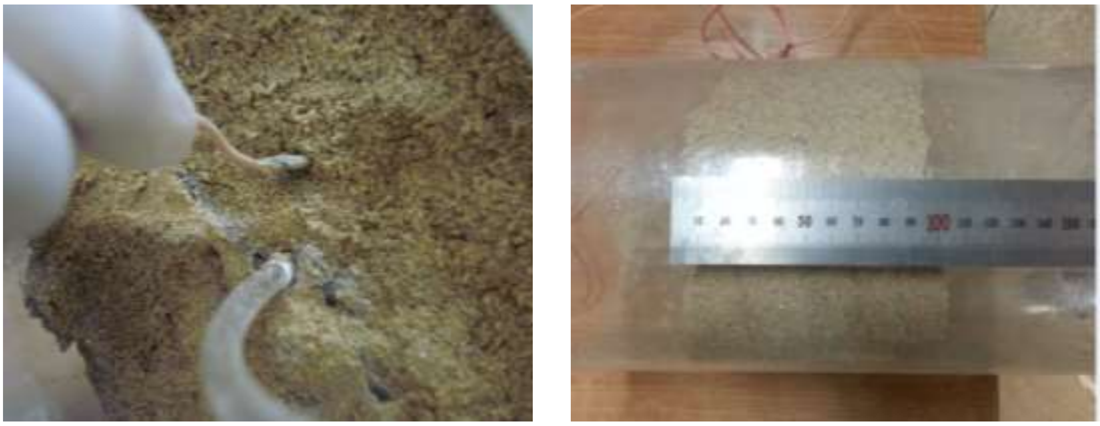


(a) Measurement points (b) Specimen molding

Figure 3. View of the shear wave velocity test

3. RESULTS OF LABORATORY TESTS

3.1 Results of the bio grouting injection

(1) Evaluation of the uniaxial compression strengths of OPC, micro cement and bio injection material 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 150kPa 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). Figure 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.

(a) After injection (b) SP-70% (c) SP-80%

(d) SP-85%

(e) SP-90%

(f) SP-96%

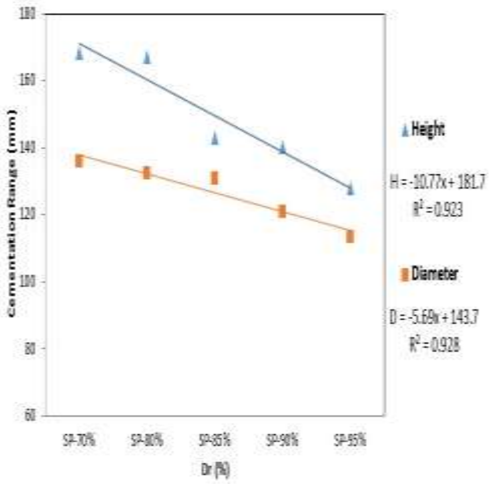
Fig. 4 Results of bio-grouting of SP specimens according to ground conditions

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

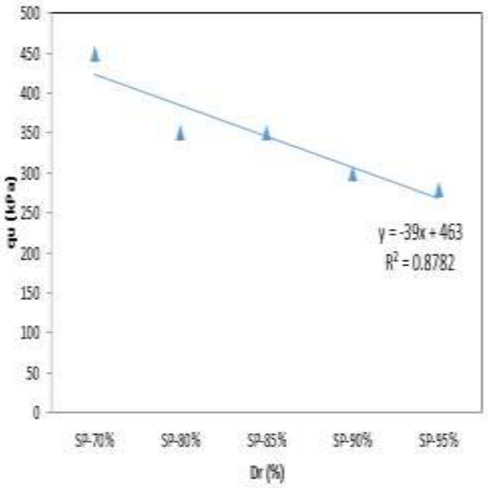
After the bio-grouting test according to the ground conditions, the strength of the cemented specimens on their top surfaces in the vicinity around the injection hole using a penetrometer as shown in Fig. 5.

Fig. 5 Measurement point of q_u

For the SP specimen, the diameter of the cementation increased to R^2 = 0.928, as the RC decreased to 70% from 95%, recording about 20% increase in the overall diameter and about 30% increase in the cementation height (R^2 = 0.923) as shown in Fig. 6(a). Also, as shown in Fig. 6(b), the cementation strength measured with the penetrometer on the top surface around the injection nozzle increased to R^2= 0.878, showing about 40% increase, as the RC decreased from 95% to 70%.



(a) Cementation range of SP specimens



(b) q_u of specimens

Figure 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 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 modulus of elasticity was measured by calculating the shear wave velocity at which specimens passed through the bender element. In a previous study, the shear wave velocity of dry pebbles was measured as 150m/s - 500m/s and that of dry sand as 150m/s - 200m/s (Cho and Lee (16)). For standard sand, the modulus of elasticity at the relative density (Dr) of 60% was measured as 80MPa. The shear wave velocity of each injection material is shown in Table 3.

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

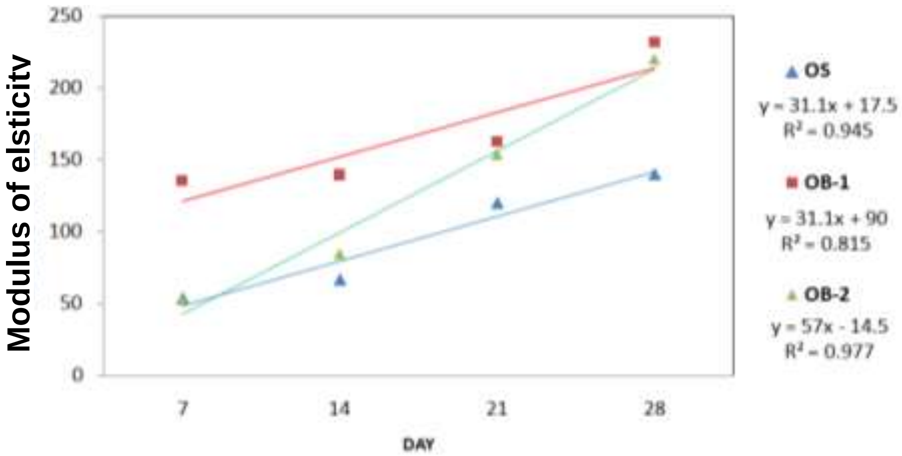
Fig. 7 (a) shows the result of analyzing the modulus of elasticity of OPC injection material. Over time, the modulus of elasticity increased by about 30% for OS, 10% for OB-1, and 40% for OB-2. Fig. 7 (b) shows the result of analyzing the modulus of elasticity of micro cement injection material. Over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

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.

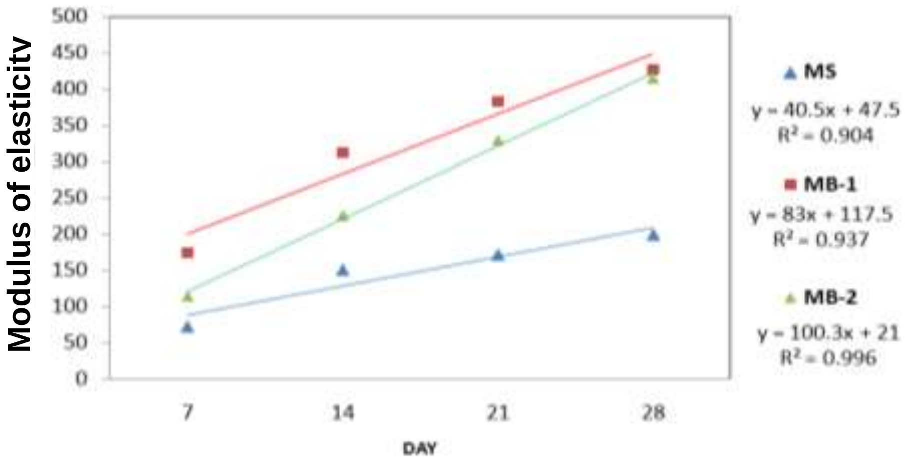
Shear wave velocity represents a rate at which wave passes along the surface of particles. Therefore, as gaps in specimens were reduced as particles were cemented, the shear wave velocity increased. Also, a high modulus of elasticity was confirmed with OB-1 and MB-1 which contained bio injection material,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

This was resulted as pores bigger than 1 ㎛ were reduced when calcium carbonate, the main component of bio injection material was added to cement, which was also confirmed by Kim and Noh (2000).

Therefore, though the increase of modulus of elasticity was insignificant when only the bio injection material was used, 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 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.



(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

3.3 Analysis of soil pollution

Pollution of the soil used for this study was analyzed with the soil collected around the injection material (28 days) 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. 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 conventional cement 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 cement and chemicals.

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

4. SUMMARY AND CONCLUSION

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:

1. 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.
2. 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.

3. 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.

4. 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.

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REFERENCES

Cheng, L., Cord-Ruwisch, R. and Shahin, M.A. “Cementation of Sand Soil by Microbially Induced Calcite Precipitation at Various Degrees of Saturation”, *Canadian Geotechnical Journal*, **50**, 81-90.

Cho, G.C., Lee, I.M. (2002), “Soil Properties Relation to Elastic Wave”, *Journal of the Korean Geotechnical Society*, **18**, 83-101.

Dejong, J.T., Mortensen, B.M., Martinez, B.C. and Nelson, D.C. (2010), “Bio-mediated Soil Improvement”, *Journal of Ecological Engineering*, **36**, 197-210.

Dejong, J.T., Fritzges, M.B. and Nüsslein, K. (2006), “Microbially Induced Cementation to Control Sand Response to Undrained Shear”, *Journal of Geotechnical and Geoenvironmental Engineering*, **132**, 1381-1392.

Feng, K. and Montoya, B.M. (2015), “Influence of Confinement and Cementation Level on the Behavior of Microbial-Induced Calcite Precipitated Sands under Monotonic Drained Loading”, *Journal of Geotechnical and Geoenvironmental Engineering*, **142**, 1-9.

Hai Lin, Suleiman, M.T., Brown, D.G. and Kavazanjian E. Jr. (2015), “Mechanical Behavior of Sands Treated by Microbially Induced Carbonate Precipitation”, *Journal of Geotechnical and Geoenvironmental Engineering*, **142**, 1-13.

Kim, D.H. and Park, K.H. (2013), “Injection Effect of Bio grout for Soft Ground”, *Advanced Science Letters*, **19**, 468-472.

Kim, D.H., Park, K.H. and Kim, D.W. (2014), “Effects of Ground Conditions on Microbial Cementation in Soils”, *Materials*, **7**, 143-156.

Kim, D.H., Park, K.H., Kim, H.C. and Lee, Y. H. (2012), “Effect of Microbial Treatment Methods on Biogrout”, *Journal of Geotechnical and Geoenvironmental Engineering*, **13**, 51-57.

Kim, D.H., Park, K.H., Kim, S.W. and Mun, S. H. (2012), “A Novel Approach to Induce Cementation of Loose Soils”, *Advanced Science Letters*, **5**, 1-6.

Kim, D.H., Sagong, M. and Park, K.H. (2013), “Improvement Method of Sand Ground Using an Environmental Friendly Bio Injection Material”, *Journal of the Korean Society for Railway*, **16**, 473-481.

Kim, D.S. and No, J.S. (2000), “Characteristic of Cement Mortar addition $CaCO_3$”, *Korea Concrete Institute Symposium*, 14-20.

Martinez, B.C., Dejong J.T., Ginn, T.R., Montoya, B.M., Barkouki, T.H., Hunt, C., Tanyu, B. and Major, D. (2013), “Experimental Optimization of Microbial-Induced Carbonate Precipitation for Soil Improvement”, *Journal of Geotechnical and Geoenvironmental Engineering*, **139**, 587-598.

Mitchell, J.K. and Santamarina, J.C. (2005), “Biological Considerations in Geotechnical Engineering”, *Journal of Geotechnical and Geoenvironmental Engineering*, **131**, 1222-1233.

Montoya, B.M. and Dejong, J.T. (2015), “Stress-Strain Behavior of Sands Cemented by Microbially Induced Calcite Precipitation”, *Journal of Geotechnical and Geoenvironmental Engineering*, **141**, 1-10.

Paassen, L.A., Harkes, M.P., Zwieten, G.A., Zon, W.H. and Star, W.R.L. (2009), “Loosdrecht, M.C.M. Scale Up of Biogrout: A Biological Ground Reinforcement Method”, *Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering*, 2328-2333.

Park, K.H. (2015), “Evaluation of Applicability of Environment Friendly Biogrouting Methods in Loose Frictional Soils”, Ph. D. thesis, *Chosun University*, Gwangju, Korea.

Park, K.H., Jeon, S.J. and Kim D.H. (2014), “Effect of Strength Enhancement of Soil Treated with Environment-Friendly Calcium Carbonate Powder”, *The Scientific World Journal*, **2014**, 1-11.

Park, K.H. and Kim, D.H. (2012), “Verification of Calcium Carbonate by Cementation of Silt and Sand using Bacteria”, *Journal of the Korean Geotechnical Society*, **28**, 53-61.

Park, K.H. and Kim, D.H. (2013), “Strength and Effectiveness of Grouting of Sand Treated with Bacteria”, *Journal of the Korean Geotechnical Society*, **29**, 65-73.

Whiffin, V.S., Paassen, L.A. and Harkes, M.P. (2007), “Microbial Carbonate Precipitation as a Soil Improvement Technique”, *Geomicrobiology Journal*, **24**, 1-7.