Strength properties of densely compacted cement-mixed gravelly soil

Propriétés de résistance des graves cimentées fortement compactées

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ABSTRACT: A series of drained triaxial compression tests (TC) were performed on specimens prepared in the laboratory and rotary core samples retrieved from the field of well-compacted cement-mixed gravelly soils (CMG). The effects of the following factors on the compressive strength q_{max} were evaluated: the degree of compaction D_c and cement content (when compacted at the optimum water content); the curing time; the grading characteristics of gravelly soil; and the specimen volume. The followings were found from the data for a wide variety of CMG having c/g= 2.0 ~ 6.0 % compacted by using two energy levels (1.0Ec & 4.5Ec). The effects of D_c are equally important as the cement content. An empirical equation is proposed using two independent variables, the soil skeleton porosity n_s, which controls the initial compressive strength, and the cement void ratio C_r, which controls the increasing manner of q_{max} with curing time. The effects of sieving method to obtain smaller particle materials for small TC specimens from an original gravelly soil having larger particles are not significant. However, significant effects of specimen volume (i.e., 72 mm x 72 mm in cross-section times 150 mm high versus 300 mm in diameter times 580 mm high) is highlighted.

RÉSUMÉ : Une campagne d'essais triaxiaux en compression a été réalisée sur des échantillons de grave, cimentée et compactée (GC), préparés en laboratoire mais également sur des échantillons carottés sur site. Les effets de différents facteurs sur les résistances en compression q_{max} ont été évalués : le degré de compaction D_c (teneur en eau de l'optimum Proctor), la teneur en ciment, le temps de cure; la distribution granulométrique et le volume de l'échantillon. Les tendances suivantes ont pu être relevées à partir de données expérimentales obtenues sur une grande variété de GC présentant différentes teneurs en ciment c/g= 2.0 ~ 6.0 % et compactées suivant deux modalités: normale et modifiée (1.0Ec & 4.5Ec). Il est apparu que les effets de la compaction ou de la teneur en ciment sur la résistance en compression étaient tout aussi importants. Une formulation empirique est proposée afin d'évaluer la résistance en compression à partir de deux variables indépendantes : la porosité du squelette n_s, qui contrôle la résistance initiale en compression, et la proportion du volume des vides occupée par le ciment C_r, qui contrôle l'augmentation de q_{max} avec le temps de cure. Les effets d'une réduction granulométrique ne sont pas significatifs. Cependant, les effets du volume de l'échantillon sont mis en évidence.

KEYWORDS: cement-mixed gravel, curing, triaxial compression, compaction, size effect

1 INTRODUCTION

Ground improvement by cement-mixing has been successfully used in many construction projects. This technology includes mixing-in-place of soft clay without compaction (i.e., the deep mixing method), under-water placing of cement-mixed soil slurry without compaction and highly compacted cement-mixed gravel for high roller-compacted concrete (RCC) dams. More recently, cement-mixed gravelly soil (CMG) compacted by energy lower than the one for RCC is used to construct bridge abutments for high-speed trains in Japan. Such use of CMG for deformation-sensitive structures as above has been motivated by a high cost-effectiveness. To develop the design and construction procedures, the stress-strain properties of CMG have been studied by many researchers (Lohani et al. 2004, Kongsuprasert & Tatsuoka 2005; Kongsukprasert et al. 2005, 2007; Tatsuoka et al. 2008, Ezaoui et al. 2010). Yet, the whole picture of effects of dry density, water content at compaction and cement content ratio on the strength and stiffness are not well understood (e.g., Horpibuslsuk et al. 2003; Consoli et al. 2007).

One of other practically important issues is the use of well-graded gravelly soil in the field with the maximum diameter exceeding 35 mm, which is too large to be tested by ordinary laboratory stress-strain tests, such as triaxial compression (TC) tests. For this reason, it is usually prepare materials for specimens for TC tests, for example, by sieving out large particles from a given original gravelly soil. So, it becomes necessary to evaluate the effects of grading characteristics (i.e., the particle size and the shape of grading curve) and the volume of specimen.

The present study aims at finding major factors that control the strength and stiffness of CMG for its proper and cost-effective use. In particular, to evaluate the effects of compacted degree of compaction, cement content, curing time, particle grading characteristics and specimen volume were evaluated, a comprehensive series of drained TC tests were performed.

2 EFFECTS OF SEVERAL FACTORS ON STRENGTH

2.1 *Specimens prepared in the laboratory*

The first TC series performed in the present study used SievedChiba Gravel (SCG in Fig. 1, crushed quarry sandstone comprising sub-angular particles). The TC specimens were rectangular prismatic (72 mm x 72 mm in cross-section times 150 mm high), for which a maximum particle size of 10 mm was selected. Fig. 2a shows compaction curves for standard and modified Proctor energy levels (1.0Ec= 550 kJ/m^3 and 4.5E$_c$) and cement/gravel ratio in weight c/g = 2.5 % and 4.0 % of SCG. ρ_{d_max}=2.12 g/cm^3 and w_{opt}= 9.3 % were obtained for 1Ec and ρ_{d_max}=2.21 g/cm^3 and w_{opt}= 7.4 % for 4.5Ec. Effects of cement-mixing on the compaction curves are negligible (Ezaoui et al., 2010). The TC specimens were produced by tamping moist cement-mixed gravelly soil immediately after adding water for respective optimum water contents w_{opt} to a degree of compaction D_c= 95 %, where D_c=$\rho_{d\_test}/\rho_{d\_max}$ x 100 % for 1.0E$_c$ or 4.5E$_c$ (Fig. 2a). The weight and height of each of the five sub-layers were carefully controlled. In the test results shown hereafter, vertical (axial) and horizontal (lateral) strains, ε_v and ε_h, measured locally with of a pair of vertical local deformation transducers (LDTs) arranged on two opposite lateral faces of specimen and horizontal LDTs arranged on the other two opposite lateral faces are presented.

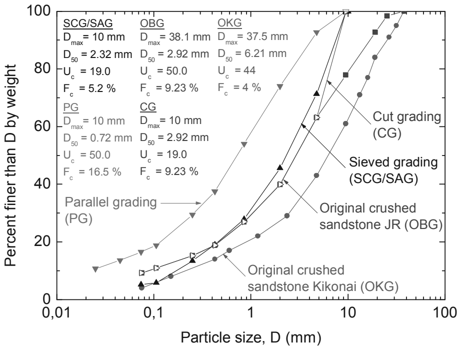
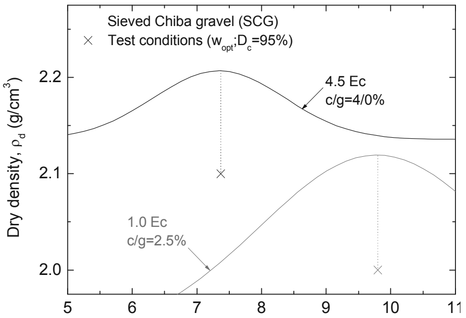
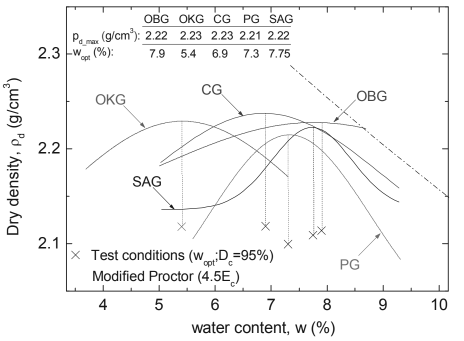


Figure 1. Grading curves and characteristics of the tested cement-mixed gravels



a)



b)

Figure. 2. Compaction curves: a) SCG for 1.0Ec & 4.5 E_c and c/g= 2.5% & 4/0 %; and b) five cement-mixed gravelly soils presented in Fig. 1 for 4.5Ec and c/g= 4.0% (except for PG and OKG)

Fig. 3 presents the development of the compressive strength q_{max} at confining pressure of 20 kPa with the period of initial curing under the atmospheric pressure at a constant water content (the same as prepared) of four kinds of SCG specimen prepared under different conditions (1.0E_c or 4.5E_c and c/g =2.5 or 4.0 %). The following trends can be noted. Firstly, the q_{max} value increases considerably with time, which should be due to the cement hydration process. The increase until a curing period of 14 days is rather proportional to the "initial" value at 7 days. Secondly, the q_{max} value is largely different among the four kinds of specimen (up to a factor of 100 %). Thirdly, the effects of compacted dry density ρ_d on the q_{max} value when c/g= 2.5 % are significant. An increase more than 100 % results from an increase in ρ_d of only about 5 % associated with an increase in the compaction level from 1E_c to 4.5E_c. On the other hand, when the compaction level is 1.0E_c, the q_{max} value increases by a factor of only about 40 % with an increase in c/g from 2.5 % to 4. 0% (i.e., an increase of about 60 %).

E_c and c/g are the parameters commonly used in practice, because they are easily measured and controlled. However, they are not the basic parameters that control the strength and deformation characteristics of CMG. This feature can be easily seen from the following inherent drawbacks (Watanabe et al. 2003, Kongsukprasert et al. 2005). Firstly, with materials having different specific density ρ_s, for the same c/g value and the same soil void ratio, the volume of cement per volume increases with an increase in ρ_s, despite that ρ_s has no direct effect on the stress-strain properties. Secondly, the effect of compaction level for the same c/g value (and same ρ_s) has two components: 1) a better interlocking among soil particles with a decrease in the soil void ratio; and 2) a larger amount of cement in a less volume of the total void of soil particle skeleton. Based on this consideration, two independent parameters are postulated: the soil skeleton porosity n_s (representing the structure of the skeleton of gravelly soil particles only); and the cement void ratio C_r (representing the fraction of the void of the soil skeleton occupied by cement):

$$n_s = \frac{V - V_s}{V} \tag{1}$$

$$C_r = \frac{V_c}{V_v} = \frac{V_c}{V - V_s} \tag{2}$$

where V is the total volume; V_s is the volume of gravelly soil particles; V_v is the volume of the void of the skeleton of gravelly soil ; and V_c is the volume of cement.

Ezaoui et al. (2011) also proposed the following hyperbolic function for the $q_{\max}$ value that increases with time and is a function of these two parameters independently:

$$q_{\max}\left(t_c\right) = q_0\left(n_s\right)\left[1 + \frac{a\left(C_r\right).t_c}{b + t_c}\right] \tag{3}$$

where t_c is the curing period; q_0 is the initial compressive strength (when t_c= 0) that decreases with n_s; a is the parameter showing the cementation effect that increases with C_r; and b is the constant parameter that depends on cement type. The functions $a(C_r)$ and $q_0(n_s)$ are obtained based on the data presented in Fig. 3 together with those from CD TC tests on rotary core samples retrieved from the field, as shown below.

Three solid lines presented in Fig. 4 denote the iso-strength lines for constant q_{max}=q_1, q_2 and q_3 at a specified t_c according to Eq. (3) with known values of q_0, a and b. The dash-dot curves are the corresponding c/g= constant curves. From such a plot as shown in Fig. 4, the most suitable (i.e., the most cost-effective) combination of (C_r; n_s) of a given type of CMG that achieves a given required compressive strength can be chosen referring to the cost for cement and compaction work.

2.2 *U tests on specimens made using a material use in the field*

The use of CMG is now spreading in Japan, particularly to construct bridge abutments for high speed train lines. Very recently, a geosynthetic-reinforced soil (GRS) integral bridge was constructed. The backfill immediately behind the facing is well-compacted cement-mixed gravelly soil. The grading curve of this backfill material (i.e., crushed gravel from a quarry, denoted as the Original Kikonai Gravel, OKG) is presented in Fig. 1. The compaction curve for 4.5E_c is presented in Fig. 2b. Before the construction, to determine the cement-mixing proportion, a series of U tests were performed on specimens mixed at c/g = 2.0, 4.0 and 6.0 %, compacted to D_c= 95 % at w= w_{opt} (4.5E_c) and cured for 7 and 28 days. To accommodate the maximum particle size of 37.5 mm, large specimens (150 mm in diameter and 300 mm in height) have been used.

To apply Eq. (3) to the data from these U tests, b=19.62 was used, which was obtained by analyzing a data set from a series of CD TC tests on cement-mixed SCG cured for a period of 1 ~ 180 days (Ezaoui et al., 2010, 2011). The values of $a(C_r)$ and $q_0(n_s)$ for the three c/g values and the two curing periods were determined from the reported values of $q_{\max}(t_c)$. They are plotted against their corresponding n_s and C_r values in Figs. 6a and b (round symbols). In so doing, to eliminate possible effects of specimen size and grading characteristics (discussed in the next section), these $q_{\max}$ values had been corrected to become the same values as those obtained for the smaller specimen (i.e., the data presented in Fig. 3) under the same test conditions (i.e., a curing period of 7 days; D_c= 95 %; and c/g= 4.0 %). Then, in Figs. 6a and b, only relative variations of q_0 and the parameter a due to variations in the n_s and C_r values among those U test specimens are highlighted. In these figures, the data points of SCG (square symbols) obtained from the data presented in Fig. 3 are also presented. It may be seen that these two sets of data, which are for the specimens compacted to the same D_c (i.e., 95 %) at the respective optimum water contents, are consistent with each other. Linear functions can be fitted to the q_0 - n_s and a - C_r relations with a small variance less than 10 %.

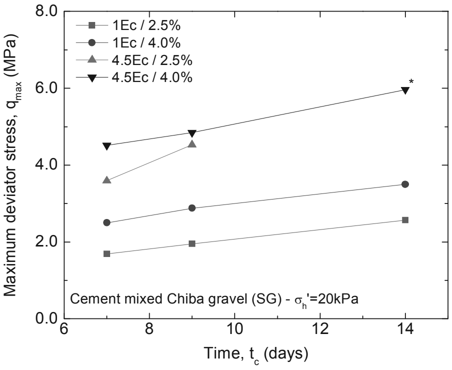


Figure 3. Development of compressive strength q_{max} with time t_c for different cement contents c/g and different compaction energy levels E_c (laboratory specimen of Sieved Chiba Gravel, SCG)

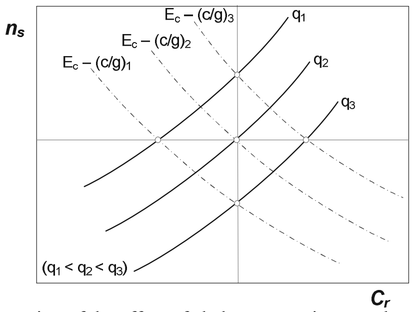


Figure 4. Illustration of the effect of skeleton porosity n_s and cement void ratio C_r on the compressive strength $q_{max}=q_{1,2,3}$

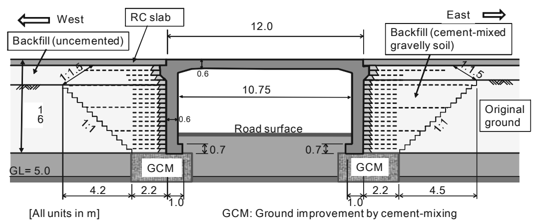


Figure 5. General structure (the width= 11.7 m) of the first prototype GRS integral bridge, for the new bullet train line at Kikonai, the south end of Hokkaido (by the courtesy of the Japan Railway Construction and Technology Agency), constructed in 2011 (Tatsuoka et al., 2012)

2.3 *TC tests on core samples retrieved from the field*

It is examined below whether the empirical relations shown in Figs. 6a and b can be applied to the data from CD TC tests on rotary core samples retrieved from the CMG backfill of the GRS integral bridge (Fig. 5). The backfill was compacted to D_c= 100 % (4.5Ec), higher than the laboratory-prepared specimens analyzed above, and at c/g= 3.0 %. The core samples were 80 mm in diameter and 160 mm or less in height. The q_{max} values evaluated by CD TC tests at confining pressure of 20 kPa are plotted against t_c (from the time of compaction in the field until respective TC tests) in Fig. 7. The data exhibit a large scatter, which is inevitable with such core samples from the field (e.g., Taheri et al., 2012). Yet, the trend that q_{max} increases with t_c is obvious. It may also be seen that, even at a relatively low c/g (= 3.0 %), the strength tends to exceed 10 MPa after t_c= three months, which is a nearly half of the strength of ordinary concrete. This property should be due to very high compaction (i.e., D_c= 100 % (4.5Ec) with $\rho_d \sim 2.23$ g/cm^3) achieved by field compaction. It is to be noted that very high stiffness values were measured with the two core samples cured for about 90 days presented in Fig. 7. That is, the small-strain Young modulus (at the isotropic stress-state) was about 35 GPa, which is the same order of magnitude as ordinary concrete. With these core specimens, n_s= 20.2 % and C_r= 9.3 % were obtained from ρ_d= 2.23 g/cm^3 and c/g= 3.0 %. Based on the respective linear relations presented in Figs. 6a and b, the parameters q_0 and a for Eq. (3) were evaluated by two methods:

<u>Method 1)</u>: By substituting n_s= 20.2 % into the linear relation in Fig. 6a, q_0= 1.61 MPa is obtained (i.e., a data point of triangular symbol 1), located on the linear relation). Then, by assuming the same coefficient b=19.62 as the laboratory-prepared specimens for Eq. (3) and using this q_0 value, an average relation is best-fitted to the data presented in Fig. 7. Then, a= 6.7 % is obtained for C_r= 9.3 % (i.e., a data point of triangular symbol 1) in Fig. 6b).

<u>Method 2)</u>: By substituting C_r= 9.3 % into the linear relation shown in Fig. 6b, a= 7.7 % is obtained (i.e., a data point of triangle symbol 2), located on the linear relation). Then, by assuming b= 19.62 as above for Eq. (3) and using this a value, an average relation is best-fitted to the data presented in Fig. 7 (which is eventually the same as the one obtained by Method 1)). Then, q_0= 1.43 MPa is obtained for n_s=20.2 % (i.e., a data point of triangular symbol 2) in Fig. 6a).

As seen from Figs. 6a and b, the results obtained by two methods are consistent. The results shown above indicate that Eq. (3) is relevant for various kinds of CMGs with different grading characteristics, different cement contents (c/g= 2.0 ~ 6.0 %) and a relatively wide range of compaction level (ρ_d= 2.0 ~ 2.23 g/cm^3).

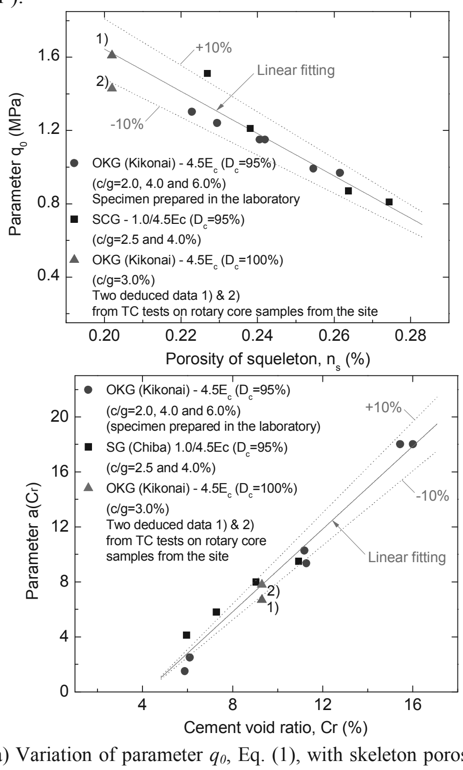


Figure 6. a) Variation of parameter q_0, Eq. (1), with skeleton porosity n_s and; b) variation of parameter C_r, Eq. (1) with cement void ratio C_r

3 EFFECTS OF SPECIMEN AND PARTICLE SIZES

The compressive strength at given confining pressure is also controlled by factors other than those analyzed in the section above, including: grading characteristics, such as the mean diameter d_{50} and the uniformity coefficient, fines content etc. (factor G); and the size of specimen (factor S) (Ezaoui et al., 2011). Two relevant parameters, among others, for factor S are: i) the particle/specimen size ratio (represented by the ratio of the specimen diameter D to d_{50}); and; ii) the specimen volume V.

Factors G and S may be different between the full-scale backfill and the one used in laboratory stress-strain tests.

To evaluate factors S and G, a series of drained TC tests were performed using small and large CMG specimens of the same gravelly soil but having four different grading curves, PG, SAG, CG and OBG shown in Fig. 1, produced from an original gravelly soil (OBG), a sub-angular crushed sandstone as Chiba gravel but from another quarry. Among these sieved materials, SAG was produced just by removing particles larger than 10 mm. The fact that SAG is easiest to produce is a strong advantage for the use in tests performed in practice. On the hand, PG is extremely time-consuming to produce, as a large amount of fine particles should be produced. So, the use of this material in practice cannot be recommended. The production of CG is intermediate. The compaction curves of these sieved materials are noticeably different due to different grading curves (Fig. 2b). The small specimens have the same size as those of which the data are presented in the preceding sections. The large specimens are 300 mm in diameter and 580 mm in height. All the specimens were prepared under the same conditions: i.e., *c/g*= 4.0 % and D_c= 95 % at the respective optimum water contents by 4.5E_c. As the ρ_{d_max} values of these sieved materials are nearly the same (Fig. 2b), the eventually obtained compacted dry densities are very similar.

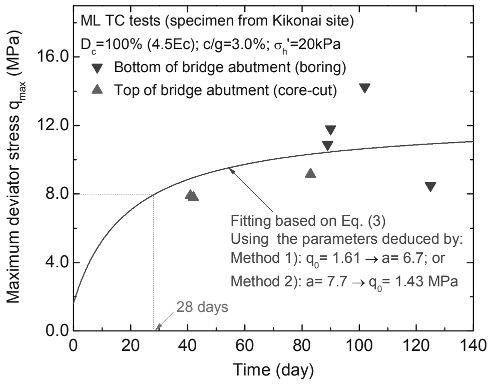


Figure 7. Compressive strength q_{max} versus total curing time for rotary core samples from the field (Kikonai GRS integral bridge) and fitting curve based on Eq. (3) with a set of deduced parameters (Fig. 6a and b)

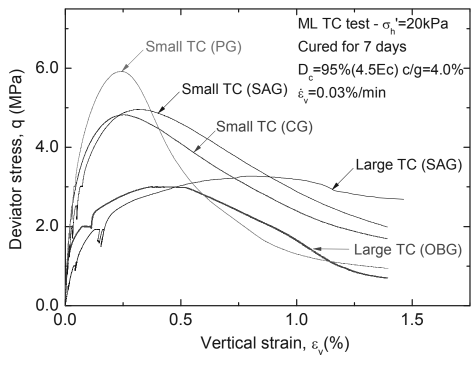


Figure 8. Deviator stress (q) – vertical strain (ε_v) relations from CD TC tests at σ_h'=20 kPa on small and large specimens having different types of cement-mixed gravel presented in Fig. 1

Fig. 8 shows the stress-strain curves at t_c= 7 days of the small and large specimens of SAG, CG and OBG. The effects of specimen size (factor S) are significant, while the effects of grading characteristics (factor G) are not so. It was found that there is no trend in the relationship between $q_{\max}$ and D/d_{50} (also with D/d_{max}). On the other hand, a well-defined trend exists in the relationship between $q_{\max}$ and the ratio of the specimen volume to the small specimen volume $V/V_{small\ TC}$ (Fig. 9): i.e., q_{max} decreases nearly 40 % with an increase in the specimen volume by a factor of nearly 50. This fact indicates that Eq. (3) should be modified to take into account this size effect. More research is necessary to examine whether this linear relation can be extended to volumes that exceeds the largest value examined in this study (such as field full-scale structures).

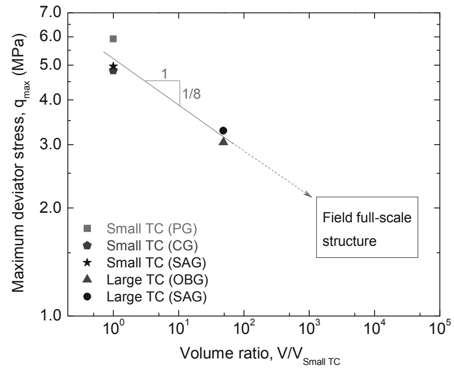


Figure 9. Compressive strength q_{max} (D_c= 95 % at 4.5Ec); *c/g*= 4.0%; & t_c=7 days) plotted against normalized volume by the volume of the small specimen $V_{Small\ TC}$

4 CONCLUSIONS

The following conclusions can be derived:

1. High compaction is very effective to obtain high strength of cement-mixed gravelly soil (CMG).
2. The porosity of the skeleton of gravelly soil only, n_s; and the fraction of the void of soil skeleton occupied by cement, C_r, are two major independent parameters for the strength of CMG. An empirical equation is proposed to predict the compressive strength of a given CMG based on a given initial compressive strength that is a function of n_s with an increase with curing time following a function of C_r.
3. Within the limit of test conditions in the present study, for the same degree of compaction at the respective optimum water contents with the same cement content, the effects of grading characteristics on the strength are not significant, while the effects of specimen volume are significant.

5 ACKNOWLEDGEMENTS

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