture of microbial solution and calcium chloride solution was injected to the specimens. The SP sample has a large amount of bio injection material precipitate around its side surface, showing a white band around the acrylic surface of the case as shown in Fig. 4(a). Fig. 4 shows the cementation after injection, according to the relative compactness (RC) of the SP specimen. It was shown that the injected mixed solution easily penetrated to the specimen and formed a white band on the acrylic surface.

(2) Assessment of the range of cementation and the strength, depending on the ground conditions

After the bio-grouting test according to the ground conditions, the strength of the cemented specimens on their top surfaces in the vicinity around the injection hole using a penetrometer as shown in Fig. 5.

As can be seen from Figs. 4(b), (c), (d), (e) and (f), the height of the grouting was measured in the same direction of the grouting and the diameter was measured to identify the range of the grouting.

For the SP specimen, as shown in Fig. 6(a), it was observed that the diameter and the height of the grouting for RC 75% were about 20% and 30%, respectively, larger than those for RC95%. As shown in Fig. 6(b), the uniaxial compressive strength of RC75% was 40% higher than that of RC95%.

(a) After injection

(b) SP-70%

(c) SP-80%

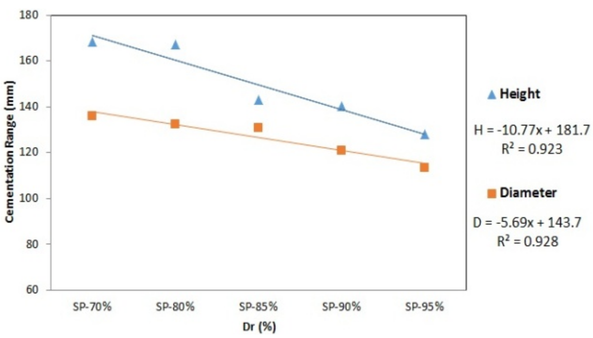
(d) SP-85%

(e) SP-90%

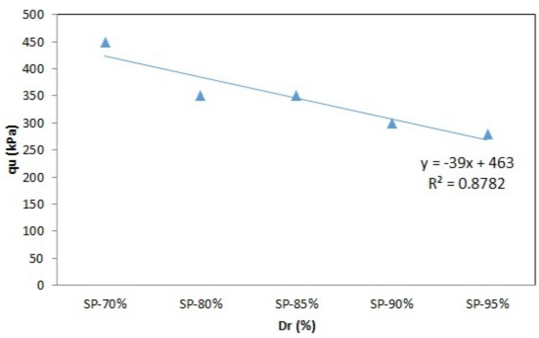
(f) SP-96%

Fig. 4 Results of bio-grouting of SP specimens according to ground conditions

Fig. 5 Measurement point of q_u



(a) Cementation range of specimens



(b) q_u of specimens

Fig. 6 Results of cementation range and q_u of SP specimens according to ground conditions

3.2 Grouting test of the injection material

In this test, the applicability of SP specimen injection was analyzed with the mixture of bio injection material and the injection material used for the conventional LW method. Instead of liquid injection (OS, MS), which had been a problem in LW method application, the bio injection

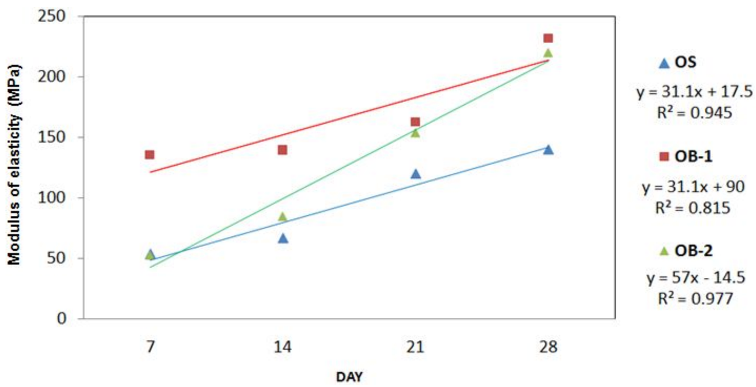
Table 3 Measurement of shear wave velocity of each injection material

Injection material	Curing time (day)	Dry density (kg/m^3)	Shear wave velocity (Vs (m/s))	Modulus of elasticity (G_{max} (MPa))
OS	7	1,673	179	54
	14	1,664	200	67
	21	1,660	269	120
	28	1,653	291	140
MS	7	1,681	207	72
	14	1,676	300	151
	21	1,672	321	172
	28	1,664	347	200
BS	7	1,667	176	12
	14	1,661	184	56
	21	1,658	204	69
	28	1,651	275	125
OB-1	7	1,627	289	136
	14	1,620	294	140
	21	1,613	318	163
	28	1,608	380	232
OB-2	7	1,616	181	53
	14	1,612	229	85
	21	1,610	309	154
	28	1,604	370	220
MB-1	7	1,658	325	175
	14	1,653	435	313
	21	1,647	483	384
	28	1,641	511	428
MB-2	7	1,644	265	115
	14	1,639	372	227
	21	1,631	450	330
	28	1,626	505	415

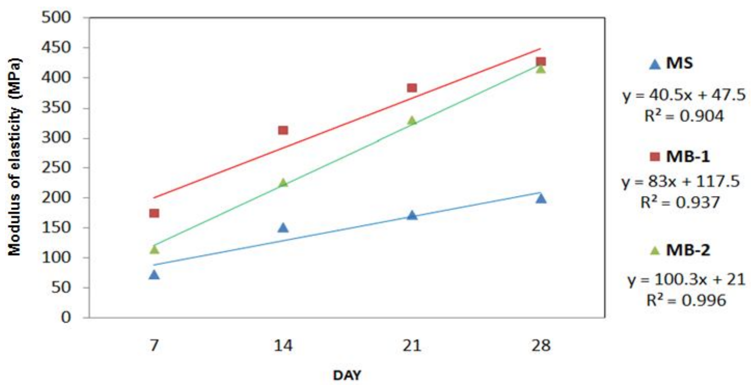
material (OB-1, MB-1) and the admixture (OB-2, MB-2) that could reduce the cement usage by 30% were used, to measure the modulus of elasticity over time. The samples were treated very carefully with the same grouting pressure of 150 kPa so that all the samples were made homogeneous.

The modulus of elasticity was measured by calculating the shear wave velocity at which specimens passed through the bender element. The Shear wave velocity during isotropic compression, as widely recognized, increased as confining pressure increased and they were correlated well (Teachavorasinskun and Pulpong 2016). In a previous study, the shear wave velocity during isotropic compression, as widely recognized, increased as confining pressure increased and they were correlated well (Teachavorasinskun and Pulpong 2016). The shear wave velocity of dry pebbles was measured as 150 m/s – 500 m/s and that of dry sand as 150 m/s – 200 m/s (Cho and Lee 2002). For standard sand, the modulus of elasticity at the relative density (Dr) of 60% was measured as 80 MPa. The shear wave velocity of each injection material is shown in Table 3.

Fig. 7(a) shows the result of analyzing the modulus of elasticity of OPC injection material. Over time, the modulus of elasticity increased by about 30% for OS, 10% for OB-1, and 40% for OB-2. Fig. 7(b) shows the result of analyzing the modulus of elasticity of micro cement injection material. Over time, the modulus of elasticity increased by about 35% for MS, 30% for MB-1, and about 60% for MB-2.



(a) Measurements of the modulus of elasticity of OPC injection material



(b) Measurements of the modulus of elasticity of micro cement injection material

Fig. 7 Measurements of modulus of elasticity

Modulus of elasticity measurements confirmed that, similarly to the results of homogenous gel, the shear modulus was measured the highest for OB-1 and MB-1 and measured the lowest for OS and BS. This was because sodium silicate No. 3 was used not to increase strength but for the purpose of blocking water. In case of OB-1 and MB-1, high modulus of elasticity was obtained through bio injection material.OB-1 and OB-2 have more grains infiltrated to the void of the soil specimen than OS and MS have. Once the grains bond with soil particles, the modulus of elasticity of the soil specimen increases.

Shear wave velocity represents a rate at which wave passes along the surface of particles. Therefore, as gaps in specimens were reduced as particles were cemented, the shear wave velocity increased. Also, a high modulus of elasticity was confirmed with OB-1 and MB-1 which contained bio injection material, particulate components.

This was resulted as pores bigger than 1 μm were reduced when calcium carbonate, the main component of bio injection material was added to cement, which was also confirmed by Kim and No (2000).

Therefore, the increase of modulus of elasticity was insignificant by using only the bio injection material. However, the modulus of elasticity became much higher than that of the conventional injection material when the bio injection material was used as admixture to cement and micro cement. This may be due to the hydration released heat reaction between calcium carbonate, the main component of the bio injection material and calcium silicate, the main component of the cement.

This test result confirmed applicability of the bio injection material, an eco-friendly material, as a substitute of sodium silicate No. 3 used for the conventional LW method.

3.3 Analysis of soil pollution

Pollution of the soil used for this study was analyzed with the soil collected around the injection material after the grouting test was completed (28 days). The soil was analyzed for such items as cadmium (Cd), copper (Cu), lead (Pb) and hexavalent chromium (Cr_6^+), as shown in Table 4.

Table 4 Results of the analysis of soil pollution by the use of injection material

Classification	Cd (mg/kg)	Cu (mg/kg)	Pb (mg/kg)	Cr_6^+ (mg/kg)
Untreated	-	1.577	5.369	-
OS	-	8.849	5.592	-
BS	-	3.555	5.316	-
MS	-	12.542	10.508	-
OB-1	-	8.662	7.023	-
OB-2	-	4.618	6.645	-
MB-1	-	8.345	10.811	-
MB-2	-	10.987	13.158	-
Criteria of concern/action for Area 1	4/12	150 / 450	200 / 600	5 / 15
Criteria of concern/action for Area 2	10/30	500 / 1,500	400 / 1,200	15 / 45
Criteria of concern/action for Area 3	60/180	2,000 / 6,000	700 / 2,100	40 / 120

Through the analysis, it was confirmed that all specimens had the pollution level below the worrisome level/countermeasure level for Region 1 and none of them had Cr_6^+ or Cd. However, it was confirmed that the copper or lead level was higher than those of the untreated specimen.

The Micro cement was found to have a high pollution level. The BS treated with Bio+ sodium silicate had a similar pollution level to that of the untreated specimen, with lower copper and lead contents than those of the untreated specimen but had a relatively lower pollution level than the OPC and the Micro cement. In short, the environmental impact of the Bio injection material on the soil pollution was found to be lower than that of the OPC and Micro cement.

4. Conclusions

In this study, an environment-friendly bio injection material was prepared in powder form using Microbial Calcite Precipitation (MCP) technique. Ground conditions to which the prepared material could be injected using bio-grouting were selected. The prepared bio-injection material mixed with the conventional injection material through 2-liquid one-step process was applied to specimens and then the modulus of elasticity over time was analyzed, to reach the following conditions:

- As a result of the bio-grouting for each ground condition at the injection pressure of 150kPa, it was confirmed that it was possible to inject into the SP specimen at the relative compactness (RC) of 95% or lower despite the lower injection pressure. In case of sandy soil, it was possible to inject the mixed solution into the soil.
- Measurement of the modulus of elasticity of injection materials shows the increase of modulus of elasticity in every specimen over time, with OB-1 and MB-1 being the highest as in sand gel. However, for OS and MS, the modulus of elasticity decreased over time. This result confirmed that OB-1 and MB-1 into which the bio injection material was mixed had a higher applicability than grouting by the injection material of the conventional OS and MS.
- Calcium carbonate, the main component of the bio injection had the hydrogen-released heat reaction with the calcium silicate of the cement. So, as the ratio of bio injection material was increased/decreased by 30%, the strength of the specimens increased/decreased by 15%. Therefore, the bio grouting should be used for the purpose of blocking water. But, for the purpose of enhancing the strength, the bio injection materials should be used only as an admixture.
- This study used the bio grouting on the limited ground conditions. But, for the actual ground, the underground stress changes with depth. Therefore, it is necessary to conduct research with such change of the underground stress taken into consideration and by making a model soil structure similar to the actual ground by applying overburden pressure so that injection pressure and injection volume of the actual field can be properly simulated.

Acknowledgments

This study was supported by research funds from Chosun University, 2015.

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