ABSTRACT

Based on observations from constant strain rate experiments and from creep and stress relaxation experiments initiated at different stress levels it is found that sand exhibits patterns of time effects different from those observed in clays. It appears that time effects in sand may be associated with crushing of particles, and a mechanistic picture of time effects in granular materials is constructed in which time effects depend on interparticle friction, grain crushing and grain rearrangement. This mechanistic picture is based on measured behavior in drained triaxial compression tests on three different sands in which strain rate effects are observed as small to negligible. While creep and relaxation are caused by the same underlying phenomenon, it appears that results of creep tests cannot be obtained from results of relaxations tests, and vice versa. The phenomenon of static fatigue of individual particles seems to be at the root of time effects in sand. A review of previous studies of static fatigue is presented. Triaxial tests on a beach sand incorporating creep and stress relaxation are followed by grain size analysis to prove that grain crushing relate to the observed time effects. Additional triaxial tests are presented in which the effect of water is demonstrated in support of the static fatigue mechanism. Load-controlled tests on individual sand particles in the form of spherical glass beads (quartz) were performed by maintaining constant loads lower than the short term crushing loads. As do rock and concrete specimens in triaxial compression, the glass beads show effects of time to crushing.

Key words: creep, sand, static fatigue, stress relaxation, time dependence, triaxial compression (IGC: D6)

INTRODUCTION

Time dependent behavior of granular materials is quite different from the viscous behavior observed in clays. The effects of strain-rate, creep and stress relaxation of clays follow a classic pattern of viscous behavior observed for most materials. For such materials the stiffness and strength increase with increasing strain rate and phenomena such as creep, relaxation and strain rate effects are governed by the same basic mechanism. This behavior is denoted as "isotach" behavior, i.e. there is a unique stress-strain-strain rate relation for a given clay. For such materials, the creep properties may be obtained from, say, a triaxial compression test and used for prediction of stress relaxation in another experiment.

For granular materials the effects of strain rate or loading rate are observed to be small to negligible, and while creep and stress relaxation are caused by the same phenomenon, namely grain crushing followed by grain rearrangement, the prediction of one phenomenon can apparently not be accomplished on the basis of the other. Such behavior is referred to as "nonisotach" behavior. The role of grain crushing is explained, and the transfer of forces through the grain structure is different in creep and relaxation tests. While each phenomenon follows similar patterns, the strains produced after one day of creep does not produce a result that correlates with the changes in stress due to one day of stress relaxation.

To throw further light on the effects of time on the behavior of sand, and as background for development of constitutive models incorporating time effects, presented here is a study of strain rate effects, creep, and stress relaxation in crushed coral sand. A mechanistic picture is introduced in which static fatigue of individual grains account for the time effects observed in experimental studies. Additional triaxial tests on a beach sand incorporating creep and stress relaxation are followed by grain size analyses to prove that grain crushing relate to the observed time effects. Further, a triaxial test is presented in which the effect of introducing water into an initially dry specimen is presented in support of the static fatigue mechanism.

PREVIOUS STUDIES

Comprehensive reviews of time dependent behavior of soils and models for characterization of this behavior have recently been presented in the literature (Augustesen...
et al., 2004; Liingaard et al., 2004). The essence of these reviews is that clay and sand behave differently with respect to time. They show that strain rate has important influence on the stress-strain behavior of clay, while widely different strain rates produce essentially the same stress-strain relation for sand, as seen in experiments presented by e.g., Tatsuoka et al. (2002), Kuwano and Jardine (2002), and Kiyota and Tatsuoka (2006). Changes in strain rate have permanent effects in clay, where switches from one to another stress-strain curve occur in response to changes in strain rate. Only temporary changes occur in the stress-strain relations for sand, as also observed by the authors listed above.

Observed behavior shows (Augustesen et al., 2004) that the phenomena of creep and stress relaxation are also different in clay and sand. For clay, creep and relaxation properties can be obtained from constant rate of strain tests, and vice versa, as shown by e.g., Leroueil and Marques (1996). The fact that creep, relaxation and strain rate effects can be modeled by the same basic viscous mechanism is referred to as “isotach” behavior.

An investigation of strain rate effects in dense Cambria sand under drained and undrained conditions at high pressures performed by Yamamuro and Lade (1993) showed no significant rate effects on the stress-strain relations. The Hostun and Toyoura sands tested by Matsushita et al. (1999) exhibited noticeable amounts of creep and relaxation but no strain rate effects. This led to one of the main conclusions: The phenomena of creep and relaxation cannot be predicted based on results of constant rate of strain tests. This is because the changes in stress-strain relations due to changes in strain rate are temporary. This behavior of sand is labeled “non-isotach” behavior. Note that Tatsuoka et al. (2008) have proposed additional sub-classifications for different types of nonisotach behavior of granular materials.

To provide a more comprehensive background for development of an appropriate constitutive model for time effects in sand, which shows nonisotach behavior, experiments have been performed to study time effects in sand.

**EXPERIMENTAL STUDIES OF SANDS**

The initial studies of time-dependent behavior of sand were conducted in a conventional triaxial apparatus. Modifications to this equipment were made to improve its capability to carry out long-term tests with steady stresses and accurate measurements at a constant temperature. Mechanical equipment with negligible drift in applied pressures and loads and measurement systems without zero drift or devices in which the zero position could be verified during experiments were employed for all testing. The triaxial equipment, the loading systems, the deformation measurement systems, and the temperature control were explained by Lade and Liu (1998).

The sand tested was crushed coral sand. The gradation consisted of grain sizes between the No. 30 and No. 140 U.S. sieves (0.60 to 0.106 mm) with a nearly straight line gradation between these two sizes. The maximum and minimum void ratios were 1.22 and 0.70. The specific gravity of sand grains was 2.88. The tests on crushed coral sand were performed on specimens with a relative density of 60% corresponding to a void ratio of 0.91. The experiments on crushed coral sand have been presented by Lade et al. (2009, 2010), and a few results relating to the present issue are given below.

Additional triaxial tests have been performed on Virginia Beach sand at high confining pressures to study particle crushing and effects of water, as implied in the phenomenon of static fatigue. The portion contained between the No. 20 and No. 40 U.S. sieves (0.850 mm to 0.425 mm) was used in these tests so that crushing would be easily visible and result in identifiable changes in the gradation curve. The sand consists of subangular to subrounded quartz grains with mean diameter = 0.638 mm; coefficient of uniformity = 1.40; specific gravity = 2.65; and maximum and minimum void ratios = 0.759 and 0.532, respectively. Tests were performed on Virginia Beach sand at a relative density of 100%.

**EXPERIMENTS ON CRUSHED CORAL SAND**

**Strain Rate Effects**

Triaxial compression tests were performed on crushed coral sand with an effective confining pressure of 200 kPa and with five different, constant axial strain rates varying from 0.00665%/min to 1.70%/min, corresponding to a
256-fold increase in strain rate. The results of these tests are shown in Figs. 1(a) and (b). They indicate that the influence of strain rate on the characteristics of the stress-strain and volume change curves is small and within the scatter of such results. Several experiments were performed with each of the five strain rates and the curves shown in Fig. 1 are those deviating most from each other. Note that the scale on the volumetric strain axis is approximately 5 times larger than the axial strain scale. Thus, deviations in volumetric strains are accentuated to demonstrate the magnitude of scatter in the worst case. Therefore, the experimental results confirm that the slopes of the curves, the volumetric strains, as well as the strengths are very little affected by the strain rate. Similar results for sand have been found by Yamamuro and Lade (1993) and by Matsushita et al. (1999). This departure from classic time-dependent behavior, according to which the stiffness and the strength increase with increasing strain rate, is significant, because it indicates that it may not be possible to employ conventional viscous type models to capture the time-dependent behavior of sands. Such models have been successfully used to characterize a number of other materials, including soils such as clays (see Liingaard et al. (2004) for comprehensive review of time effect models).

**Creep Experiments**

Conventional creep experiments were performed after the specimen had been sheared under load control corresponding to the middle strain rate of 0.106% /min. The behavior obtained under load control is slightly different from that obtained under deformation control, as discussed in detail by Lade et al. (2009). Once the desired deviator stresses of 500, 700, and 900 kPa had been reached, the specimen was allowed to creep for approximately one day (≈1440 min). After the creep stage, the deviator stress was again increased sufficiently to join the virgin or primary stress-strain curve before another creep test was initiated.

Figure 2(a) shows the stress-strain and volume change curves, and superimposed on these diagrams are the results of corresponding load controlled experiment. As creep proceeds at a given stress, the plastic yield surface moves out to higher stresses. This may be seen from the fact that further loading first produces what appears to be elastic reloading.

The volume change curves corresponding to creep, shown in Fig. 2(b), do not follow the reference curve, unlike the previous experiments on Antelope Valley sand presented by Lade (2007). This means that the potential for inelastic creep strains cannot be taken to be the same as the potential for plastic strains, as was the case for the Antelope Valley sand. The potential for inelastic strains for crushed coral sand must be inclined such that the creep volumetric strains are more contractive than those obtained from the plastic potential at the same stress point.

**Stress Relaxation Experiments**

Stress relaxation experiments were performed after primary loading with a strain rate of 0.106% /min. Once the desired stress differences of 500, 700, and 900 kPa had been reached, the axial deformation was held constant to observe the stress difference relax. Relaxation periods of 1,000 min (i.e., a little less than one day) were employed in all but a few experiments in which longer relaxation periods were used. After the stress relaxation stage, the stress difference was again increased sufficiently to join the virgin or primary stress-strain curve before another relaxation test was initiated.

Figure 3(a) shows the stress-strain relations obtained from the basic experiment performed with stress relaxation at the three desired stress differences and at a stress point beyond peak failure. Reloading after stress relaxation exhibits structuration effects similar to those observed after periods of creep, i.e., a temporary increase in the deviator strength beyond that corresponding to the primary loading curve. In all cases, the stress-strain curve appears to unite with or become the primary stress-strain relation well before the next stress relaxation point is reached.

Figure 3(b) shows that volumetric contraction of the specimen is associated with relaxation of the stress difference, whether or not the specimen is contracting or dilat-
Comparison with results from deformation controlled test with and without stress relaxation stages: (a) stress-strain and (b) volume change relations from drained triaxial compression test on crushed coral sand with stress relaxation stages of 1,000 min at stress differences of 500, 700, and 900 kPa.

Comparison of Creep and Stress Relaxation

The stress relaxation may be compared with the creep observations by plotting the points of initiation and the end points after a certain amount of time on the same diagram. To overcome the small differences in the primary stress-strain curves from the two experiments in Figs. 2 and 3, the stress-strain curve shown in Fig. 3(a) is used as the base curve from which creep and stress relaxation are initiated.

The comparison of stress relaxation and creep after one day is shown in Fig. 4 in which the points of initiation of creep have been located on this base curve, while the end points obtained after approximately 1 day of creep are shown relative to the initiation points. The data from both types of tests are very consistent, and they show how much the axial strains change due to creep and how much the axial stresses change due to relaxation, respectively. It is clear that the amount of creep and the amount of relaxation resulting after 1 day define curves that are located at quite different positions.

Figure 5 shows a comparison of creep and stress relaxation effects after one day plotted from a common stress-strain curve for comparable experiments performed to study time effect on Antelope Valley sand (Lade, 2007). As for the crushed coral sand, the experiments on Antelope Valley sand showed that strain rate effects are negligible, and Fig. 5 indicates that the observed stress relaxation behavior does not correspond with the measured creep behavior.

To avoid interference with the creep process during the experiments, the deviator loads were constant and not adjusted according to the cross-sectional area to achieve constant deviator stresses. Thus, both Figs. 4 and 5 show branches of creep with slightly decreasing deviator stresses.

EXPERIMENTS ON VIRGINIA BEACH SAND

Comparison of Creep and Stress Relaxation

It is proposed herein that particle crushing is at the root of time effects in granular materials through the
phenomenon of static fatigue. However, sieve analysis of the tested crushed coral sand and Antelope Valley sand were not performed, because such sieve analyses could not be trusted as explained below. Therefore, a study of the much stronger Virginia Beach sand, which consists of subangular to subrounded quartz particles, was conducted and sieve analyses were performed to prove that particle crushing relate directly to the observed time effects. The details of the equipment, specimen preparation and testing procedures are given by Karimpour and Lade (2010). The experiments were performed in a high pressure triaxial cell with an effective confining pressure of 8,000 kPa at which pressure significant crushing occurs in the Virginia Beach sand.

Similar to observations for crushed coral sand (see Fig. 1) and Antelope Valley sand, experiments on Virginia Beach sand also indicated that strain rate effects on stress-strain and strength behavior are small (Karimpour and Lade, 2010). Figure 6 shows a comparison of creep and stress relaxation effects in Virginia Beach sand. Each of these experiments were performed by shearing a freshly deposited specimens at a constant strain rate of 0.0416% /min up to the point at which the specimens were allowed to creep or to stress relax for one day. The results are plotted from a common stress-strain curve and the initial or final points of each creep and stress relaxation test are indicated by an identification number. This allowed the grain size distribution to be determined at the end of each creep and stress relaxation test.

Relations between Particle Crushing, Energy Input and Time Effects

The grain size distribution curves are shown in Fig. 7 for each of the experiments shown in Fig. 6. It is clear that considerable particle crushing occurs in the tests, and some of the observed crushing relates to creep, as explained in the following. It should be noted that negligible amounts of particle breakage occurs during stress relaxation for which negligible strains occur (Karimpour and Lade, 2010) and the solid circles in Fig. 7 therefore correspond to the breakage that occurred during shearing up to the point at which the stress relaxation is initiated.

Figure 7 shows that the amounts of particle breakage are related to the locations along the stress-strain curve at which the creep and stress relaxation are terminated. To quantify this relationship, the particle breakage is represented by Hardin’s particle breakage factor (Hardin, 1985) and the locations at which creep and stress relaxation are terminated is represented by the energy input per unit volume of the specimen.

Hardin’s particle breakage factor is defined as:

$$B = \frac{B_t}{B_p}$$ (1)

in which $B_t$ is the total breakage represented by the area between the original and the final gradation curves, as shown in Fig. 8, and $B_p$ is the breakage potential represented by the area over the original grain size curve and limited to U.S. sieve No. 200.

The energy input per unit volume is calculated from

$$E = \sigma_c \cdot \Delta \varepsilon_v + \Sigma (\sigma_i - \sigma_c) \cdot \Delta \varepsilon_a$$ (2)

in which $\sigma_c$ is the effective confining pressure, $\Delta \varepsilon_v$ is an increment in volumetric strain, $(\sigma_i - \sigma_c)$ is the deviator stress, and $\Delta \varepsilon_a$ is an increment in axial strain.
Figure 9 shows the relation between Hardin’s particle breakage and the energy input per unit volume for the experiments shown in Fig. 6. A unique and almost linear relation is observed between the amount of particle breakage and the energy input per unit volume to the specimens, which were all sheared at an effective confining pressure of 8,000 kPa. While stress relaxation occurs with no strains and therefore relates to zero energy input, a portion of the energy input relates to the time-dependent phenomenon of creep. It is therefore evident that time effects are related to the crushing of particles. This will be further elaborated below, where the phenomenon of static fatigue is reviewed.

Figure 6 indicates that the observed stress relaxation behavior does not correspond with the measured creep behavior. It is concluded that none of the three sands exhibits classic viscous effects. Note also that the amounts of disagreement between the stress-strain relations after one day of creep or stress relaxation are quite different for the three sands. The fact that the same basic mechanism can account for creep, stress relaxation, and rate dependency and can serve as basis for prediction of one from the other, as is the case for clays, indicates that the material complies with the “correspondence principle” according to Sheahan and Kaliakin (1999). The experiments presented here showed noticeable amounts of creep and relaxation but no strain rate effects. Further, the stress relaxation and the creep responses do not appear to follow the correspondence principle, i.e., two different stress-strain relations are obtained after 1 day, as indicated for three different sands in Figs. 4, 5 and 6. Thus, it appears that the phenomena of creep, stress relaxation and strain rate effects in sand cannot be predicted from the same type of test using a viscous type model.

PROPOSED MECHANISTIC PICTURE OF TIME EFFECTS IN SANDS

Particle breakage has often been observed to be associated with time effects in granular materials, and a mechanistic picture of time effects may be constructed on the basis of this phenomenon. Particle breakage may not occur and time effects are negligible in granular materials at very low stresses. Time effects become significant with increasing confining pressure and increasing stress difference, as has been observed in several studies (see Yamamuro and Lade, 1993). These studies also noted the association between particle crushing and its occurrence with time.

Figure 10(a) shows an assembly of grains that have been loaded up to a given stress difference and either creep or stress relaxation occurs from this point. The diagram shows the force chains down through the assembly. The grain in the middle fractures in the beginning of either of these two types of time effects. The responses of the grain assembly are quite different for the two phenomena. Figure 10(b) shows what happens during creep in which the vertical stress is held constant. The assembly adjusts its structure to carry the vertical stress. This requires adjustment of the grains and it results in some vertical deformation and new force chains are created to match the externally applied stress. The redundancy in the grain structure allows new force chains to be created and engage other grains that may break. But slowly the amount of breakage will reduce and the creep will slow down with time, just as observed in the experiments.

Figure 10(c) shows what happens in the stress relaxation experiment. After the grain has broken, the grain structure is not able to carry the vertical stress, but since the assembly is prevented from vertical deformation, the stress relaxes. New force chains are created around the broken grain which does not carry any load. It is the small amount of grain movement in the creep tests that allows new contacts to be created and forces to be carried through the grain skeleton. Without this adjustment and consequent deformation to achieve the adjustment, the grain structure is able to transmit only a reduced load and stress relaxation is the consequence. It can also be seen that if a lower limit to the relaxed stress exists, then it depends on the grain strength rather than its frictional properties. Thus, the amount of difference between the creep and stress relaxation for the three sands shown in Figs. 4, 5 and 6 may be explained in terms of and relates primarily to different grain strengths.

It may be seen that a relation between creep and stress relaxation does not exist, because the two explanations
do not allow a transition from one to the other phenomenon. Thus, Figs. 4, 5, and 6 show that the amounts of creep and the amounts of stress relaxation after one day do not converge towards the same curves. In fact, the two sets of curves are quite different and one cannot be obtained from the other. This nonisotach behavior is quite different from that of the isotach, viscous behavior exhibited by clays.

With only friction (and slippage when the frictional resistance is overcome) and particle breakage (when the strengths of the particles are overcome) as basic behavior constituents, how can the observed time effects be explained for granular materials? Experiments on rock specimens have clearly shown that their strengths are strongly dependent on time. Crushing of single sand particles indicates that they behave similar to rock specimens in the sense that their crushing strengths are time-dependent. This phenomenon is referred to as static fatigue or delayed fracture.

**STATIC FATIGUE**

Static fatigue is a phenomenon that leads to fracture and crushing of individual soil particles. Brittle fracture of materials such as quartz, feldspar, concrete and rock are similar to those of glasses and other ceramics, all brittle materials, in which fracture occurs due to time-dependent crack propagation and with negligible deformation prior to fracture. Sustained static loading of a soil particle may eventually lead to fracture at stresses considerably smaller than the short-term strength (Lawn, 1993; Lemaitre and Chaboche, 1994; Suresh, 1998; Callister, 2005).

*Internal Microcracks*

Rock materials, from which most soil particles derive, contain a distribution of flaws or microcracks caused by their formation history. In igneous rocks, residual stresses are created at grain boundaries and at interfaces between grains with dissimilar thermal expansion coefficients and with dissimilar elastic properties, and they produce a distribution of microcracking during cooling from the high formation temperatures of the magma. Similar microcracks are formed in metamorphic rocks as the exposure of the parent material to high pressures and temperatures is reduced as they emerge and are exposed to mechanical and chemical weathering at the Earth’s surface. Sedimentary rocks are full of microcracks between the grains and their boundaries with cementing agents. In addition, pores and gas bubbles may be included in any type of rock. These pre-existing flaws serve as potential sites of nucleation and further propagation of major cracks.

As a result, the strengths of rock specimens vary with size as described by Weibull (1951), who observed that the strength of brittle solids is a statistical phenomenon caused by a pre-existing distribution of flaws in specimens with the same shape:

\[
\sigma_{1ult} = \sigma_{2ult} \left( \frac{V_2}{V_1} \right)^{1/m}
\]

in which \(\sigma_{1ult}\) is the strength of a particle with volume \(V_1\) and \(\sigma_{2ult}\) is the strength a particle with similar shape and volume \(V_2\). The value of the exponent \(m\) is in the order of 6–18 for different types of coal (Jaeger and Cook, 1969). Thus, larger particles are weaker than smaller particles, because larger particles are more likely to contain critically oriented microcracks and are therefore exposed to fracture at lower stresses than smaller particles. Considerable scatter occurs in the fracture of brittle solids and statistical treatment of experimental results is necessary to achieve sensible results.

Single particle crushing has been studied in a number of experimental investigations performed in recent years (e.g., McDowell and Bolton, 1998; Nakata et al., 1999, 2001a, b; Tang et al., 2001; Kou et al., 2001; Bolton et al., 2008). In a study of the fracture strength of spherical sodium lime glass beads with diameters of 2, 3, and 6 mm, the expression in Eq. (1) was found to describe the strength variation with sphere volume very well, and the value of the exponent \(m\) was determined to be \(m = 3\) (Lade and Karimpour 2010).

*Surface Cracks*

In addition to the internal microscopic flaws, surface cracks may be produced near particle contacts (Suresh, 1998) due to (1) stationary normal loading, which produces elastic indentation and tensile stresses parallel to the surface outside the actual contact, (2) partial slip and complete sliding at the particle contacts, which results in non-uniform shear stress distribution and tearing parallel to the surface, and (3) rolling of particles, which results in varying normal and shear stresses underneath the contact point. Thus, surface cracks may be produced as explained by contact mechanics and tensile fracture of the particles while the soil mass is compressed and sheared.

The surfaces of granular soil particles are also known to be rough such that contacts between particles occur at extremely small asperities. At the atomic level the particle surfaces are very uneven and full of rough features at which stress concentrations may produce additional cracks.

*Effects of Blasting*

Rockfill is produced by blasting of solid rock and this process results in very angular particles with a large number of surface cracks created by the stress waves, especially by the tensile stress through following the initial compressive wave from the blast. Surface cracks play an important role in static fatigue, because the environment, especially the presence of humidity or water, in which the soil is present, has great influence on the speed of crack propagation, as explained below.

*Loading of Brittle Solids*

As a brittle solid is loaded in shear, it goes through
several stages, indicated in Fig. 11 (after van Mier, 2009). During the first stage the microscopic flaws grow in size due to stress concentrations at the highly stressed regions around the crack tips, as shown schematically in Fig. 12. During the second stage the microcracks begin to coalesce to form larger cracks which eventually lead to catastrophic fracture of the specimen. During this second stage, which is basically stable in the sense that additional load can be added, the propagation of the larger cracks occurs at an accelerating rate with very little accompanying plastic deformation. The third stage consists of structural instability and complete fracture of the specimen. Static fatigue refers to the crack growth that occurs under sustained loading and that leads to the catastrophic fracture in the third stage. The crack growth occurs at the sharp ends of the cracks due to stress corrosion, and it is primarily the strength of the atomic bonds at the crack tips that controls the fracture resistance.

**Speed of Fracture Propagation**

The speed with which fractures propagate in brittle solids and therefore the progression of static fatigue is strongly influenced by mechanical and environmental factors. Clearly the state of stress is of primary importance. At higher tensile stresses the microcracks begin to grow at a faster rate, and the time to complete fracture diminishes. Brittle fracture test results can exhibit considerable amounts of scatter, but Charles (1958) has expressed a relation between tensile strength of glass specimens and time-to-fracture as follows:

\[ \sigma_{ult} = \sigma_{2ult} \left( \frac{t_2}{t_1} \right)^{1/n} \]  

in which \( \sigma_{ult} \) is the strength of a particle with time-to-fracture \( t_1 \) and \( \sigma_{2ult} \) is the strength of a particle with time-to-fracture \( t_2 \). Typical values of the exponent \( n \) are reported as 16 for glass (Charles, 1958), 98 for Carrara marble and 8 for Pennant sandstone (Cruden, 1974).

Lade and Karimpour (2010) loaded sodium lime glass beads of three different sizes and sustained the load at certain percentages of the short-term strengths to study the time-dependent static fatigue. They found the scatter of test results to be so pronounced that it was not possible to characterize the time effects for single particles by the expression in Eq. (2). Nevertheless, static fatigue was clearly observed in the sense that fracture occurred after some time (from seconds to days) when the beads were loaded up to the vicinity of their short term strengths. The time-dependent strengths of non-spherical single grains with a variety of shapes are likely to be even more difficult to predict. However, when integrated over a large number of particles, as in a triaxial specimen which contains millions of particles, the time-dependent behavior is very systematic and conforms to a regular pattern.

**Environmental Effects**

The speed of crack growth in the second stage is also decisively influenced by the environment to which the surface cracks are exposed. It is the rupture of atomic bonds at the crack tips that constitute the principal mode of failure. Figure 13 shows a model of a sharp crack at the atomic level. The bonds between the atoms act as nonlinear elastic springs that snap when the atoms are sufficiently separated. In addition, it has been found that the presence of water or water vapor has profound influence on the chemical reactions that lead to weakening and tensile failure near the crack tips. Thus, in glass (quartz) the water molecules may react with the silica atoms at the crack tips exposed to tensile stresses with the effect of unzipping the atomic bonds, as exemplified in the diagram in Fig. 14. The chemical reactions occurring at the crack tip are schematically indicated in Fig. 15(a) for glass and water and 15(b) for glass and water in an alkaline solution (Michalske and Freiman, 1981, 1983;
This in turn sharpens the crack tips and increases the crack propagation speeds. Therefore, the brittle material appears to be more brittle with accelerating crack propagation speeds in the presence of water. Thus, the pH in the humid environment as well as the presence of other chemical components near the crack tips may serve to increase the speed of stress corrosion (Wiederhorn, 1975). Oldecop and Alonso (2007) investigated the effect of water on the time-dependent behavior of rockfill and they found that the settlement of rockfill dams with time could be understood in terms of the water-enhanced static fatigue of the rockfill.

**Effects of Water Introduction in Dry Granular Material**

Because brittle material appears to be more brittle with accelerating crack propagation speeds in the presence of water, an experiment was performed on an initially dry sand to study the effect of introducing water into an already highly stressed granular material. A triaxial specimen was prepared of oven-dry Virginia Beach sand, isotropically confined at 8,000 kPa, and percolated with gaseous CO$_2$ before shearing under strain control to a deviator stress near 14,000 kPa as shown in Fig. 16. Water was then introduced from the base to saturate the specimen. It is clear that introduction of water causes fracture and partial collapse of the particle structure during the upwards migration of the water front in the specimen. This experiment confirms that particles are more brittle in the presence of water, and together with the relations between particle crushing, energy input, and the observed time effects, this helps confirm that the mechanism of static fatigue controls time effects in granular materials.

**Overall Effect of Static Fatigue**

The overall stress-strain-time behavior of specimens or particles of brittle solids that exhibit static fatigue is indicated in Fig. 17 (Rusch, 1960). As the stress on the specimen is held constant below the short-term fracture stress, the time to fracture increases with decreasing stress until fracture does not occur at all at some limiting stress,
which may be characterized as a percentage of the short-term fracture strength.

The resulting overall stress-strain-time behavior of a triaxial specimen consists of the integrated response of millions of particles in the granular material in which force chains are established, meander, and become stronger with increasing load. Compared with the response of individual particles, which may show considerable variation and scatter, the responses of the triaxial specimens exhibit very little scatter in their stress-strain-time relations, as seen in the studies of crushed coral sand, Antelope Valley sand and Virginia Beach sand discussed here.

EFFECT OF PARTICLE STRENGTH

While the strengths of the particles in the three types of sand whose results are shown in Figs. 4, 5, and 6 were not explicitly measured, an impression of the crushability of the particles was obtained from the sand that came out of the specimens after testing. For the purpose of the present study, the crushed coral sand was initially sieved and the sand used for testing was composed to create an initial straight grain size curve with the original intent of possibly sieving the soil after testing. However, what was retrieved after testing was a paste that was not amiable to sieve analysis. Thus, the crushed coral sand consisted of very soft and weak grains.

The Antelope Valley sand, whose results are shown in Fig. 5, was a relatively friable sand obtained from a streamed in the desert north of Los Angeles. While crushing was evident from the grain sizes that came out of the specimens after testing, the sand was so friable that reliable grain size analyses could not be obtained from shaking a stack of sieves, which could easily cause additional particle crushing. However, individual grains were visible after testing and they were likely stronger than the crushed coral sand. Both these studies were conducted at effective confining pressures near 200 kPa.

The third study was performed on Virginia Beach sand, consisting mainly of quartz. This study was carried out with effective confining pressures of 8,000 kPa at which considerable amounts of crushing occur. It is clear that this sand had the strongest particles of the three sands, because considerable crushing magnitudes were required to crush this sand.

Comparing the differences between the one day creep curves and the one day stress relaxation curves for the three sands in Figs. 4, 5, and 6, it appears that these differences may depend primarily on the grain crushability. While other factors such as particle size distribution, particle shape and mineral composition may also play a role, the pattern is not discernable on the basis of the three studies presented here, because both the particle strengths and the stress magnitudes varied in the experiments. However, it appears that the particle strength is related to the nonisotach behavior observed for granular materials. Additional studies are required to determine any behavior pattern.

CONCLUSIONS

Observations from experiments show that strain rate effects are negligible for sands, unlike for clays in which strain rate effects are significant. Further, the observed stress relaxation behavior of granular materials were not in “correspondence” with the measured creep behavior for three different sands. Triaxial experiments with branches of creep at different deviator stresses formed a consistent stress-strain relation after one day of creep, and similar tests with stress relaxation also formed a consistent stress-strain relation after one day of relaxation. However, the two relations were quite different with the relation after one day of stress relaxation showing much larger strains at the same deviator stresses. These differences appear to be related to the particle strength, but no pattern is discernable from the existing experiments. It is concluded that sands do not exhibit classic viscous effects, and their behavior is indicated as “nonisotach”, while the typical viscous behavior of clay is termed “isotach”. Thus, there are significant differences in the time-dependent behavior patterns of sands and clays.

A mechanistic picture of time effects in sands is proposed in which interparticle friction, grain crushing, and grain rearrangement play the key roles. Grain crushing is a time dependent phenomenon known as static fatigue and this accounts for the time dependency observed in granular materials. The characteristics of the phenomenon of static fatigue are reviewed and the experiments on crushed coral sand, Antelope Valley sand and Virginia Beach sand confirmed that the phenomenon of static fatigue can explain the behavior patterns observed in granular materials.

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