Experimental and Field Study on a Ground Improvement Material Without Using Cement

セメントを使用しない地盤改良材の室内および現地における実験的研究

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The strength of the improved soil using a newly developed cement-free solidification material was verified through a series of indoor and field tests focusing on powder-based shallow layer improvement method. Results demonstrated that the unconfined compressive strength of the treated soil increased over time, showing a clear time dependent strength gain in both indoor and field conditions. When compared to conventional cement treated soil, the new material exhibited comparable strength performance. Additionally, it significantly reduced the elution of hexavalent chromium and achieved a 46 % reduction in CO_2 emissions, highlighting its low environmental impact. From these results, it was concluded that the improved soil using the new cement-free solidification material performs well, as well as the cement treated soil, and it is promising as an applicable sustainable ground improvement material.

Keywords: Ground improvement, Unconfined compressive strength, Hexavalent chromium, CO_2 emission

新たに開発したセメントを使用しない地盤改良用固化材を用いた改良土の強度を確認するために，粉体工法による浅層改良を対象とした一連の室内試験および現地試験を実施した。その結果，室内試験および現地試験にて，改良土の一軸圧縮強さは時間の経過とともに増加する傾向が見られた。また，新固化材による改良土は従来のセメント改良土と同等の強度発現性能を有すること，さらに，有害な六価クロムの溶出量を大幅に低減し，CO_2排出量を 46 %削減することが確認された。これらの結果から，セメントを使用しない新固化材は,環境負荷低減に寄与する地盤改良材として有望であると結論づけられた。

キーワード：地盤改良，一軸圧縮強さ，六価クロム，CO_2排出量

1. Introduction

Cement-based solidifying materials are widely used for ground improvement and soil stabilization all over the world. In Japan, approximately 20 % of domestic cement demand, around 8 million tons, are using for ground improvement annually[1)]. These materials, primarily composed of Portland cement, are essential for enhancing the strength and stability of soft or problematic soils. However, environmental concerns emerged due to the high carbon dioxide (CO_2) emissions associated with Portland cement production estimated as 756 kg-CO_2/t [2)]. In addition to that, when cement based solidifying materials are used with volcanic ash soils, the amount of hexavalent chromium eluted can sometimes exceed the standard limits. In response to the growing environmental concerns, Ministry of the Environment in Japan revised the groundwater quality standard related to hexavalent chromium in 2022, lowering the permissible

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concentration from 0.05 mg/L to 0.02 mg/L. This stricter regulation reflects heightened awareness of the health risks associated with hexavalent chromium contamination. It is also anticipated that soil environmental standards may be revised in the future to align with these updated groundwater criteria.

Therefore, this study focuses on a newly developed solidifying material that does not contain cement (hereafter referred to as the Developed material) and its application on shallow ground improvement for temporary construction works using a powder-based method. To evaluate its performance, a commercially available cement-based solidifying material specifically designed to reduce hexavalent chromium elution (hereafter referred to as the Traditional material) was used for the comparison. This study evaluated both unconfined compressive strength and the amount of hexavalent chromium eluted from the improved soil by conducting indoor tests. Additionally, CO_2 emissions were calculated based on the quantity of the solidifying material required to achieve the target strength, allowing for a comparative analysis of environmental impact. Further, a field experiment was conducted to verify strength of the improved soil under site conditions. Findings were compared with the results of Traditional material for discussing the applicability of Developed material.

Table 1. Physical properties of soil

	Unit	Soil A	Soil B	Soil C	Soil D
Specific gravity	g/cm^3	2.780	2.609	2.698	2.629
Natural water content	%	59.4	42.4	74.9	112.0
Gravel	%	0.1	20.9	4.6	0.1
Sand	%	10.6	36.5	33.4	31.4
Silt	%	27.2	24.7	44.0	37.7
Clay	%	62.1	18.0	18.0	30.8
Liquid limit	%	89.2	81.8	93.2	167.8
Plastic limit	%	47.4	57.8	64.0	74.3
Plasticity Index	-	41.8	24.0	29.2	93.5
Classification	-	Volcanic ash soil (Type II)	Fine grained gravelly sand	Volcanic ash soil (Type II)	Volcanic ash soil (Type II)
Ignition loss	%	-	18.9	13.2	16.7
Unconfined compressive strength	kN/m^2	30.4	142	68.3	66.6

2. Indoor experiment

2.1 Materials used

Table 1 shows the physical properties of the used four types of soil as soil A, soil B, soil C and soil D. Those soils were collected from shallow layers of sites around Kanto area. Soil A, C and D are categorized as volcanic ash soil, and they have different fine content and different natural water content. Soil B contains higher sand content compared to other three types of soil, however since this soil has higher ignition loss, soil B is also used in this study to see the effect on the strength. All soils were sieved by 9.5 mm sieve before sample preparation.

As the solidifying materials, the Developed material which is a mixture of blast furnace slag powder, lime and gypsum were used. For comparing the results, a commercially available Traditional material was used. **Table 2** shows the CO_2 emission of each material. The CO_2 emission of the Developed material was calculated based on the data from the journal of Japan Society of Civil Engineers[3)] while the CO_2 emission of Traditional material was calculated based on interviews with manufacturers.

Table 2. CO_2 emission of materials

Item	Traditional material	Developed material			
			Lime	Slag	Gypsum
CO_2 emission [kg-CO_2/t]	500	270	844.6[3)]	26.5[3)]	16.1[3)]

Table 3. Dosage of solidification material

Soil type	Solidification material	Dosage (kg/m^3)
Soil A	Developed material Traditional material	100 175 250
Soil B	Developed material Traditional material	100 150 200
Soil C	Developed material Traditional material	100 175 250
Soil D	Developed material Traditional material	100 150 200 250

2.2 Test method

Table 3 shows the improved soil specimen preparation conditions for each soil. A predetermined amount of solidification material powder was added to the soil under the condition of natural water content. Soil and solidification material were mixed for several minutes using a mixer. The soil specimens of diameter 50 mm and height of 100 mm were prepared according to JCAS L-01 (Strength test method for improved soil using cement-based solidification materials), for the unconfined compression test. The image of prepared soil specimens for each type of soil is shown in **Fig. 1**. The pH values of original soils were in the range of 7.5~9.0. The pH of the solidified soil mixtures appeared to be in the range of 10~12. All the specimens were cured under sealed conditions at a temperature of 20 °C. The unconfined compressive strength was measured according to JIS A 1216 (Method for unconfined compression test of soils) at respective curing days as shown in **Table 4**. Due to the limited availability of soil D, only the specimens for 7 and 28 days were prepared with Traditional material. In each case three specimens were used for the test, and the average results of those three specimens are reported in this paper.

In each case the improved soil samples were collected from the specimen after conducting the unconfined compression test on 7 days of curing, and the elution amount of hexavalent chromium was measured by the Diphenyl carbazide (DPC) spectrophotometric method in accordance with the environment agency notification no. 46.

Table 4. Curing period of improved soil

Soil type	Curing days
Soil A	7, 31, 56, 91
Soil B	7, 31, 56, 91
Soil C	7, 28, 56, 87
Soil D	7, 28, 56, 91 Traditional material 7, 28

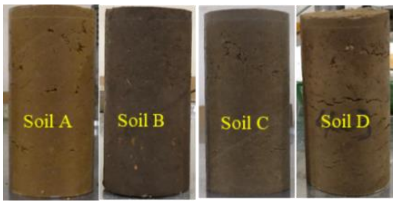


Fig. 1. Images of improved soil specimens

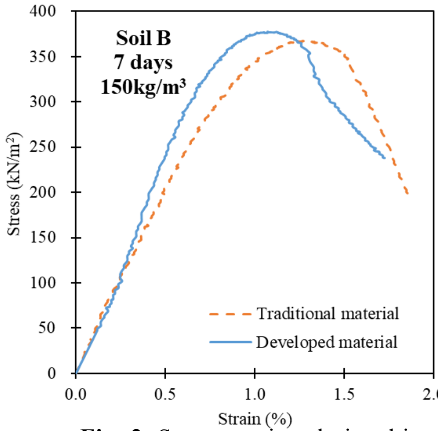


Fig. 2. Stress strain relationship

3. Indoor test results

3.1 Unconfined compression test

3.1.1 Effect of solidification material dosage

Fig. 2 shows the typical stress strain relationship of improved soil specimens using Traditional material and Developed material for soil B with the dosage of 150 kg/m^3. Improved soil using Developed material shows a similar stress strain relationship to the improved soil using Traditional material. The unconfined compressive strength after curing for 7 days is shown in **Fig. 3** for all types of soil. Under all conditions, the unconfined compressive strength increased when increasing the dosage of solidification material. Regardless of the type of solidifying material, the unconfined compressive strength was lower in the improved soil B and D than in soil A and C. According to the previous studies[4)], in the case of volcanic ash soil and organic soil unconfined compressive strength decreases as the amount of allophane increases in the natural soil. Even though the exact allophane content of each soil was not measured in this study, it was assumed that allophane might be one of the possible factors the lower strength in soil B and D. Furthermore, hexavalent chromium elution test results in section **3.2** proved a difference in soil minerals of soil B and D when comparing to soil A and C.

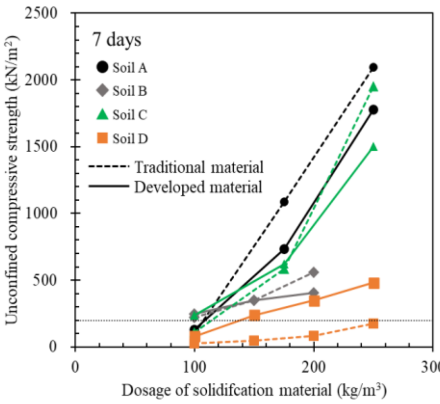


Fig. 3. Effect of solidification material dosage on strength

In the case of soil D, the strength of Developed material was greater than the strength of Traditional material irrespective to the solidification material dosage. In the case of soil A, B and C, in higher dosage such as 250 kg/m^3 improved soil using Traditional material shows higher strength than Developed material. Although the strength development characteristics of the two solidifying agents vary depending on the soil type being improved, the degree of increment in unconfined compressive strength with increased dosage showed a similar trend.

3.1.2 Effect of curing period

Fig. 4 (a), (b), (c), (d) and (e) shows the strength results with respect to the curing period for the dosages of 100, 150, 175, 200 and 250 kg/m^3 respectively. Irrespective of the type of soil, type of solidification material and the dosage, the strength increases when increasing the curing period. At the dosage of 100 kg/m^3 and 150 kg/m^3, improved soil using Developed material shows higher strength than Traditional material for each soil type in all curing periods. On the other hand, when the dosage of solidification material was 175 kg/m^3 or more, the unconfined compressive strength was higher when the Developed material was used in soil C and D and for Traditional material in soil A and B.

Table 5 shows the increment rate of unconfined compressive strength from 7 days to 28 days (31 days) and from 28 days to 91 days. Irrespective of the soil type, in all cases the strength increment rates were within the range of 1.2~1.7[5]), which is the typical rate for all cement based traditional materials. The strength gaining mechanism of the Developed material assumed to be different from the Traditional material. However, finding results proved that strength gain follows a similar timeline to the Traditional material.

Table 5. Strength increment rate

Soil type	Solidification material	Dosage (kg/m^3)	Strength increment rate: Curing period 7 to 28 days		Strength increment rate: Curing period 28 to 91 days	
Soil A	Traditional material	100	1.8	Average 1.5	1.8	Average 1.4
		175	1.2		1.2	
		250	1.4		1.3	
	Developed material	100	1.7	Average 1.4	1.6	Average 1.4
		175	1.2		1.5	
		250	1.2		1.2	
Soil B	Traditional material	100	1.5	Average 1.3	1.2	Average 1.3
		150	1.2		1.3	
		200	1.2		1.3	
	Developed material	100	1.3	Average 1.4	1.5	Average 1.4
		150	1.4		1.4	
		200	1.3		1.4	
Soil C	Traditional material	100	1.3	Average 1.4	1.4	Average 1.5
		175	1.6		1.5	
		250	1.3		1.6	
	Developed material	100	1.7	Average 1.9	1.1	Average 1.5
		175	1.6		2.2	
		250	2.3		1.4	
Soil D	Traditional material	100	1.8	Average 1.5		
		150	1.4			
		200	1.4			
		250	1.6			
	Developed material	100	1.7	Average 1.6	1.4	Average 1.5
		150	1.6		1.5	
		200	1.6		1.5	
		250	1.7		1.8	

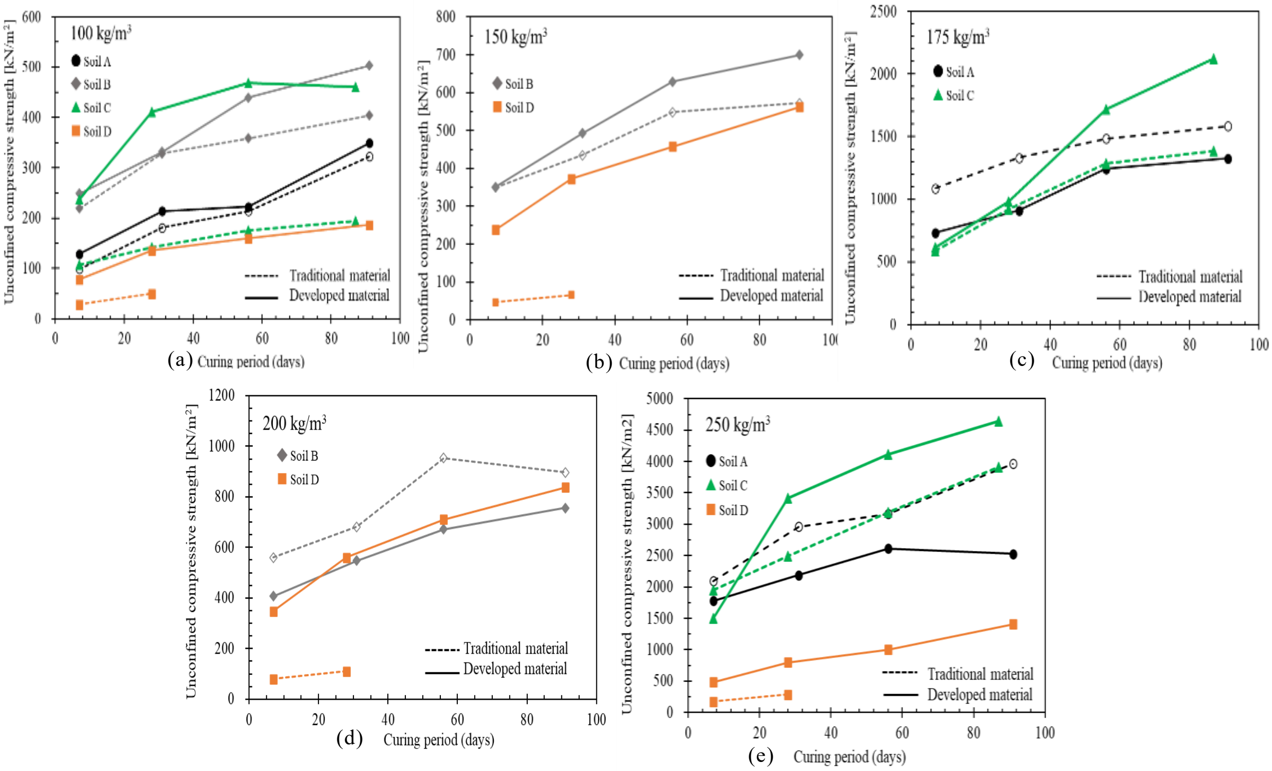


Fig. 4. Effect of curing period on with dosage of solidification material

3.2 Hexavalent chromium elution test

Hexavalent chromium is a chemical compound in the Portland cement based materials (such as Traditional material) and when it interact with soil minerals, there is a possibilty to leach out. Leaching amount depends on the presence of organic matter or clay minerals. **Fig. 5** shows the relationship between the amount of solidification material added and the amount of hexavalent chromium eluted after 7 days of curing for Traditional material and for the Developed material of all soil types.

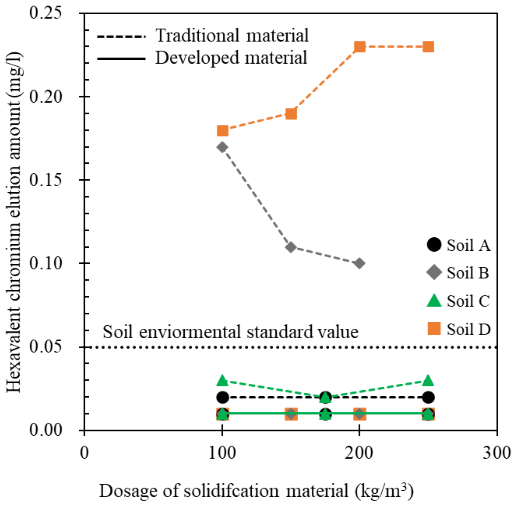


Fig. 5. Hexavalent chromium elution amount

When Traditional material was used as solidification material, soil B and D, showed elution amounts of hexavalent chromium which exceeded the current soil environmental standard value of 0.05 mg/l. In the case of soil A and C the elution amounts were within the standard value. This difference in the elution amount of hexavalent chromium clearly implies the difference between the soil minerals in each type of soil. The effect of those soil minerals on the strength of the improved soil can be clearly distinguished in **Fig. 3** where lower strengths were achieved by soil B and D. According to **Fig. 5**, in soil B, the leaching amount reduced when increasing the dosage of Traditional material increased. On the other hand, in soil D leaching amount is increased. This may be due to the lower strength achieved by soil D as shown in **Fig. 3**. When increasing the dosage of solidification material, the leaching amount of hexavalent chromium is possible to increase due to the higher availability of that compound. However, when increasing the dosage, the strength increases by leading to a denser and less permeable soil matrix which can physically restrict the elution amount of hexavalent chromium. Hence the leaching amount of hexavalent chromium is a balance of the dosage and the achieved strength of the relevant soil[6].

When Developed material was used as solidification material, the leaching amount of hexavalent chromium were 0.01 mg/l or less than 0.01 mg/l irrespective to the type of soil or the dosage. This is because Developed material does not contain cement or a material which contain hexavalent chromium. These results confirmed that hexavalent chromium elution amount can be reduce significantly by using Developed material.

3.3 CO_2 emission

In this study, the target was shallow layer soil improvement for temporary installations. The targeted design strength at site was set as 100 kN/m^2 at 7 days. Since powder mixing generally conducted by backhoe, which might induce non-uniform material mixing, field and indoor strength ratio of 0.5[7] was used. By using equation (1)[7] target unconfined compressive strength of indoor test was evaluated as 200 kN/m^2. Here, q_{ul}: indoor target strength (kN/m^2), q_{uck}: field design strength (kN/m^2), α_{kl}: field and indoor strength ratio.

$$q_{ul} = q_{uck} / \alpha_{kl} \tag{1}$$

The required dosage of Traditional material and the Developed material for achieving the targeted indoor strength was evaluated based on **Fig. 3** and the obtained values are summarized in **Table 6**. For soil A and B, target strength could be achieved by same dosage for both solidification material. In the case of soil D, a higher dosage of Traditional material than Developed material was required. The CO_2 emission for improving one meter cube of each soil was evaluated for each solidification

Table 6. Comparison of CO_2 emission

	Traditional material		Developed material		
	Dosage (kg/m^3)	CO_2 emmision (kg-CO_2/m^3)	Dosage (kg/m^3)	CO_2 emmision (kg-CO_2/m^3)	CO_2 reduction (%)
Soil A	110	55	110	30	46
Soil B	100	50	100	27	46
Soil C	100	50	115	31	38
Soil D	250	125	140	38	70

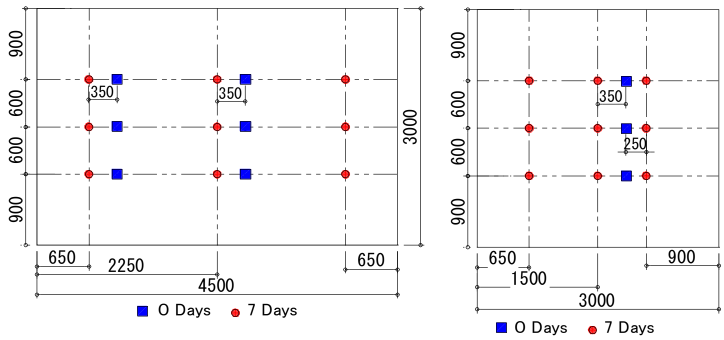
material based on the required dosage. In here, the CO_2 emission of Traditional material was considered as 500 kg-CO_2/t and the Developed material was a 270 kg-CO_2/t as shown in **Table 2**. By using Developed material, CO_2 emission could be reduced by 46 % for soil A and B and 38 % for soil C respectively. In the case of soil D, it was possible to achieve 70 % CO_2 reduction due to larger difference in the dosage of solidification material.

In a site where shallow layer soil improvement works for temporary installations, CO_2 emission can occur due to the production of material, transportation to the site and due to the fuel used for the machinery. Among them it was found that 90 % (calculation by author based on actual site data) of the CO_2 is emitted in the production of solidification material. By adopting sustainable solidification material like Developed material environmental impact can be reduced significantly.

4. Field experiment

4.1 Test method

Field experiment was conducted on a site of soil B where shallow layer improvement was required for moving heavy vehicles before the construction works started. The image of improved areas for Traditional material and the Developed material is shown in **Fig. 6** (a) and (b) respectively. The shallow improvement depth was 0.5 m. The target strength field was 150 kN/m^2. The dosage of Traditional material and the Developed material was set as 150 kg/m^3. The required amount of powder of each material was laid on the improving area and the mixing works were conducted by backhoe until reaching the targeted improved depth of 0.5 m. Site experimental area was previously a parking area. Hence there were lots of large rocks and gravel underneath the surface layer. While mixing, those rocks were taken out as much as possible. After mixing were finished, the improved depth was measured and confirmed by doing phenolphthalein test for each corner of the rectangular test area. Phenolphthalein changes from clear to a red-pink color where pH is greater than 9[8]. This indication can be used to confirm if there is a variation in the mixing of solidification material. Then the improved soil was compacted by using a roller compactor. After the compaction, site compaction densities for each case were measured by conducting sand cone test (JIS A 1214) in each area. Site compaction density of the area where Traditional material was used was 1.258 g/cm^3 (97 % of compaction) and the respect value for Developed material was 1.206 g/cm^3 (93 % of compaction).



(a) Traditional material　　(b) Developed material

Fig. 6. Dimensions of improved area and the locations for cone test

After finishing the compaction, the dynamic cone penetration test (JGS1433) was conducted in six locations for Traditional material area and three locations of Developed material area as shown in **Fig. 6**. At each location, the test was conducted up to 70 cm in depth. Then the improved areas were covered with sheets until 7 days of curing. After 7 days dynamic penetration tests were conducted at 9 locations for each case as shown in the **Fig. 6**. This test involves driving a metal cone point angle of 60 degrees and diameter of 25 mm into the ground using a 5 kg weight dropped from a 500±10 mm height. The cone is attached to a rod, and the number of blows (N) required to drive the cone a

$$N_d = 100\frac{N}{\Delta h} \tag{2}$$

$$\left.\begin{aligned} q_u &= 25 + 5\,N_d \;(N_d > 4) \\ q_u &= 11\,N_d \;(N_d \leq 4) \end{aligned}\right\} \tag{3}$$

certain distance around 100 mm (Δh) were recorded. From this, the penetration rate (N_d) was calculated using equation (2). The unconfined compressive strength (q_u (kN/m^2)) of each depth was evaluated using equation (3). Equation (3) is an empirical equation based on clayey soil, which is stated in Japanese standards and explanations of geotechnical and geoenvironmental investigation methods[9]. Same equation was reported to be used for evaluating the strength of cement treated soil in several studies[10].

Table 7. Dynamic cone penetration test results (Traditional material center 7days)

Depth	Number of blows (N)	Penetration depth Δh (mm)	Penetration rate, N_d (N/mm)	Unconfined compressive strength, q_u(kN/m^2)	
10	0	10	0.0		Strength of improved depth 0～40cm Average:109kN/m^2
100	16	90	17.8	113.9	
204	20	104	19.2	121.2	
301	16	97	16.5	107.5	
402	14	101	13.9	94.3	
511	10	109	9.2	70.9	Strength of unimproved depth 50cm～70cm Average:69kN/m^2
605	7	94	7.4	62.2	
699	9	94	9.6	72.9	

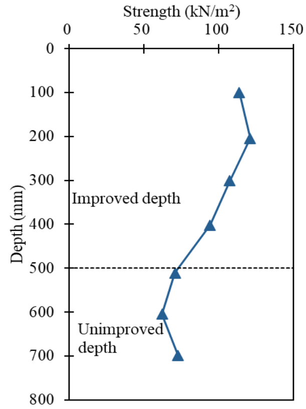


Fig. 7. Strength variation along the depth

4.2 Test results

Table 7. shows an example for the dynamic cone penetration test results and the evaluated unconfined compressive strength for the center of the area where Traditional material was used, after 7 days of curing. The average of the strength evaluated under the depth of 0~40 cm was considered as the strength of improved depth and the strength evaluated under the depth of 50~70 cm was considered as the strength of unimproved depth. **Fig. 7** shows strength variation along the depth graphically.

The strength of all test locations shown in **Fig. 6** (a) and (b) were averaged for each case with respect to the curing period and evaluated the strength for improved depth and unimproved depth separately as shown in **Fig. 8**. The standard deviation of the evaluated strength is also indicated in the same figure. In the case of unimproved depth, the strength varies between 60~80 kN/m^2 irrespective to the type of solidification material used and the curing period. In the case of improved depth, at 0 curing days the strength was greater than the strength of unimproved depth in both solidification materials. This may be due to the difference in the compaction density between shallow depth and deeper depth. However, the strength increased clearly with the curing period for both Traditional material and the Developed material in the improved depth.

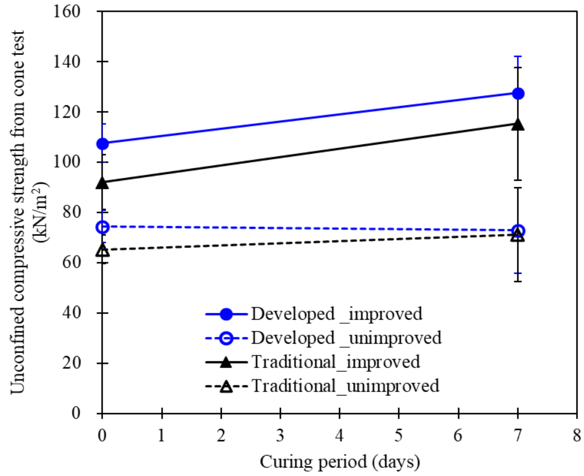


Fig. 8. Strength variation in improved and unimproved depth

The strength ratio between field test and the indoor tests were evaluated for each solidification material based on the unconfined compressive strength of 7 days curing as shown in **Table 8**. Strength ratio of 0.33 and 0.32 were achieved by Traditional material and Developed material respectively. In here, the indoor strength was evaluated directly from unconfined compressive strength test while the filed strength was evaluated indirectly based on an empirical equation as explained in section **2.2** and **4.1** respectively. Lower strength ratio values might be resulted by indirect evaluation of the field strength.

Table 8. Field/indoor strength ratio

	Traditional material	Developed material
Indoor strength (kN/m^2)	350.3	403.3
Field strength (kN/m^2)	115.2	127.6
Strength ratio	0.33	0.32

However, the obtained strength ratios are within the value of 0.3~0.7 which is the standard strength ratio for shallow improvement using powder method with backhoe[7]. Developed material shows similar performance to the Traditional material even in the field experiment by promising the possible applicability on the field of soil improvement.

5. Conclusion

In this study, the performance of a newly developed solidifying material that does not contain cement was evaluated. A series of indoor experiments and field tests were conducted to study the performance of the Developed material targeting shallow layer improvement. Several types of volcanic ash soils were used. Furthermore, the obtained results were compared with Traditional material (commercially available cementitious material) for verifying the Developed material and its applicability as a construction material.

The findings can be summarized as follows.

i) Mechanical properties of soil can be improved using Developed material.
ii) Unconfined compressive strength of the improved soil using Developed material showed similar trend to the Traditional material when increasing the dosage.
iii) Developed material showed time dependent strength gain similar to the strength gaining trend of Traditional material.
iv) Developed material can reduce the hexavalent chromium elution significantly even under the conditions where Traditional material exceeded the standard limit of 0.05 mg/l.
v) CO_2 emission can be reduced by 46 % by using the Developed material as per the same dosage of Traditional material. Further reduction of CO_2 emission can be achieved by reducing dosage of solidification material.
vi) Field experiment results also showed time dependent strength gain similar to the strength gaining trend of Traditional material.
vii) Field/ Indoor strength ratio was confirmed for both Developed material and Traditional material and it was in the acceptable limit.

As a summary, it can be concluded that the improved soil using the Developed material without using cement, performs to the same level as the cement treated soil and it might be a promising sustainable ground improvement material.

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