Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul 2017

Strength and stiffness of compacted cement-mixed gravelly soil controlled by the degree of saturation

Résistance à la compression et rigidité des sols graveleux cimentés et compactés gouvernées par le degré de saturation

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ABSTRACT: Drained triaxial compression tests were performed on cement-mixed well-graded gravelly soil (CMG) compacted and cured in the laboratory and core samples retrieved from a full-scale soil structure. The strength and stiffness of CMG increase significantly with an increase in the dry density. The strength and stiffness of CMG prepared in the laboratory are consistent with those of core samples under otherwise the same conditions. Irrespective of compaction energy level (CEL), the strength exhibits a sharp peak when compacted to a degree of saturation (S_r) slightly lower than the value at which the maximum dry density is obtained for a given CEL. The value of S_r at the end of compaction is one of the fundamental parameters for the strength and stiffness of CMG.

RÉSUMÉ : Des essais de compression triaxiale en conditions drainées ont été réalisés sur des échantillons de sols graveleux cimentés et compactés en laboratoire ainsi que sur des échantillons prélevés sur une structure existante afin d'évaluer leur résistance à la compression et leur rigidité. Les résultats révèlent que la résistance et la rigidité de ces matériaux augmentent significativement avec la densité sèche et que les valeurs obtenues sur les échantillons réalisés en laboratoire sont comparables à celles des échantillons prélevés sur la structure pour des densités et des teneurs en ciment similaires. Un pic de résistance est également observé pour un degré de saturation légèrement inférieur à celui pour lequel la densité sèche maximale est obtenue, et ce indépendamment de l'énergie de compaction. Ceci démontre que le degré de saturation après compaction est un paramètre fondamental gouvernant la résistance à la compression et la rigidité de ces sols.

KEYWORDS: Cement-mixed gravel, Degree of compaction, Degree of saturation, Strength and stiffness, Triaxial compression test

1 INTRODUCTION. FIRST LEVEL HEADING

Well-compacted cement-mixed well-graded gravelly soil (CMG) is often used to construct important permanent structures requiring a high stability and limited deformation. Typically Fig. 1 shows the first geosynthetic-reinforced soil (GRS) integral bridge constructed at Kikonai for a new fast-train line, opened March 2016 (Yonezawa et al. 2014: Tatsuoka & Watanabe 2015: Tatsuoka et al. 2016). CMG was well-compacted to be strong and stiff enough for a high seismic stability of the abutments and a minimum bump immediately behind the facing. After the backfill and ground deformation by the weight of the geogrid-reinforced CMG backfill had taken place sufficiently, full-height rigid facings were constructed firmly connected to the geogrid reinforcement. Finally a girder was constructed with both ends integrated to the facings. Based on the results from a comprehensive series of drained triaxial compression (TC) tests (e.g., Watanabe et al. 2003: Lohani et al. 2004: Kongsukprasert et al. 2005), it has been specified for such projects as the one shown in Fig. 1 that CMG is compacted at the optimum water content w_{opt} by Modified Proctor (4.5Ec) to a dry density ρ_d equal to at least 95 % of the maximum $(\rho_d)_{max}$ for 4.5Ec.

In this study, a series of drained TC tests were performed on CMG specimens prepared in the laboratory and core samples from the field. The results were analyzed together with those from previous studies. Significant effects of compaction on the strength and stiffness of CMG were confirmed. It was found that the strength and stiffness of CMG are controlled by the degree of saturation when compacted and cured.

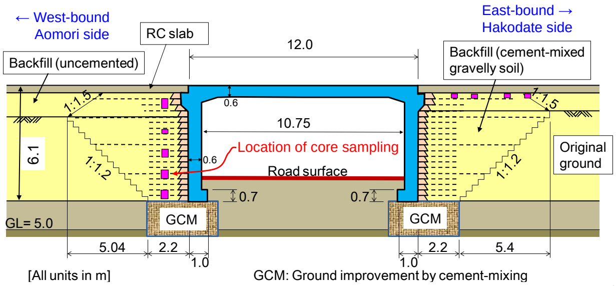


Figure 1. First GRS integral bridge at Kikonai (in the south end of Hokkaido Island) for a new high-speed train line (Shinkan-sen).

2 SIGNIFICANT EFFECT OF COMPACTION

Fig. 2 shows compaction curves of Chiba gravelly soil (Fig. 3) by Standard and Modified Proctors (1Ec & 4.5Ec), where ρ_d is the total dry density of soil and cement. Effects of cement-mixing on the compaction curve are negligible for a cement-to-gravel weight ratio c/g of 2.5 - 4 %, typical of those used in the field. So, the TC specimens of CMG were compacted to different degrees of compaction $(D_c)_{4.5Ec}$= "ρ_d of soil & cement" / "$(\rho_d)_{max}$ for 4.5Ec of soil (without cement)" x 100 %.

Fig. 4 shows results from typical drained TC tests on moist rectangular prismatic specimens (72 mm x 72 mm x 150 mm high) of Chiba gravelly soil mixed with ordinary Portland cement, compacted at w= $(w_{opt})_{4.5Fc}$ and cured at constant w and 20° C for t_c= 7 days. Throughout this study, the confining pressure σ'$_c$ was 20 kPa and the axial strain rate was 0.03 %/min. The axial strain was measured externally and locally with a pair of LDT. The lateral strain of the rectangular prismatic specimen was measured locally with six lateral LDTs.

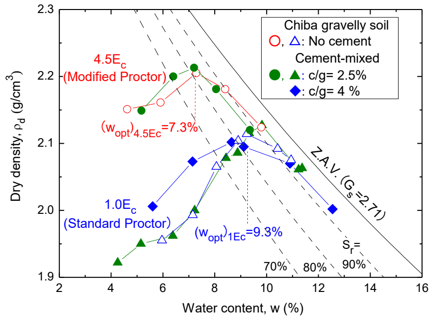
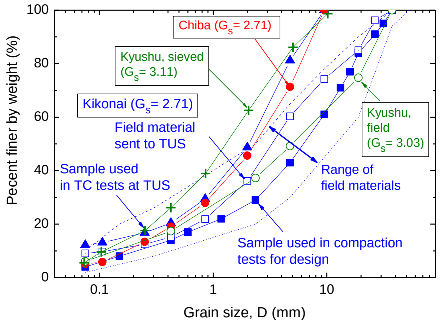


Figure 2. Compaction curves of Chiba gravelly soil.



Name (mother rock type)	Material	Specific gravity, G_s	$(\rho_d)_{max.4.5Ec}$ (g/cm^3)	References
Takada, Kyushu (gabbro)	Field material, also used in TC tests (15 cm-d)	3.03	2.675	Watanabe et al. (2003)
	Sieved material used in TC tests (7.5 cm-d)	3.11	2.494	Lohani et al. (2004)
Chiba (sandstone)	Sieved material used in TC tests	2.71	2.213	Ezaoui et al. (2011)
Kikonai (limestone)	Field material	2.71	2.226	This study
	Sieved material used in TC tests (7.5 cm-d)	2.71	2.295	

Figure 3. Grading curves & other properties of gravelly soils (sub-angular sieved crushed quarry hard rocks) referred in this paper.

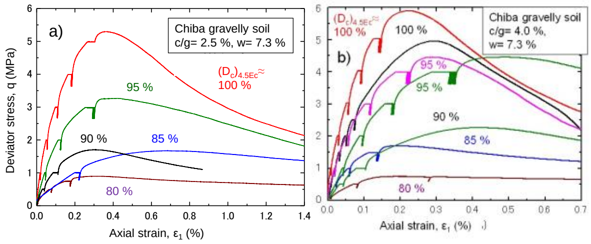


Figure 4. q -ε_1 (external) relations, drained TC (σ'$_c$= 20 kPa) of Chiba CMG (w= $(w_{opt})_{4.5Ec}$ & t_c = 7 days): c/g= a) 2.5 %; and b) 4.0 %.

The effects of compaction on the stress-strain properties are significant (Fig. 4). As the different gravelly soils have different $(\rho_d)_{max}$ values for the same CEL (Fig. 3 & Table 1) and D_c is used in field compaction control, the compressive strength q_{max} and the initial Young's modulus E_0 (at local ε_1 < 0.001 %) are plotted against $(D_c)_{4.5Ec}$ (Figs. 5a & b). The effects of c/g on q_{max} and E_0 increase significantly with an increase in $(D_c)_{4.5Ec}$. It is also the case for t_c other than 7 days (Ezaoui et al. 2011).

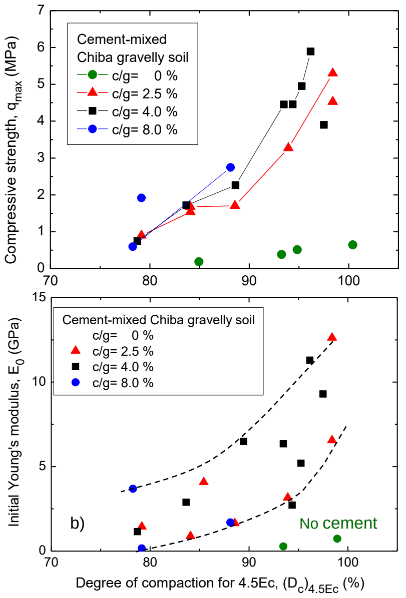


Figure 5. q_{max} & E_0 - $(D_c)_{4.5Ec}$ relations from TC tests (Fig. 4 & others).

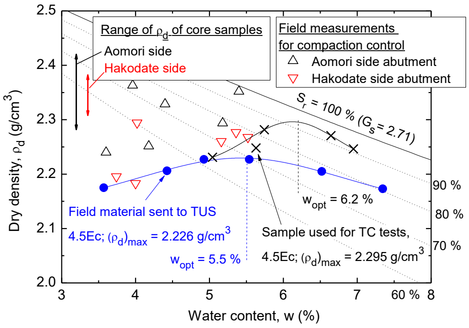


Figure 6. Compaction curves of a typical field material and the sample used for TC tests and field compacted states in the abutments at Kikonai.

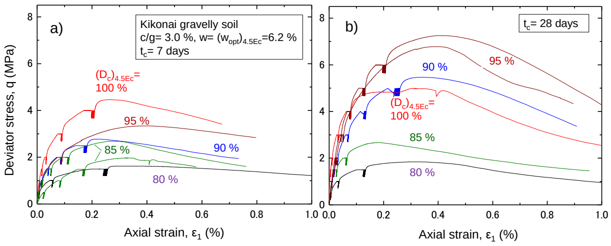


Figure 7. q -ε_1 relations from drained TC (σ'$_c$=20 kPa) of Kikonai CMG compacted in the laboratory (c/g= 3.0 %): t_c=: a) 7 days; & b) 28 days.

Fig. 6 shows the compaction curves of the gravelly soil used to construct the abutments (Fig. 1). Cylindrical TC specimens (75 mm d x 150 mm h) of the sieved gravelly soil (Fig. 3) mixed with Portland blast-furnace cement type B of c/g= 3 % as in the construction were produced by compaction at w= w_{opt} (= 6.2 %) to different $(D_c)_{4.5Ec}$ values and cured for different periods (t_c= 7, 28 & 56 days). The lateral strain was locally measured with three clip gauges (Lohani et al. 2004). It may be seen from Figs. 7 and 8 that, as Chiba CMG (Figs. 4 & 5), the effects of $(D_c)_{4.5Ec}$ on the strength and stiffness are significant, while the effect increases significantly with t_c up to 28 days.

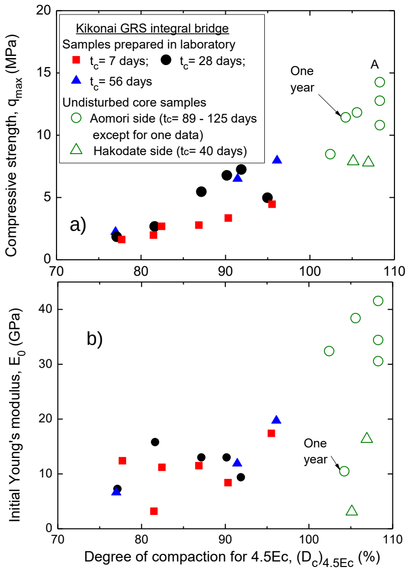


Figure 8. Comparison between specimens prepared in the laboratory and core samples of Kikonai CMG, c/g= 3 %: a) q_{max}; and b) E_0 from drained TC (σ'$_c$= 20 kPa) shown in Fig. 7 and others.

3 COMPARISON BETWEEN MATERIALS COMPACTED IN THE LABORATORY AND IN THE FIELD

Many rotary core samples of CMG (116 mm in diameter) were retrieved from the abutments (Fig. 1). The ρ_d values of the core samples are similar as those measured during field compaction control (Fig. 6). These ρ_d values are generally higher than $(\rho_d)_{max}$ by the laboratory compaction test (4.5Ec) of a typical field material, indicating very good compaction. As seen from Fig. 8, the values of q_{max} and E_0 of the core samples are consistent with those of the laboratory specimens, except for several low E_0 values due likely to sample disturbance.

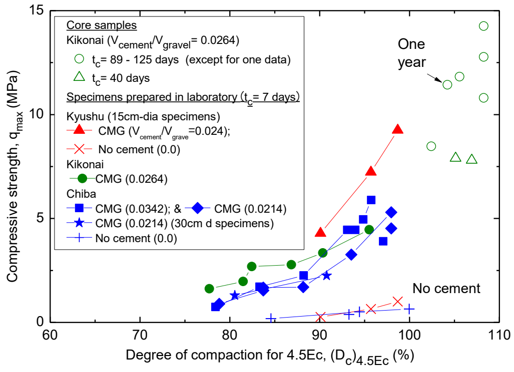


Figure 9. q_{max} – $(D_c)_{4.5Ec}$ relations from drained TC (σ'$_c$= 20 kPa) on specimens prepared in the laboratory (t_c= 7 days) and core samples.

Fig. 9 compares the drained TC q_{max} – $(D_c)_{4.5Ec}$ relations of CMG (t_c= 7 days) of three gravelly soil types, Chiba, Kikonai and Kyushu, compacted at respective w_{opt} values for 4.5Ec in the laboratory, together with those of Kikonai core samples. CMG was also used to construct a GRS bridge abutment at Takada, Kyushu (Watanabe et al. 2003; Tatsuoka et al. 2005). The TC specimens of Kyushu CMG prepared in the laboratory were 15 cm d x 30 cm h. The relations of the three CMGs having similar cement to gravel volume ratios V_{cement}/V_{gravel}= 0.0214 – 0.0342 are very similar. This parameter is more relevant than *c*/*g* for these gravelly soils having largely different G_s values (Fig. 3). By comparing the relations of these CMGs with those of uncemented gravelly soils, it is obvious that the strength increase by cement-mixing becomes very large when $(D_c)_{4.5Ec}$ > 95 %. This fact supports the current practice that CMG is compacted at $w \approx w_{opt}$ to at least $(D_c)_{4.5Ec}$= 95 %.

ϕ=44.8° & c=1.4 MPa was obtained by a multi-stage TC test performed at σ'$_c$= 20 kPa then 500 kPa on a core sample of $(D_c)_{4.5Ec}$= 106 % & t_c= 90 days (data point A in Fig. 8a). The fact that this high ϕ value is similar to the value when uncemented indicates large frictional interlocking with CMG. Similar high ϕ values were obtained with Chiba and Kyushu CMGs compacted in the laboratory (Watanabe et al. 2003).

4 EFFECT OF THE DEGREE OF SATURATION

As shown in Fig. 10a, the TC specimens (mostly 7.5 cm d x 15 cm h) of Chiba CMG were compacted at different CELs (1Ec, 4.5Ec & 9Ec) with c/g= 2.5 %; or to different ρ_d values with c/g= 2.5, 4 and 8 %. Part of the data presented in Fig. 5 and those of sieved Kyushu gravelly soil (c/g= 2.5 % & 4.5Ec) are also plotted in Figs. 10a & b. In Fig. 10b, the q_{max} values (t_c= 7 days) are plotted against the molding water content, *w*. With Chiba and Kyushu CMGs (*c*/*g*= 2.5 %) compacted at different CELs, q_{max} exhibits a sharp peak, $[q_{max}]_{peak}$, when *w* is slightly lower than w_{opt} for the respective CELs. Besides, with an increase in CEL, w_{opt} decreases and $[q_{max}]_{peak}$ increases, as indicated by a broken curve, and the values of w_{opt} and $[q_{max}]_{peak}$ are different among the different soil types. So, it is usually not simple to specify a relevant *w* value for field compaction.

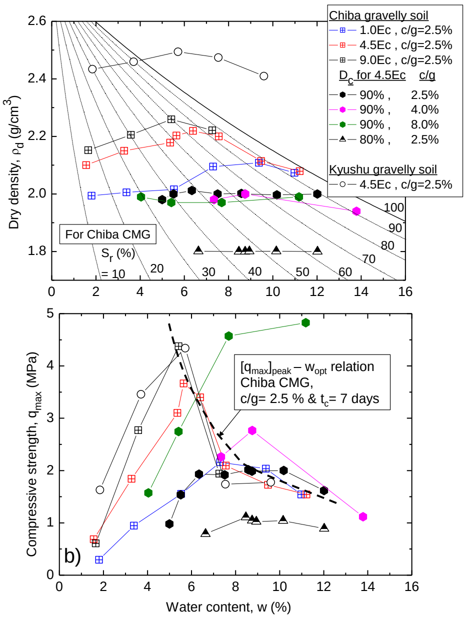


Figure 10. a) ρ_d - *w* curves (S_r contours for Chiba CMG); and b) q_{max} – *w* relations from drained TC (σ'$_c$= 20 kPa) of Chiba & Kyushu CMGs (t_c= 7 days) (Lohani et al. 2004, Kongsukprasert et al. 2005 & this study).

When uncemented, the optimum degree of saturation $(S_r)_{opt}$, at which $(\rho_d)_{max}$ is obtained at a given CEL, is insensitive to variations in CEL and soil type (Tatsuoka 2015). So, the abscissa of Figs. 10a & b was changed from *w* to S_r (Figs. 11a & b). The $(S_r)_{opt}$ values of Chiba CMG compacted at 1Ec, 4.5Ec & 9Ec are similar (≈ 70 %), while $[q_{max}]_{peak}$ is obtained when S_r= 60 – 70 %. Kyushu CMG (*c*/*g*= 2.5 % & 4.5Ec) also exhibits $[q_{max}]_{peak}$ when S_r= 60 – 70 %. Moreover, the q_{max} values of Chiba CMG with different *c*/*g* values compacted to $(D_c)_{4.5Ec}$= 90 % also exhibit a peak when S_r= 60 – 70 %.

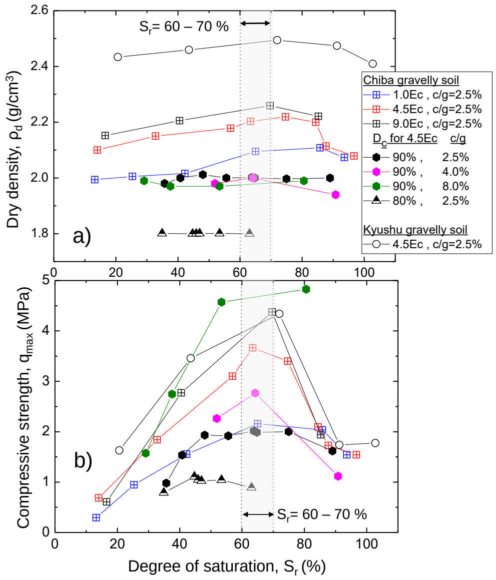


Figure 11. a) ρ_d - S_r curves; and b) q_{max} – S_r relations from drained TC (σ'_c= 20 kPa) of Chiba & Kyushu CMGs (t_c= 7 days).

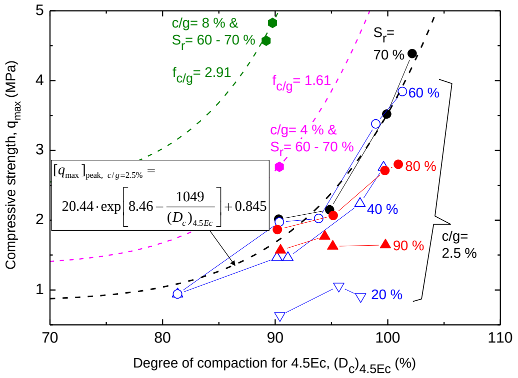


Figure 12. q_{max} – $(D_c)_{4.5Ec}$ relations for different values of S_r and c/g of Chiba CMG (t_c= 7 days).

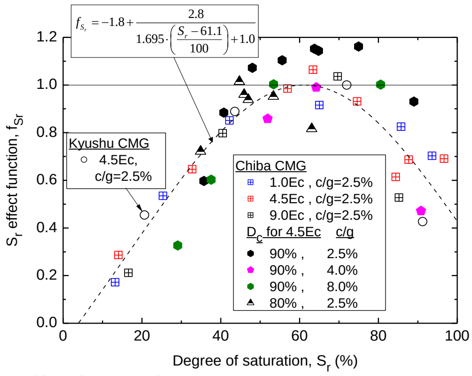


Figure 13. S_r effect function for Chiba & Kyushu CMGs (t_c= 7 days).

q_{max} (MPa) for different values of c/g (%) and S_r (%) when σ'_c= 20 kPa & t_c= 7 days (Fig. 11) was formulated as Eq. (1):

$$q_{max} = [q_{max}]_{peak,\ c/g=2.5\%} \cdot f_{c/g}(c/g) \cdot f_{S_r}(S_r) \qquad (1)$$

where $[q_{max}]_{peak,\ c/g=2.5\%}$ is the peak value of q_{max} (when S_r= 60 – 70 %) for c/g= 2.5 %. To this end, the values of q_{max} and ρ_d (thus $(D_c)_{4.5E}$) for different S_r values obtained from the relations shown in Figs. 11a & b were plotted in Fig. 12. The $[q_{max}]_{peak,\ c/g=2.5\%}$ - $(D_c)_{4.5E}$ relation for S_r= 60 – 70 % when c/g= 2.5 % was fitted by an equation shown in Fig. 12. The ratios of the values of $[q_{max}]_{peak}$ for c/g= 4 % and 8 % to the value when c/g= 2.5% for the same $(D_c)_{4.5E}$ are defined as the cement-mixing effect function $f_{c/g}$. The two top broken curves represent the $[q_{max}]_{peak,\ c/g=2.5\%} \cdot f_{c/g}$ – $(D_c)_{4.5E}$ relations for c/g= 4 % and 8 %.

In Fig. 12, for the same $(D_c)_{4.5E}$, the q_{max} value when c/g= 2.5 % decreases significantly as S_r increases and decreases from 60 – 70 %. The ratio of q_{max} for given values of S_r and c/g to the corresponding value of $[q_{max}]_{peak,\ c/g=2.5\%} \cdot f_{c/g}(c/g)$ is defined as the S_r effect function f_{Sr}. These ratios for the data shown in Fig. 11b are plotted against S_r (Fig. 13). With Kyushu CMG, the ratio was adjusted so that the peak value becomes 1.0. A nearly unique f_{Sr} – S_r relation is obtained. The relation is fitted by the equation presented in Fig. 13, which exhibits the peak of f_{Sr} when S_r= 61.1 %, slightly lower than $(S_r)_{opt} \approx$ 70 %. With an increase in S_r, the strength of cement paste decreases while its amount increases. It is likely that, when $S_r \approx (S_r)_{opt}$, not only $(\rho_d)_{max}$ but also the best combination of the strength and amount of cement paste is obtained. So, the q_{max} value is maximized when S_r becomes slightly lower than $(S_r)_{opt}$ irrespective of CEL and soil type.

5 CONCLUSIONS

The following conclusions were obtained. 1) The strength and stiffness of cement-mixed gravelly soil (CMG) prepared in the laboratory and in the field were consistent with each other. 2) The strength and stiffness of CMG increases by better compaction, particularly when the degree of compaction $(D_c)_{4.5Ec}$ becomes higher than about 95 %. 3) Irrespective of compaction energy level (CEL) and soil type, the strength exhibits a sharp peak when the degree of saturation S_r is slightly lower than the optimum degree of saturation $(S_r)_{opt}$, at which $(\rho_d)_{max}$ is obtained for a fixed CEL. So, S_r is one of the fundamental parameters for the strength and stiffness of CMG.

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