AGEING AND VISCOS EFFECTS ON THE DEFORMATION AND STRENGTH CHARACTERISTICS OF CEMENT-MIXED GRAVELLY SOIL IN TRIAXIAL COMPRESSION

LALANA KONGSUUKRASERT\(^{i}\) and FUMIO TATSUOKA\(^{ii}\)

ABSTRACT

To investigate ageing and viscous effects on the strength and deformation characteristics of densely compacted cement-mixed gravelly soil as well as their interactions, a series of drained triaxial compression (TC) tests were performed on moist specimens compacted at water contents close to the optimum, employing several specially designed loading histories. Ageing effects were evaluated by using specimens cured at unconfined conditions as well as different anisotropic TC stress conditions for different periods, while loading rate effects due to viscous property by changing stepwise the strain rate and applying drained sustained loading during otherwise monotonic loading (ML). The strength and pre-peak stiffness generally increased by ageing (i.e., curing in this case), like young concrete. Noticeable loading rate effects due to viscous effects were observed, of which the trend was rather independent of curing period (i.e., ageing period). When ML was restarted at the original strain rate following sustained loading at an anisotropic stress state, the material became very stiff in a relatively large stress range that developed by coupled effects of ageing and viscosity. For the same total ageing period until failure, the peak strength became larger when aged at a higher shear stress for a longer period when compared to the value predicted based on the peak strength when aged unconfined or confined without a shear stress. The viscous property was quantified. The basic features of viscosity were found to be similar to those of unbound granular materials.

Key words: ageing effect, cement-mixed gravelly soil, creep, deformation and strength, triaxial compression test, viscosity (IGC: D6/D7)

INTRODUCTION

The first new type bridge abutment comprising the backfill of highly compacted cement-mixed well-graded gravelly soil was successfully constructed in 2003 for a new bullet train line (Shinkansen) in Kyushu, Japan (Aoki et al., 2003; Watanabe et al., 2003b; Tatsuoka, 2004). To ensure that this new construction technology can satisfy the specified structural requirements (i.e., a high stability, in particular a high seismic stability, and a high rigidity with small residual deformation for a long life time), a high construction speed and a high cost-effectiveness, a series of technical investigations were performed. As part of those investigations, the influencing factors for the strength and deformation characteristics of cement-mixed gravelly soil both during construction (short-term) as well as after opening to service (long-term) were identified and their effects were evaluated (Watanabe et al., 2003a; Kongsukprasert and Tatsuoka, 2003; Lohani et al., 2004; Kongsukprasert et al., 2005).

The stress-strain behaviour of cement-mixed soil is highly time-dependent by two different factors, ageing and viscosity (e.g., Tatsuoka et al., 2000, 2001). The strength and the pre-peak stiffness of cement-mixed soil generally increase with time by positive ageing effects during curing, like young concrete. Consoli et al. (2000) showed that the effects of curing on the triaxial compressive strength of a soil derived from weathered granite that was lightly mixed with rapid-hardening Portland cement became larger when cured isotropically confined than when cured unconfined. However, the strength increase was not significant. Cement-mixed soil exhibits loading rate effects on the deformation and strength characteristics due to its viscous property, including the effects of strain rate on the stress-strain relation and peak strength, creep deformation and stress relaxation, like natural sedimentary soft rock (e.g., Hayano et al., 2001). The viscosity of unbound clay, sand and gravel (Di Benedetto et al., 2002; Tatsuoka et al., 2002; Tatsuoka, 2005) and sedimentary soft rock (Hayano et al., 2001) can be quantified from stress changes that take place upon a step change in the strain rate during otherwise monotonic
loading (ML) at a constant strain rate.

The stress-strain behaviour when these two factors (i.e., ageing and viscosity) are active is complicated. For example, when monotonic or cyclic loading at a constant strain rate was restarted after some period of sustained loading in drained triaxial compression (TC), cement-mixed sand (Barbosa-Cruz and Tatsuoka, 1999; Kong sukprasert and Tatsuoka, 2001) and cement-mixed soft clay (Sugai et al., 2003) exhibited a large stress range in which the stress-strain behaviour was very stiff, close to the elastic one. Moreover, the size of high-stiffness stress range was considerably larger than the one with unbound soils having no ageing property (e.g., young reconstituted clay and clean sand) under otherwise the same conditions. It has also been reported that a sand derived from weathered sandstone (Rotta et al., 2003) and kaolin (Deng and Tatsuoka, 2005), both lightly mixed with rapid-hardening Portland cement, exhibited a similar large expansion of high-stiffness stress range when ML was restarted after sustained loading in, respectively, isotropic and one-dimensional compression. The authors also found by a preliminary investigation (Kongsukprasert and Tatsuoka, 2003) that it was also the case with densely compacted cement-mixed gravelly soil in drained triaxial compression. This trend in behaviour described above is one of the important advantages for the use of densely compacted cement-mixed gravelly soil as the backfill for transportation structures, such as bridge abutments, that should support safely traffic load for a long duration. This is because, after a certain period, the behaviour under such traffic loading conditions becomes essentially elastic with a high stiffness exhibiting negligible residual deformation.

With respect to the viscous property (excluding the effects by delayed dissipation of excess pore water pressure) of geomaterial, a tremendous amount of experimental research has been performed so far, which includes those on the viscous property of granular material (e.g., Murayama et al., 1984; Mejia et al., 1988; Yamamuro and Lade, 1993; Nakamura et al., 1999; Lade and Liu, 1998, 2001; Kuwano and Jardine, 2002; Nawir et al., 2003a, b; Tatsuoka et al., 2004). The viscous properties of so-called ‘young’ and ‘aged’ geomaterials were studied by a number of researchers, as summarized by Tatsuoka et al. (1999a, 2000, 2001; Augustesen et al., 2004). In comparison, experimental study on the effects of both ageing and viscosity on the stress-strain behaviour of geomaterials as well as their interactions has been very limited (e.g., Leroueil and Marques, 1996; Vaughn, 1997; Leroueil and Hight, 2002; Kongsukprasert and Tatsuoka, 2003; Sugai et al., 2003). In addition, a number of constitutive models accounting for the viscous property for geomaterial have been proposed (e.g., Adachi et al. 1996; Vermeer and Neher, 1999; Imai et al., 2003; Oka et al., 2003). However, the study on constitutive modeling incorporating the effects of both ageing and viscosity and their interactions is few (e.g., Tatsuoka et al., 2003; Di Benedetto et al., 2004).

In view of the above, a comprehensive series of consolidated drained (CD) triaxial compression (TC) tests were performed using densely compacted specimens of a cement-mixed well-graded gravelly soil, as used in the field, employing several loading histories designed to separate the effects of ageing and viscosity while identifying their interactions.

**TIME EFFECT: DEFINITIONS AND ILLUSTRATIONS**

Changes in the stress-strain behaviour of geomaterial (i.e., soil and rock) with time are usually termed “the time effect”. The time effect consists of the following two components: ageing effect and loading rate effect (or viscous effect), which result from different physical mechanisms (Table 1):

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Mechanism and material property</th>
<th>Major parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ageing</td>
<td>Time-dependent: Changes with time in the material property, e.g., cementation, weathering, etc.</td>
<td>Time with a fixed origin (t_0)</td>
</tr>
<tr>
<td>Loading rate effect</td>
<td>Rate-dependent: Response of a material due to its viscous property</td>
<td>Irreversible strain (\varepsilon'')</td>
</tr>
<tr>
<td>(effect of strain rate, creep, stress relaxation, etc.)</td>
<td></td>
<td>6 a mean for an engineering period</td>
</tr>
</tbody>
</table>

a) Ageing effect is herein defined as changes with time in the intrinsic stress-strain property (including elasticity, plasticity and viscosity). Typical positive and negative ageing effects are cementation and weathering. The relevant variable to describe this component is the time having a specific origin (not the general time) or any relevant parameter in physical or chemical terms directly representing the ageing process.

b) Loading rate effect is herein defined as a time-dependent stress-strain response of a given type of geomaterial due to the viscous property, including effects of strain rate on the stress-strain relation, creep deformation and stress relaxation. The relevant variable to describe this component is the irreversible (or inelastic or visco-plastic) strain rate, while any constitutive model using the general time to describe the viscous property cannot be objective (e.g., Tatsuoka et al., 2000, 2001).

Figure 1(a) shows the relationships between the deviator stress and the axial strains that would be obtained by conceptual CD TC tests following the different loading histories shown in Fig. 1(b), designed to highlight the ageing and viscous effects and their possible interactions.
Suppose that, in tests (1), (2), (3), (4), (6) and (7), ML is performed at the same relatively high strain rate while ML in tests (5) and (8) at the same relatively low strain rates. It is herein assumed that, when the stress-strain behaviour from test (1) is compared with the one from another test, the geomaterials used in test (1) and the concerned test have the same stress-strain property including the viscous and ageing properties.

In test (1), a geomaterial is subjected to continuous ML without any sustained loading either at the origin (with zero deviator stress) nor at an intermediate stage (with a non-zero deviator stress).

In test (2), a geomaterial having ageing property, which may or may not have viscous property, is subjected to ML at the same relatively high strain rate as test (1) after some period of sustained loading at the origin. The difference between the stress-strain relations in tests (1) and (2) is defined as to the ageing effect that develops at the origin (as in test (2)).

In test (3), a geomaterial having ageing property but not viscous property is subjected to sustained loading after having reached state a during otherwise ML at the same relatively high strain rate as in tests (1) and (2). The duration of sustained loading is the same as the one at the origin in test (2). No creep deformation takes place during the sustained loading, without the stress-strain state moving from state a. The difference between the stress-strain relations after ML is restarted from state a in tests (3) and (1) is defined as the ageing effect that develops during the sustained loading at state a in test (3). The subsequent stress-strain relation in test (3) rejoins the one in test (2) when the geomaterial has no viscous property in test (2) as in test (3).

In test (4), a geomaterial having viscous property but not ageing property is subjected to sustained loading from state a until state b' for the same duration as the sustained loading at the origin in test (2). Creep deformation takes place during the sustained loading due to the viscous property. Due to the effects of positive ageing effects, however, the total creep deformation is smaller than the one in test (4) (without ageing effects) (Tatsuoka et al., 2003). It is assumed that the geomaterial in test (2) has the same ageing and viscous properties as those in test (6). It is considered that there is no interaction between the ageing and viscous effects. Then, the stress-strain relation after the restart of ML at the original constant strain rate from state b' eventually rejoins the one from test (2). This is the case with lightly cemented kaolin in CD TC (Komoto et al., 2004).

In test (7), a geomaterial having both ageing and viscous properties is subjected to sustained loading from state a until state b' as in test (6). It is assumed that the geomaterial in test (2) has the same ageing and viscous properties as those in test (7). It is considered that there are significant positive interactions between the ageing and viscous effects in test (7). Then, the stress-strain relation in test (7) after the restart of ML from state b' over-shoots the one from test (2) and exhibits the peak strength that is larger than the one for the same total ageing period in test (2). It is shown later in this paper that this is the case with the densely compacted cement-mixed well-graded gravelly soil tested in the present study.

In test (8), a geomaterial having both ageing and viscous properties is subjected to ML at a low strain rate as test
called model Chiba gravel, has a specific gravity $G_s$ equal to 2.74. Due to a relatively long period of the research program (for about six years), eventually five different batches, approximately 200 kg each, were used (Fig. 2). Batch No. 1 was used in the tests named with a single initial ‘J’ as well as in tests JA001 – JA004 and tests JS001 – JS002, while batch No. 2 in the rest of the tests named with initials ‘JA’, ‘JS’ and ‘SR’; and batch Nos. 3, 4 and 5 in the tests named with the initials ‘SP’, ‘MR’ and ‘RD’, respectively. The results from tests RD will be reported in Kongsukprasert and Tatsuoka (2005). Effects of using different batches on the test results were generally small, as described later in this paper. Ordinary Portland cement with $G_s=3.16$ obtained from a single bag of 20 kg kept in an airtight container was used throughout the present study.

**Specimen Preparation**

Compaction tests were performed on batch No. 1 using a mould with an inner diameter of 10 cm and an inner volume of 1,000 cm$^3$ at an energy level $E_0=550$ kJ/m$^3$ (the standard Proctor). The optimum water contents, $w_{opt}$, for the original material (without cement) and the cement-mixed material (with a cement-to-gravel ratio by dry weight $c/g=2.5\%$) were essentially the same, equal to about 8.75% (Fig. 3).

Each specimen was prepared by mixing a relevant amount of gravelly soil with a prescribed amount of cement powder to attain the respectively specified $c/g$ value and then with a relevant amount of water to attain an initial water content, $w$, in the ratio to the dry weight of solid (soil plus cement), equal to $w_{opt}$ for $E_0 = 8.75\%$. The mixture was kept in a closed container during the whole subsequent preparation process, within 25 – 35 minutes, to prevent excessive changes in the water content. The specimen was compacted manually in five even layers in a rectangular prismatic mould (95 mm × 95 mm × 190 mm) to the respective target compacted dry density of solid ($\rho_d$). The compacted specimens were cured being sealed inside the compaction mould under the atmospheric pressure at constant water content in a temperature-controlled room (25 °C) for five days. When
the initial curing period, $t_{cu}$, which is defined as zero at
the start of compaction, was longer than five days, the
specimens were removed from the mould and wrapped
with a piece of kitchen wrapping plastic sheet for further
curing at constant water content under the atmospheric
pressure at constant water content. The specimen was
subjected to CD TC loading at the water content when
prepared and cured, without water-saturation.

**Triaxial Compression Testing Procedures**

An automated triaxial test apparatus was used. To
achieve prescribed complicated loading histories,
displacement-controlled axial loading was performed
using a precision gear system that can respond sharply to
control signals from a computer without allowing any
noticeable backlash at load reversal (Tatsuoka et al.,
1994, 1999a; Santucci de Magistris et al., 1999). Axial
strains were sensitively and accurately measured by using
a pair of 160 mm-long longitudinal LDTs (Goto et al.,
1991) set on the opposite side faces of the specimen (refer
to Fig. 9 in Kongsukprasert et al., 2005). When the effective
confining pressure is changed, lateral strains of a stiff
material locally measured in the direction perpendicular
to the specimen side face could be largely over-estimated
due to the effects of membrane penetration and bedding
error (Hayano et al., 1997). To alleviate this problem,
rectangular prismatic specimens were used, instead of
cylindrical ones, and local lateral strains were measured
in the direction in parallel to the specimen side face with
three pairs of 70 mm-long lateral LDTs set at 5/6, 3/6
and 1/6 of the specimen height on the opposite specimen
side faces. Isotropic deformation in the horizontal planes
was assumed to obtain average local lateral strains from
the readings of the lateral LDTs. The stress-strain behav-
ior obtained from CD TC tests on cement-mixed sand
with this setup in which the effective lateral pressure was
changed is reported in Kongsukprasert et al. (2001).

The specimen was isotropically consolidated to a con-
fining pressure ($\sigma_3$) equal to 19.8 kPa by means of partial
vacuum and cured for one hour unless otherwise specified
before starting drained ML in drained TC at constant $\sigma_3$
($= 19.8$ kPa). The axial strain rates reported in this paper
are those obtained from the displacement rates of the
loading piston. The locally measured axial strain rates
were smaller to varying extents than these values due to
system compliance and bedding error. In many of the TC
tests, at a number of arbitrary stress states during
otherwise ML, sustained loading, step changes in the
axial strain rate and one or five small unload/reload
cycles with a single axial strain amplitude of about
0.005% were applied to evaluate viscosity and elasticity at
each stress state. The small strain stiffness from these
tests will be reported by Kongsukprasert and Tatsuoka
(2005).

### Table 2. Test conditions and part of results from CD TC tests to evaluate the effects of initial curing

<table>
<thead>
<tr>
<th>Series</th>
<th>Test</th>
<th>Batch no.</th>
<th>$w_r$ (%)</th>
<th>$\rho_d$ (g/cm$^3$)</th>
<th>$c/g$ (%)</th>
<th>Initial curing period, $t_{cu}$ (day)</th>
<th>Total curing period$^1$ (days)</th>
<th>$E_{0.05}$ (GPa)</th>
<th>$E_5$ (GPa)</th>
<th>$q_{max}$ (kPa)</th>
<th>$e_{0.05}$</th>
<th>$e_{max}$ (%)</th>
<th>$E_0/q_{max}$</th>
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<td>1</td>
<td>8.746</td>
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<td>2.000</td>
<td>7.04</td>
<td>7.07</td>
<td>3.19</td>
<td>5.33</td>
<td>1987.6</td>
<td>0.312</td>
<td>2.68E+03</td>
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<td></td>
<td>J016</td>
<td>2</td>
<td>8.709</td>
<td>2.000</td>
<td>2.491</td>
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<td>13.96</td>
<td>5.15</td>
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<td>J002</td>
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<td>30.08</td>
<td>5.20</td>
<td>7.35</td>
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<td>2.79</td>
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<td>1.04</td>
<td>0.81</td>
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<td>1030.7</td>
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<td>2.500</td>
<td>3.09</td>
<td>3.12</td>
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<td>7.11</td>
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<td>MR004</td>
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<td>2.100</td>
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<td>3.19</td>
<td>1.89</td>
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<td>8.747</td>
<td>2.100</td>
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<td>MR003*</td>
<td>4.</td>
<td>8.778</td>
<td>2.099</td>
<td>2.508</td>
<td>59.67</td>
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<td>4700.0</td>
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*$^1$ The total curing period until the peak stress state.
* The compressive strength, $q_{max}$, was inferred from the stress-strain curve not reaching the peak strength.

![Fig. 3. Compaction curves of model Chiba gravel with and without cement content ($c/g = 2.5\%$), batch No. 1 (Kongsukprasert et al., 2005)](image-url)
EFFECTS OF INITIAL AGEING UNDER ATMOSPHERIC PRESSURE

To evaluate the basic effects of initial unconfined curing on the strength and deformation characteristics, a series of CD TC tests were performed at an axial strain rate, $\dot{\varepsilon}_a$, equal to 0.03%/min on specimens having different cement contents, $c/g$, and dry densities of solid, $\rho_d$, all compacted at $w_i = w_{opt} = 8.75\%$, that were aged for different periods of initial curing, $t_{ini}$, under the atmospheric pressure (Table 2). Figures 4(a) and 4(b) show the test results for $\rho_d = 2.0 \text{ g/cm}^3$ and $c/g = 2.5\%$, while Fig. 4(c) for $\rho_d = 2.0 \text{ g/cm}^3$ and $c/g = 4.0\%$; and Fig. 4(d) for $\rho_d = 2.1 \text{ g/cm}^3$ and $c/g = 2.5\%$, where $q$ is the deviator stress, $\sigma'_a$ (effective axial stress) $- \sigma'_c$ (effective confining pressure). Figures 5(a), 5(b) and 5(c) show the relationships between the compressive strength, $q_{max}$, and the initial curing time, $t_{ini}$. The $q_{max}$ values when $t_{ini} = 60$ days of series 3 and 4 presented in Figs. 5(b) and 5(c) were inferred from the stress-strain curves not reaching the peak stress state due to a limited loading capacity (50 kN) of the apparatus. The $q_{max}$ value at $t_c = 30$ days of series 2 presented in Fig. 5(a) was inferred from the linear ($q_{max}$) and log ($t_c$) relation fitted to the data at $t_c = 14$ and 60 days presented in Fig. 5(c). The following trends in behaviour may be seen from these figures:

1) The effects of different batches are insignificant (Figs. 4(a), 4(b) and Fig. 5).

2) The average stiffness in the pre-peak stress regime (i.e., pre-peak stiffness) and the peak strength...
increase significantly with $t_{\text{ini}}$, like young concrete.

3) The pre-peak stress-strain relation becomes more linear with an increase in $t_{\text{ini}}$, particularly at $t_{\text{ini}}$ larger than 7 days.
4) The axial strain at peak deviator stress is rather independent of $t_{\text{ini}}$, after initial curing for $t_{\text{ini}}=37$ days.
5) The effects of $t_{\text{ini}}$ on the pre-peak relationship between the volumetric strain, $\varepsilon_{\text{vol}}$, and the axial strain, $\varepsilon_a$, are not obvious.
6) The effects of $t_{\text{ini}}$ on the post-peak $q-\varepsilon_a-\varepsilon_{\text{vol}}$ relations are not systematic, which is likely due to unsystematic development of shear band(s) in the post-peak regime.

It is shown in the next section that the pre-peak stress-strain behaviour and the peak strength are not uniquely controlled by the total curing period (i.e., the total ageing period) but could be largely affected by the interactions between ageing and viscous effects during the loading process.

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**INTERACTIONS BETWEEN AGEING AND VISCOUS EFFECTS**

**Effects of Sustained Loading at an Anisotropic Stress State**

To evaluate the effects of sustained loading at an anisotropic stress state on creep deformation and subsequent stress-strain behaviour, tests J002, J017 (Table 2) and JA003 (Table 3) were performed ($\sigma' = 19.8$ kPa, $w_i = 8.75\%$, $q_0 = 2.0$ g/cm$^3$ and $c/g = 2.5\%$). The test results are presented in Figs. 6(a) and 6(b). In these and similar figures, the strains were defined zero at the start of drained TC loading, where $q = 0$. The results from continuous ML TC tests J002 ($t_{\text{ini}} = 30$ days) and J017 ($t_{\text{ini}} = 60$ days) presented in Figs. 6(a) and 6(b) are the same as those presented in Fig. 4(a). In test JA003, after initial curing for $t_{\text{ini}} = 37$ days, the specimen was subjected to drained ML at $\varepsilon_a = -0.03\%/\text{min}$ and then drained sustained loading at $q = 2$ MPa for 30 days. Subsequently, to evaluate the extent of high-stiffness region, relatively large unloading was made at $\varepsilon_a = -0.03\%/\text{min}$ before ML towards ultimate compressive failure was restarted at the original axial strain rate, $\varepsilon_a = 0.03\%/\text{min}$. In Figs. 6(a) and 6(b), the stress-strain relations for continuous ML when $t_{\text{ini}} = 37$ and 67 days that were deduced from the measured stress-strain relations from continuous ML when $t_{\text{ini}} = 30$ and 60 days are also presented. These deduced relations were obtained by linear interpolation assuming that the stress at the same strain increases linearly with elapsed time within the respective concerned period of curing. The time histories of axial, lateral, shear and volumetric strain increments during the sustained loading at $q = 2$ MPa in test JA003 are presented in Fig. 6(c). In Fig. 6(d), the values of peak-to-peak secant Young's modulus, $E_{\text{eq}}$, from the respective single small unload/reload cycle applied before and after the sustained loading are plotted against the $q$ value from which the respective unloading was made. The following trends in behaviour in test JA003 may be seen from these figures:

1) The specimen exhibited noticeable creep axial strains only for a very short duration immediately after the start of sustained loading at $q = 2$ MPa, which is due to the viscous property of the material. The flow characteristics during this very short period follow the one during continuous ML (Fig. 6(b)). However, as seen from Fig. 6(c), subsequently, the creep axial strain rate started decreasing rapidly and then became nearly zero. With unbound granular materials, the increase in the creep axial strain continues for a much longer period under the similar sustained loading conditions (e.g., Di Benedetto et al., 2002; Tatsuoka et al., 2002). It is likely that this trend of very early cease of creep axial straining, seen from Fig. 6(c), is due to effects of a kind of structuration associated with the development of cementation during the sustained loading, as noted by a significant increase in the $E_{\text{eq}}$ value by the sustained loading (Fig. 6(d)). Tatsuoka et al. (2003) explained...
this trend in behaviour by the development of the yield stress for the inviscid stress-reversible strain relation due to ageing effects during sustained loading.

2) The specimen width started contracting after the major creep strain has taken place for a very short duration following the start of sustained loading, which resulted in a volume contraction and a decrease in the shear strain with time, although they are very small. The flow characteristics at this later stage of sustained loading do not follow the one during ML at a constant strain rate (Fig. 6(b)). This peculiar behaviour was observed in all the other similar tests (as shown later in this paper). It appears that this phenomenon is linked to the time-dependent chemical effects of hydration process of cement consuming pore water (as part of the ageing effects), which resulted in the shrinkage of the fabric of soil particles.

3) When unloading was started and then ML towards ultimate compressive failure was restarted following the sustained loading at \( q = 2 \ MPa \) in test JA003, the specimen exhibited nearly elastic behaviour in a relatively large stress range extending to deviator stresses not only below the sustained stress but also above. The reloading curve then exceeded the stress-strain relation for continuous ML when \( t_{ini} = 37 \) days and further the one when \( t_{ini} = 67 \) days, which are equal to, respectively, the total curing times at the start and end of the sustained loading in test JA003. The development of a large high-stiffness stress range by sustained loading is due to combined effects of ageing and viscosity. Without ageing effects, a high-stiffness stress range develops only by viscous effects (i.e., the 'apparent' ageing effects, Table 1) and its size is much smaller. Subsequently, the specimen exhibited clear yielding and then a peak strength that was noticeably higher than the value for the same total curing period \( t_{ini} = 67 \) days obtained by continuous ML from the origin (\( q = 0 \)).

The development of a high-stiffness stress range by sustained loading that is considerably larger than the one in the case without ageing effects has also been observed with cement-mixed poorly graded sand in CD TC (Barbosa-Cruz and Tatsuoka, 1999) as well as with lightly cemented kaolin in CD TC (Komoto et al., 2004) and in one-dimensional compression (Deng and Tatsuoka, 2005; Tatsuoka, 2005). It seems therefore that this trend in behaviour, seen in Figs. 6(a) and 6(b), is general when ageing effects are active during sustained loading.

## Effects of Shear Stress Level and Duration of Sustained Loading

To evaluate the effects of shear stress level and duration of drained sustained loading on the creep deformation property and subsequent stress-strain behaviour, two series of CD TC tests, named JAS and SP, were performed (see Table 3). The loading paths are shown in Figs. 7(a) and 7(b). The curing time is defined zero at the start of compaction, as mentioned earlier. The two extremely slow CD TC tests depicted in Fig. 7(a) are explained later in this paper. The specimens of JAS series (Fig. 7(a)) were firstly subjected to the nearly same initial ageing history (i.e., \( t_{ini} = 7 \) days, or close to it, under the atmospheric pressure and one hour of isotropic consolidation at \( q' = 19.8 \) kPa) and then TC loading at \( \gamma = 0.03\% \) with the following drained sustained loading histories:

1) in tests JA005, JA001, JA010 and JA007, a single sustained loading stage for 65 hours was applied at \( q = 0, 1.0 \) MPa, 1.25 MPa and 1.5 MPa, respectively;
2) In test JA004, four multiple sustained loading stages were applied at \( q = 1.0 \) MPa and \( 1.25 \) MPa (each for 21 hours and 40 minutes), 1.5 MPa for 13.5 hours and 1.75 MPa for 8 hours and 10 minutes.

The stress-strain relations from tests J and JA (Fig. 7(a)) are presented in Fig. 8. The results from tests SP (Fig. 7(b)) will be reported in Kongsukprasert and Tatsuoka (2005). In Fig. 8, the stress-strain curves from continuous ML tests JA016 and J016, in which the specimen was initially cured for, respectively, \( t_{c1} = 7 \) days (equal to the initial curing period for the TC tests with sustained loading at anisotropic stress states described in this figure) and \( t_{c2} = 14 \) days (longer than the total curing time, \( t_c \), at the peak stress state for most of the TC tests described in this figure) are also presented as a reference. Note that a small segmental unloading stress-strain relation seen at the end of the respective sustained loading stage was obtained by applying a unload/reload cycle with a small strain amplitude to evaluate the elastic property. Similar unload/reload cycles were applied at other moments during otherwise ML at a constant strain rate. In Figs. 7(a) and 7(b), the end point of the respective loading history path represents the peak stress state. A solid line in each of Figs. 7(a) and 7(b) represents the relationship between the \( q_{max} \) value and the total ageing time at peak, \( t_c \), when subjected to continuous ML at \( \varepsilon_a = 0.03\% / \min \) until the peak stress. These data were obtained from, respectively, the results presented in Fig. 4 and those from other similar tests performed under the test conditions for SP series. The part for \( t_c \) larger than 14 days of the \( q_{max} - t_c \) curve when Cured Only Unconfined presented in Fig. 7(b) is the one inferred as explained earlier related to Fig. 5(a). The following trends in behaviour may be seen from Fig. 8:

1) A large high-stiffness stress range developed by the respective drained sustained loading history at an anisotropic stress state in the same manner as seen in Figs. 6(a) and 6(b).

2) It may be seen by careful examination of the data that the size of high stiffness stress range increased with an increase in the sustained loading period. However, the effects of shear stress during sustained loading on the size are not very obvious. It was also the case with cement-mixed poorly graded sand.
Fig. 7. Loading histories for TC tests ($\sigma_0 = 19.8 \text{kPa}$) to evaluate effects of shear stress level and duration of drained sustained loading on the subsequent stress-strain behaviour: a) JAS series and b) SP series

(Barbosa-Cruz and Tatsuoka, 1999) and cement-mixed kaolin (Komoto et al., 2004). On the other hand, the development of a high stiffness stress range is not significant when cured confined at $q = 0$ (test JA005). Therefore, when dealing with the whole pre-peak stress range, the effects of shear stress during sustained loading on the size of high-stiffness stress range cannot be ignored. A more detailed analysis is shown later in this paper.

3) Creep strain increments for the same duration of sustained loading increased with an increase in the deviator stress at sustained loading.

4) In all the tests with a single or multiple sustained loading stages at anisotropic stress states, the stress-strain relation after the restart of ML at the original strain rate following the respective sustained loading stage overshot the one for the same total curing period obtained by continuous ML from the origin ($q = 0$), in a similar way as the test results presented in Figs. 6(a) and 6(b). Moreover, by sustained loading at an anisotropic stress state, the peak strength became larger than the value for the same total curing period when subjected to continuous ML. This trend can be clearly seen also from Figs. 7(a) and 7(b). The trend that both of the amount of stress-overshooting and the additional gain of the $q_{\text{max}}$ value by sustained loading at an anisotropic stress state increased with an increase in the shear stress level and the duration of sustained loading under otherwise the same conditions is analysed below.

5) In the post-peak stress-strain regime, as far as ML at a constant strain rate continued, the stress increment additionally gained by sustained loading at an anisotropic stress state in the pre-peak regime gradually decreased with an increase in the strain and finally vanished. This trend can also be seen from Fig. 6(a).

Such an increase in the stress overshooting with an increase in the shear stress during sustained loading as described above may be due to that the structure of soil particles that has been modified to resist more efficiently against the applied deviator stresses that has increased until the present moment is reinforced by cementation developed at the inter-particle contact points during sustained loading. Then, as the stress state at sustained loading becomes closer to the peak stress state, the chance for the reloading stress-strain relation to be still overshooting the peak stress state obtained by continuous ML increases, resulting in a higher peak strength than the value when ML at a constant strain rate continues until the peak stress state. A gradual loss of the overshooting stress during subsequent ML at a constant strain rate in the post-peak strain-softening regime may be due to damage by large irreversible strains to the structure that was additionally developed by sustained loading at an anisotropic stress state. On the other hand, the peak strength for the same curing period did not increase noticeably by drained sustained loading at an anisotropic stress state in the CD TC tests on cement-mixed poorly graded sand (Barbosa-Cruz and Tatsuoka, 1999) and cement-mixed kaolin (Komoto et al., 2004). That would be due to the fact that the strain increment between the end of the sustained loading and the peak stress state were relatively large in those tests and therefore some large damage to the structure of soil particles may have taken place before reaching the peak stress state. It is to be noted that another factor for the gradual loss of the overshooting stress with an increase in the irreversible strain is the specific viscous property called the TESRA viscosity, explained later in this paper.

Very Slow Monotonic Loading Tests
To examine whether significant ageing effects can develop also during very slow ML, two CD TC tests, JS008 and JS009, were performed at very low average axial strain rates (basically 0.0001% /min) on specimens initially cured unconfined for $t_{\text{eq}} = 7$ and 8 days (Table 3). Their loading paths are presented in Fig. 7(a). The total duration between the start of TC loading from $q = 0$ and the peak stress state was about 8 days (test JS008) and 6 days (test JS009). The overall stress-strain relations are presented in Fig. 9 while some typical local relations for different small strain ranges in Figs. 10(a) through 10(d). In test JS009, the axial strain rate, $\dot{e}_a$, was changed step-
Fig. 8. Effects of sustained loading at different shear stress levels and for different durations during otherwise ML (series JAS, \(\sigma'_a = 19.8\) kPa): stress-strain relations at small strains from a) continuous ML tests and tests with a single sustained loading stage and b) continuous ML tests and test JA004.

In Fig. 9, the stress-strain relations from continuous ML tests JA016 and J016, which were performed at a much faster \(\dot{\varepsilon}_a(=0.03\%/\text{min})\) on the specimens with \(t_{\text{mu}} = \) respectively 7 days (equal to or close to the \(t_{\text{mu}}\) value at the start of very slow TC loading) and 14 days (similar to the total curing period, \(t_c\), at the peak stress state in the two very slow loading tests) are presented for a reference. In Figs. 9 and 10, \(x\) denotes the basic axial strain rate, equal to 0.03\%/min.

The following trends in behaviour may be seen from Figs. 9 and 10:

1. Despite the same total curing period, the peak strengths in tests JS008 and JS009 performed at very low \(\dot{\varepsilon}_a\)s at the peak stress state (= 0.0003\%/min in test JS008 and 0.0001\%/min in test JS009) were significantly higher than those when subjected to continuous ML at a much higher axial strain rate, \(\dot{\varepsilon}_a = 0.03\%/\text{min}\) (see also Fig. 7(a)). This result indicates that significant ageing effects developed in these two very slow loading tests and they resulted into an additional strength gain when compared to the case of continuous ML at a higher \(\dot{\varepsilon}_a\). This issue is analysed in the next section.
2) Significant ageing effects during very slow ML can also be seen in Fig. 10. That is, the q value suddenly increased with a step increase in \( \dot{e}_a \) by loading rate effects due to the viscous property. Subsequently, the deviator stress started increasing but at a much lower rate than the one during continuous ML at the lower \( \dot{e}_a \) before a step increase, which was due to a decrease in the developing rate of ageing effect associated with an increase in \( \dot{e}_a \). Corresponding to the above, the q value suddenly decreased with a step decrease in \( \dot{e}_a \) also by loading rate effects due to the viscous property. Subsequently, with an increase in the axial strain, the deviator stress started increasing at a noticeably higher rate than the one during continuous ML at the higher \( \dot{e}_a \) before a step decrease, which was due to an increase in the developing rate of ageing effect associated with a decrease in \( \dot{e}_a \).

3) In these two very slow loading tests, it appears that the ageing effects were generally larger than the viscous effects, which resulted in a higher overall tangent stiffness than the value for the same total curing period when sheared at a higher \( \dot{e}_a \) (Fig. 9). The viscous property seen in Figs. 9 and 10 is analysed later in this paper.

4) The specimen became slightly more contractive after a step decrease in \( \dot{e}_a \) and vice versa (Fig. 10). The reason for such a change in the flow characteristics as described above is not known.

In summary, the ageing effects during ML at a constant strain rate becomes more significant as the strain rate becomes lower, while loading rate effects due to the viscous property are observed when the strain rate changes suddenly during otherwise ML at any constant strain rate. The magnitude of the sudden change in the deviator stress upon a step change in the irreversible shear strain rate is proportional to the logarithm of the ratio of irreversible shear strain rates after and before a step change, as shown later in this paper.

**Additional Strength Gain by Sustained Loading at an Anisotropic Stress State and Very Slow Loading**

It is shown above that the peak strength at the same total curing time becomes larger when cured for a longer period at a larger deviator stress whether ageing effects develop during drained sustained loading at a fixed stress state or continuous drained monotonic loading. By
analysing the data presented in Figs. 8, 9 and 10 and those from the SP series tests (reported in Kongsukprasert and Tatsuoka, 2005), it was found that, at the same total curing time, \( t_c \), at the peak stress state, the peak strength became systematically larger with an increase in the ratio \( A = \frac{\text{area } C}{\text{area } T} \), defined in Fig. 11(a), where:

1) \( T \) is the area surrounded by the \( q=0 \) axis, the \( \text{A-A'} \) curve (representing \( q_{\text{max}} \) for relatively fast continuous ML at \( \dot{\varepsilon}_a = 0.03\% / \text{min} \) on the specimens cured unconfined or confined at \( q = 0 \) for different periods) and the loading paths of two relatively fast continuous ML tests performed at the curing times at the start and end of the concerned test (with an intermediate sustained loading stage(s) or at a very low \( \dot{\varepsilon}_a \)); and

2) \( C \) is the area surrounded by the \( q=0 \) axis, the \( \text{A-A'} \) curve, the loading history path of the concerned test and the loading path of the relatively fast continuous ML test (at \( \dot{\varepsilon}_a = 0.03\% / \text{min} \)) performed at the curing time at the peak stress state in the concerned test.

The ratio \( A \) increases when subjected to either sustained loading for a longer period or slower loading at higher deviator stresses.

For specimens cured unconfined or confined at \( q = 0 \) for some period, \( t_{\text{ini}} \), and then subjected to relatively fast continuous ML drained TC at \( \dot{\varepsilon}_a = 0.03\% / \text{min} \) from \( q = 0 \), the loading duration between the start of ML and the peak stress state was negligible when compared with the period \( t_{\text{ini}} = t_c \). Then, the values of \( q_{\text{max}} \) at total curing times equal to \( t_c \) and \( t_c + \Delta t_c \), denoted as \( (q_{\text{max}})_o(t_c) \) and \( (q_{\text{max}})_o(t_c + \Delta t_c) \), are related to each other as:

\[
(q_{\text{max}})_o(t_c + \Delta t_c) = (q_{\text{max}})_o(t_c) + S \cdot \Delta t_c
\]

where \( S \) is the average slope of the \( (q_{\text{max}})_o - t_c \) relation between \( t_c \) and \( t_c + \Delta t_c \) of curve AA' in Fig. 11(a); and \( S \cdot \Delta t_c \) is the strength gain by ageing effects that has developed when cured unconfined or confined at \( q = 0 \) (denoted as \( \Delta q_o \) in Fig. 11(a)). For the analysis shown below, the \( (q_{\text{max}})_o - t_c \) relations from continuous relatively fast drained ML tests at \( \dot{\varepsilon}_a = 0.03\% / \text{min} \) (without intermediate sustained loading stages) presented in Figs. 7(a) and (b) were used as curve AA'. Then, the \( q_{\text{max}} \) value at a total curing time \( t_c + \Delta t_c \) at the peak stress state of a specimen that is cured at a non-zero \( q \) or monotonically loaded at a low strain rate is obtained as:

\[
q_{\text{max}}(t_c + \Delta t_c) = (q_{\text{max}})_o(t_c) + \Delta q_o + \Delta q_{\text{gain}}
\]

\[
= (q_{\text{max}})_o(t_c) + \Delta q_o (1 + B)
\]

where \( B \) is the ratio of the additional strength gain by
Table 4. List of the test results presented in Fig. 12 (the values of $q_{\text{max}}$ in the parenthesis are those after corrected to an axial strain rate equal to 0.03%/min)

<table>
<thead>
<tr>
<th>Series</th>
<th>Test</th>
<th>Initial curing period, $t_{\text{ini}}$ (day)</th>
<th>Total curing period, $t_{\text{t}}$ (day)</th>
<th>$q_{\text{max}}$ at $t_{\text{ini}}$ (kPa) for ML</th>
<th>$q_{\text{max}}$ at $t_{\text{t}}$ (kPa) measured</th>
<th>$\Delta q_{\text{o}}$ (kPa)</th>
<th>$\Delta q_{\text{gain}}$ (kPa)</th>
<th>$B = \Delta q_{\text{gain}} / \Delta q_{\text{o}}$</th>
<th>$A = C / T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>JAS</td>
<td>JA015</td>
<td>3.16</td>
<td>7.19</td>
<td>2106.6</td>
<td>1921.7</td>
<td>517.8</td>
<td>184.9</td>
<td>0.357</td>
<td>0.414</td>
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<tr>
<td></td>
<td>JA005</td>
<td>7.07</td>
<td>9.81</td>
<td>2164.4</td>
<td>2177.3</td>
<td>271.7</td>
<td>-13.0</td>
<td>-0.048</td>
<td>0.014</td>
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<tr>
<td></td>
<td>JA009</td>
<td>7.01</td>
<td>7.95</td>
<td>2019.0</td>
<td>2030.7</td>
<td>104.8</td>
<td>13.2</td>
<td>0.145</td>
<td>0.498</td>
</tr>
<tr>
<td></td>
<td>JA001</td>
<td>7.05</td>
<td>9.80</td>
<td>2140.1</td>
<td>2176.3</td>
<td>37.2</td>
<td>-36.1</td>
<td>-0.133</td>
<td>0.476</td>
</tr>
<tr>
<td></td>
<td>JA008</td>
<td>7.16</td>
<td>11.71</td>
<td>2374.0</td>
<td>2354.7</td>
<td>44.7</td>
<td>19.2</td>
<td>0.044</td>
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<td></td>
<td>JA010</td>
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<td>9.64</td>
<td>2353.3</td>
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<td>192.1</td>
<td>91.3</td>
<td>0.690</td>
<td>0.601</td>
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<td></td>
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<td>7.88</td>
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<td>1996.9</td>
<td>107.2</td>
<td>172.5</td>
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<td></td>
<td>JA007</td>
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<td>2509.9</td>
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<td>341.8</td>
<td>314.8</td>
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<td></td>
<td>JA004</td>
<td>6.76</td>
<td>9.50</td>
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<td>117.2</td>
<td>0.415</td>
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<td></td>
<td>JA003</td>
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<td>3629.5</td>
<td>3542.7</td>
<td>403.8</td>
<td>86.8</td>
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<tr>
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<td>JS009</td>
<td>7.15</td>
<td>13.17</td>
<td>3267.3</td>
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<td></td>
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<td>839.2</td>
<td>1245.6</td>
<td>1.376</td>
<td>0.771</td>
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<td>SP</td>
<td>SP004</td>
<td>7.38</td>
<td>11.92</td>
<td>2334.3</td>
<td>2082.6</td>
<td>348.0</td>
<td>251.7</td>
<td>0.723</td>
<td>0.560</td>
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<tr>
<td></td>
<td>SP003</td>
<td>14.40</td>
<td>17.44</td>
<td>2516.2</td>
<td>(2605.1)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

i) Continuous ML at a high strain rate (i.e., 0.03%/min).
ii) The value in column (1) could not be confidently determined due to a lack of data.

ageing effects at a non-zero $q$ (denoted as $\Delta q_{\text{gain}}$ in Fig. 11(a)) to $\Delta q_{\text{o}} = S \cdot dt$ (the strength gain by ageing unconfined or confined at $q = 0$). The relationships between the parameters $A$ and $B$ are presented in Fig. 11(c) and the corresponding data are listed in Table 4. The curve fitted to the data points for the strain rate, equal to 0.03%/min, is also presented. Here, to account for the viscous effects on $q_{\text{max}}$, the measured $q_{\text{max}}$ values from three tests have been corrected to the values at $\varepsilon_t = 0.03$/min based on the average relation presented in Fig. 11(b). The data points in Fig. 11(b) were obtained from continuous ML tests at different $\varepsilon_t$ values (presented in Figs. 12 and 13). It may be seen that the $q_{\text{max}}$ value increases by a factor of 1.052 with an increase in $\varepsilon_t$ by a factor of 10. It was assumed that the strength gain by the ageing effects, $\Delta q_{\text{o}} + \Delta q_{\text{gain}}$, is negligible in the data presented in Fig. 11(b), performed at $\varepsilon_t$ not very different from 0.03%/min. It is likely that this assumption is acceptable, despite that it is not very rigorous, and the viscous effects are only slightly underestimated with the average relation presented in Fig. 11(b). Therefore, it is likely that the exact $A$ and $B$ relation defined for $q_{\text{max}}$ at $\varepsilon_t = 0.03$/min that is utterly free from the viscous effects is located only slightly above the fitted curve presented in Fig. 11(c).

3) When the parameter $A$ becomes about 0.4 (i.e., when cured at a relatively higher shear stress or sheared at a relatively lower strain rate), the parameter $B$ increases from zero in a non-linear fashion at an increasing rate with an increase in $A$.

Despite a significance of these findings described above, the test conditions employed in the present study were rather limited when compared to those that might be encountered in the field. A further study will be necessary to find whether the relationship presented in Fig. 11(c) is also relevant to more general conditions in terms of stress conditions, stress history, cement/gravel ratio, compacted void ratio, the particle characteristics of gravelly soil and so on.

LOADING RATE EFFECTS DUE TO VISCOUS PROPERTY

To evaluate the viscous property separately from the ageing effects, two series of CD TC tests were performed. In the first series, the following three CD TC tests were performed at relatively high $\varepsilon_t$ values so that the ageing effects that develop during ML became insignificant. In the first two tests, ML was continued at $\varepsilon_t = 0.01$/min (test JS001) and 0.03%/min (test J023). In the other test (test JS002), the $\varepsilon_t$ value was changed stepwise many times during otherwise ML at a constant $\varepsilon_t$ between 0.001%/min and 0.1%/min. Figure 12 shows the results from these three tests. Table 5 summarises the test conditions and part of the test results.

The following trends in behaviour may be seen from Fig. 12:

1) The average pre-peak stiffness became higher and the compressive strength became lager with an increase in $A$. The following trends in behaviour may be seen from Fig. 12:

1) There is a high correlation between the two parameters $A$ and $B$.
2) The effects of the parameter $A$ on the parameter $B$ are very small when $A$ is lower than about 0.4 (i.e., when cured unconfined or confined at $q = 0$ or a relatively low value and sheared at a relatively high strain rate).

2) There is a high correlation between the two parameters $A$ and $B$.
in $\varepsilon_a$ under otherwise the same conditions. This trend should be due to the viscous property, like ordinary unbound geomaterials.

2) In test JS002, the deviator stress rapidly changed immediately after each step change in $\varepsilon_a$. The deviator stress jump, $\Delta q$, increased with an increase in the $q$ value at which the axial strain was stepwise changed (this feature is analysed below).

3) In the pre-peak regime, it seems that the $\Delta q$ value that developed upon a step change in $\varepsilon_a$ was essentially persistent as far as subsequently ML continued at a constant $\varepsilon_a$. Then, after having exhibited a marked change in the tangent modulus, the stress-strain curve tended to join the relation that would have been obtained if ML had continued at the constant $\varepsilon_a$ after the respective step change from the start of loading.

With respect to the last point, the stress-strain relation when ML continued at the same $\varepsilon_a$ was not exactly the same among these three tests, which can be considered due to an evitable variance among these tests. Therefore, it is not possible to conclude only based on the test results presented in Fig. 12 that, when changes in the stress-strain behaviour by ageing effects in a given test are negligible, the current deviator stress, $q$, is uniquely determined by the instantaneous axial strain, $\varepsilon_a$, and its rate, $\dot{\varepsilon}_a$ (or more rigorously by the instantaneous irreversible shear strain, $\gamma^i$, and its rate, $\dot{\gamma}^i$) irrespectively of previous strain history. If it is the case, the viscous property is the one called the “isotach” type (Sukje, 1969), which has been observed with sedimentary softrock (Hayano et al., 2001) and some kinds of soft clay (e.g., Tatsuoka et al., 2002; Komoto et al., 2003). When based on the test results presented in Fig. 12, it can only be said that it is likely that the isotach viscosity is relevant to the pre-peak stress-strain behaviour of the cement-mixed gravelly soil tested in the present study. On the other hand, the trend of isotach viscosity was much weaker in the post-peak regime.

To evaluate the viscous property more systematically, another series of CD TC tests (the second series) were performed on specimens initially cured for different periods, $t_{ini}$: 3 days (test SR002); 7 days (tests JS004, JS007 and SR001); and 14 days (tests JS005 and JS006). The values of $c/g$, $w_i$ and $\rho_d$ are basically the same among all these specimens (Table 5). The axial strain rate, $\varepsilon_a$, was changed stepwise by factors of 5, 25 and 125 during otherwise ML at a constant $\varepsilon_a$ in each test. Figure 13 shows the test results, where $x$ means the basic axial strain rate, equal to 0.03%/min. Two typical moments when
the strain rate was changed; decreased and increased are denoted by the letters D and U in Fig. 13(b). The following trends in behaviour may be seen:

1) The trend of loading rate effect due to the viscous property is basically the same for the different initial curing periods, $t_{ini}$, between 3 and 14 days. Moreover, corresponding to an increase in the strength due to ageing effects, the difference between the deviator stresses among different $\sigma_i$ values at the same axial strain increases by ageing effects, which increase with an increase in the curing period.

2) It appears that the isotach viscosity prevails in the pre-peak regime. A set of continuous curves for the respective curing period presented in Fig. 13(b) denote the stress-strain curves at different constant strain rates that were deduced from the measured segmental stress-strain curves for different constant strain rates. In the post-peak regime, on the other hand, the sudden deviator stress change, $\Delta q$, that has developed upon a step change in $\dot{\sigma}_i$ is not persistent but decays with an increase in the axial strain as far as ML continues at a constant $\dot{\varepsilon}_a$. Correspondingly, the stress-strain curves for different strain rates appear to join the unique curve that is independent of $\varepsilon_a$. This trend of behaviour was observed from the start of loading with clean sands and has been called the TESRA (Temporary Effects of Strain Rate and Acceleration) viscosity (Di Benedetto et al., 2002; Tatsuoka et al., 2002).

3) At axial strains less than about 0.15%, where the specimens are contractive when sheared, the specimens become more contractive by a step increase in $\dot{\varepsilon}_a$. The reason for this trend is not known. At larger axial strains, where the specimens are dilative when sheared, the loading rate effect on the relationship between the volumetric and axial strains is not clear.

It appears that a slight change in the tangent slope of the volumetric strain and axial strain curve upon a step change in $\dot{\varepsilon}_a$ is mostly due to elastic strain increments that develop by a stress change taking place upon a step change in $\dot{\varepsilon}_a$.

The following discussions are also relevant with respect to the transformation of viscous property from the isotach type to the TESRA type:

a) It appears that, with the cement-mixed gravelly soil tested in the present study, the transformation starts not far before the peak stress state and the viscosity in the post-peak regime is of the TESRA type.

b) Sedimentary soft rock, which is a well-bound geomaterial, exhibits obviously the isotach type viscosity in the pre-peak regime (Hayano et al., 2001). It can be considered that true cohesion, as intact sedimentary soft rock has, is well maintained in the pre-peak regime with the cement-mixed gravelly soil. Moreover, the base well-graded gravelly soil (Chiba gravel without cement-mixing) exhibits the isotach viscosity in the pre-peak regime (Anh Dan et al., 2004). Referring to these two facts, it is natural that the cement-mixed gravelly soil exhibits basically the isotach type viscosity in the pre-peak regime.

c) It is likely that bonded inter-particle contacts are damaged more with an increase in the irreversible strain. In particular, in the post-peak regime, the specimen is separated into different blocks with a shear band (or bands) developing in between, indicating that the cementation has been largely damaged or nearly totally lost in the shear band(s). Moreover, with any type of unbound geomaterial tested by the authors and their colleagues (Tatsuoka, 2005), the viscous property observed in

Fig. 13. Results from TC tests ($\sigma_i' = 19.8$ kPa) with step changes in the axial strain rate for different initial ageing periods: a) overall behaviour and b) behaviour at small strains.
the post-peak regime is more-or-less of the TESRA type. The observation that the viscous property of the cement-mixed gravelly soil also becomes the TESRA type in the post-peak regime is consistent with the fact described above.

It is shown in the preceding section that, when ML is restarted following a sustained loading stage at a non-zero \( q \) lasting for some duration, the stress overshoots the stress-strain relation for the same total curing period obtained from a continuous ML test at the same \( \dot{e}_a \) (see Figs. 6 and 8). Then, the overshooting stress gradually decays with an increase in the axial strain as long as ML continues at a constant \( \dot{e}_a \). The test results presented in Fig. 13 suggest that this decay in the overshooting stress observed when approaching the peak stress state and in the post-peak regime is due partly to the TESRA viscous property and partly to the damage by shear straining discussed above.

**Quantification of Viscous Property**

Matsushita et al. (1999) and Di Benedetto et al. (2002) showed that the viscous property of unbound geomaterial can be quantified based on the stress change upon a step change in the irreversible strain rate during otherwise ML at a constant strain rate. Hayano et al. (2001) showed that a similar methodology is also relevant to sedimentary soft rock. To examine this point with cement-mixed gravelly soil, “the change in the deviator stress due solely to a respective change in the irreversible axial strain rate, \( \Delta \dot{q} \),” was obtained as illustrated in Fig. 14(a) from the pre-peak stress-strain data presented in Figs. 12 and 13. The respective \( \Delta \dot{q} \) value was then plotted against the corresponding average deviator stress, \( \dot{q} \), which is defined as “the \( q \) value where the step change in the strain rate was made” plus or minus a half of “the sudden change in \( q \) upon a step change in the strain rate, \( \Delta q \)” (Fig. 14(a)). In so doing, the irreversible axial strain rate was obtained as \( \dot{\varepsilon}_a^i = \dot{\varepsilon}_a - \dot{\varepsilon}_a^e \), where \( \dot{\varepsilon}_a \) is the current axial strain rate and \( \dot{\varepsilon}_a^e \) is the current elastic strain rate obtained as \( \dot{\varepsilon}_a^e = \frac{E_{eq}(\sigma, \tau_c)}{\dot{\sigma}} \), where \( \dot{\sigma}_a \) is the current deviator stress rate, \( \dot{q} \), in the present case, and \( E_{eq}(\sigma, \tau_c) \) is the current elastic Young’s modulus, which is a function of the instantaneous stress, \( \sigma \), and the total curing time, \( \tau_c \). The function \( E_{eq}(\sigma, \tau_c) \) was carefully evaluated by applying small unload/reload cycles during otherwise ML in a number of CD TC tests on cement-mixed gravelly soil specimens cured for different periods (Kongsukprasert and Tatsuoka, 2005).

It may be seen from Fig. 14(b) that an unique linear relation exists for each ratio of the \( \dot{\varepsilon}_a^i \) values after and before a step change, \( \frac{\dot{\varepsilon}_a^i \text{ after}}{\dot{\varepsilon}_a^i \text{ before}} \), irrespective of different values of \( q \) and different initial curing periods, \( \tau_{ini} \). Here, the total curing period at the respective event, \( \tau_c \) is nearly the same as \( \tau_{ini} \) within the limit of test conditions for these data. Note that the ratio \( \frac{\dot{\varepsilon}_a^i \text{ after}}{\dot{\varepsilon}_a^i \text{ before}} \) is very close to the irreversible shear strain ratio, \( \frac{\dot{\varphi}^i \text{ after}}{\dot{\varphi}^i \text{ before}} \), where \( \dot{\varphi}^i = \dot{\varepsilon}_a^i - \dot{\varepsilon}_a^e \). It may also be seen that the slope of each relation becomes larger with an increase in

\[ \Delta q/p_s = m \cdot (q + q_c)/p_s \]  

Equation (3) is obtained from Eq. (4c) by replacing the confining pressure \( \sigma_c^i \) with the intersect \( q_c \). The \( q_c \) value in

**Fig. 14.** a) Definition of \( \Delta q \) and \( \dot{q} \), b) \( \Delta q/p_s - \dot{q}/p_s \) ratios for different ratios of axial strain rates after and before a step change and c) rate-sensitivity coefficient \( \beta \) from TC tests in which the axial strain rate was changed stepwise during otherwise ML.
the present case, which is equal to 1,512 kPa, is considerably larger than 19.8 kPa. This difference would be due to significant effects of cementation with the cement-mixed gravelly soil. Therefore, not only the intersect \( q_c \) but also the parameter \( m \) should be basically a function of curing time, \( t_c \), as well as the cement content, \( c/g \), and other relevant parameters related to the cementation effects. However, the effects of \( t_c \) were not noticeable and could not be evaluated in the present study.

Based on the fact described above, the respective measured value of \( (\Delta q/p_a)_{\text{at}t=0}/(q+q_a)/p_a \) was plotted against the corresponding value of \( [(\varepsilon_a)_{\text{after}}/(\varepsilon_a)_{\text{before}}] \) in Fig. 14(c). It may be seen that the relation seen in this figure is highly unique and linear. The relation can be represented as:

\[
\frac{(\Delta q/p_a)_{\text{at}t=0}}{(q+q_a)/p_a} = \beta \cdot \log \left[ \frac{[(\varepsilon_a)_{\text{after}}/(\varepsilon_a)_{\text{before}}]}{\varepsilon_a} \right] \tag{5}
\]

where \( \beta \) is a constant, called the rate-sensitivity coefficient (Tatsuoka, 2005), which is equal to 0.0388 in the present case. The right hand term of Eq. (5) can be rewritten as follows:

\[
\beta \cdot \log \left[ \frac{[(\varepsilon_a)_{\text{after}}/(\varepsilon_a)_{\text{before}}]}{\varepsilon_a} \right] = b \cdot \ln \left[ \frac{[(\varepsilon_a)_{\text{after}}/(\varepsilon_a)_{\text{before}}]}{\varepsilon_a} \right] = b \cdot d \ln (\dot{\varepsilon}^v); \quad \beta = b \ln 10 \tag{6}
\]

Figure 15 compares the \( \beta \) value of the cement-mixed gravelly soil tested in the present study with those obtained based on Eq. (7) from drained triaxial compression (TC) and plane strain compression (PSC) tests at constant \( \sigma' \) on several types of unbound geomaterial:

\[
(\Delta R)_{\text{at}t=0} = \beta \cdot \log \left[ \frac{[(\varepsilon_a)_{\text{after}}/(\varepsilon_a)_{\text{before}}]}{\varepsilon_a} \right] \tag{7}
\]

where \( R \) is the principal stress ratio at which the strain rate is stepwise changed. Equation (5) becomes the same as Eq. (7) by replacing \( \sigma'_i \) with \( q_c \). It may be seen from Fig. 15 that the \( \beta \) values of the unbound granular materials are of the order of 0.02–0.03. The details of the test conditions for these data are reported in Di Benedetto et al. (2004) and Tatsuoka (2005). It may also be seen that the \( \beta \) value of the cement-mixed gravelly soil tested in the present study is only slightly larger than the values of these unbound geomaterials. Considering also that many other features of the viscous property of the cement-mixed gravelly soil are similar to those of unbound materials, it appears that the basic features of the viscous property of the cement-mixed gravelly soil are very similar to those of unbound geomaterials.

A brief discussion on the viscous property of cemented material presented above, which is very important when implementing them into constitutive modelling accounting for the material viscosity, is given below. In the non-linear three-component model for unbound geomaterial proposed by Di Benedetto et al. (2002) and Tatsuoka et al. (2002), the stress in general terms, \( \sigma \), is decomposed into the inviscid and viscous components, \( \sigma'^i \) and \( \sigma'^v \), while the strain rate in general terms, \( \dot{\varepsilon} \), into the elastic and irreversible (or inelastic or visco-plastic) components, \( \dot{\varepsilon}^e \) and \( \dot{\varepsilon}^v \). By applying this model to the present case of cemented materials, we obtain the following equation by referring to Eqs. (5) and (6) while noting that \( q+q_i = q'^i + q_i + q'^v \), where \( q'^i \) and \( q'^v \) are the inviscid and viscous components of \( q \):

\[
\frac{(dq'^i)_{\text{at}t=0}}{q'^i + q'^v} = b \cdot d \ln (\dot{\varepsilon}^v) \tag{8}
\]

where \( (dq'^i)_{\text{at}t=0} \) is the increment of the viscous deviator stress component that develops while the irreversible strain is kept constant. Di Benedetto et al. (2002) and Tatsuoka et al. (2002) showed that, when the isochast viscosity is relevant, the viscous stress component \( \sigma'^v \) when \( \dot{\varepsilon}^v \) is always positive is obtained as:

\[
\sigma'^v = \sigma'^i \cdot g_v(\dot{\varepsilon}^v) \tag{9a}
\]

where \( g_v(\dot{\varepsilon}^v) \) is the viscosity function, which is a highly non-linear function of instantaneous irreversible axial strain, \( \dot{\varepsilon}^v \). By applying Eq. (9a) to the present case while referring to Eq. (8) and by knowing that \( q_c \) is an inviscid stress component, we obtain:

\[
q'^i = (q'^i + q_i) \cdot g_v(\dot{\varepsilon}^v) \tag{9b}
\]

By substituting Eq. (9b) into Eq. (8) and noting that \( (dq')_{\text{at}t=0} = 0 \) (as \( q'^i \) is a unique function of instantaneous irreversible axial strain, \( \dot{\varepsilon}^v \)), we obtain:

\[
\frac{(q'^i + q_i) \cdot d[g_v(\dot{\varepsilon}^v)]}{(q'^i + q_i) \cdot [1 + g_v(\dot{\varepsilon}^v)]} = b \cdot d \ln (\dot{\varepsilon}^v) \tag{10a}
\]

\[
\frac{d[g_v(\dot{\varepsilon}^v)]}{[1 + g_v(\dot{\varepsilon}^v)]} = b \cdot d \ln (\dot{\varepsilon}^v) \tag{10b}
\]

\[
d \ln \left[ \frac{1 + g_v(\dot{\varepsilon}^v)}{\dot{\varepsilon}^v} \right] = d \ln (\dot{\varepsilon}^v) \tag{10c}
\]

The solution of \( g_v(\dot{\varepsilon}^v) \) from Eq. (10c) is:

\[
1.0 + g_v(\dot{\varepsilon}^v) = c_v \cdot (\dot{\varepsilon}^v)^b; \quad g_v(\dot{\varepsilon}^v) = c_v \cdot (\dot{\varepsilon}^v)^b - 1.0 \tag{11}
\]

where \( c_v \) is a constant. Equation (11) is valid only for a range of \( \dot{\varepsilon}^v \) for which Eq. (5) was derived. In fact, with unbound granular materials, as \( \dot{\varepsilon}^v \) approaches toward zero, \( g_v(\dot{\varepsilon}^v) \) converges toward zero, which means that Eq. (11) becomes invalid when \( \dot{\varepsilon}^v \) becomes smaller than a certain limit (Di Benedetto et al., 2002). Hayano et al. (2001) showed that the non-linear three-component model based on Eq. (11) can simulate very well the stress-strain-time
behaviour of sedimentary softrock; a) in ML at different constant strain rates; b) when and after the strain rate is stepwise and gradually changes; and c) during sustained loading and stress relaxation in drained TC (in which \(e_\varepsilon\) is always positive and larger than a certain value). A similar simulation for cement-mixed gravelly soil will be reported elsewhere in the near future by the authors.

CONCLUSIONS

The following conclusions with respect to the ageing and viscous effects on the deformation and strength characteristics of cement-mixed gravelly soil can be derived from the test results presented in this paper:

1) The average pre-peak stiffness, the elastic stiffness, and the peak strength increased by ageing effects whether they were developed under unconfined or confined conditions.

2) Noticeable loading rate effects due to viscous property were observed in drained monotonic loading (ML) tests at different strain rates as well as when applying drained sustained loading and step changes in the strain rate during otherwise ML at a constant strain rate.

3) Due to coupled effects of ageing and viscosity, when ML was restarted at the original strain rate following sustained loading, the stress-strain behaviour became very stiff for a stress range that was much larger than the one in the case without ageing effects.

4) Noticeable ageing effects that were more significant than the viscous effects developed in the two very slow drained ML tests performed in this study.

5) At the same total ageing period (or total curing period) at the peak stress state, the peak strength became larger when aged for a longer period at a higher deviator stress during sustained loading and very slow ML, when compared to the value when sheared continuously at a relatively high strain rate after having been cured unconfined or confined at zero deviator stress. An empirical equation was derived to express the additional strength gain by this factor.

6) The viscous property was quantified based on stress changes taking place upon a step change in the strain rate applied during otherwise ML at a constant strain rate. The rate-sensitivity coefficient, \(\beta\), was obtained by modifying the procedure that had been used for unbound geomaterials. The obtained \(\beta\) value was only slightly larger than those of unbound granular materials. The basic features of the evaluated viscous property, including the above, are in general similar to those of unbound granular materials.

Some limited discussions were made on the constitutive modelling procedure accounting for the viscous property of cement-mixed gravelly soil evaluated in the present study. Obviously, more comprehensive study will be necessary to find whether the equations presented in this paper can be applied to more general stress conditions at different and varying confining pressures and so on.

ACKNOWLEDGEMENTS

This study was performed at the University of Tokyo. The help of the staff of the Geotechnical Laboratory is greatly appreciated. Financial support from the Ministry of Education, Culture and Sport, Government of Japan to the first author is greatly acknowledged.

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