PARTICLE-CRUSHING OF A DECOMPOSED GRANITE SOIL UNDER SHEAR STRESSES

NORIHIKO MIURA* and SUKEO O-HARA**

ABSTRACT

The effect of particle-crushing on the shear characteristics of a decomposed granite soil was investigated by a triaxial compression test and a repeated triaxial test. The increase in surface area, \( \Delta S \) is used as the measure for the amount of particle-crushing, and it is shown that the amount of particle-crushing \( \Delta S \) induced by the shear stresses has a close relation to the plastic work done \( W \).

The particle-crushing property of the sample under shear stresses is defined by the rate of increase of the surface area \( S \) to the plastic work done \( W (\Delta S/dW) \), which is called the "particle-crushing rate" in this paper, and a close relation is found between the particle-crushing rate and the dilatancy rate or the shear strength.

The particle-crushing property of the decomposed granite soil examined in this study is compared with that of a sand under high pressures (Miura et al., 1977), and it is concluded that the particle-crushing phenomenon of the decomposed granite soil under low pressures is substantially the same as the particle-crushing phenomenon of the Toyoura sand under high pressures.

The particle-crushing phenomenon under repeated deviator stresses is also investigated, and it is suggested that the amount of particle-crushing \( \Delta S \) is also a function of the plastic work done \( W \).

Key words: decomposed granite soil, dilatancy, grain shape, particle-breakage (particle-crushing), repeated load, shear strength, triaxial compression test

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INTRODUCTION

Decomposed granite soils are produced in the weathering phase of granites, and the soils widely distribute in the western region of Japan. It is known that decomposed granite soils have such special properties as: a) Mechanical properties considerably scatter with the degree of weathering; b) A marked decrease in shear strength occurs when the soil is submerged; c) Particles are so weak that a remarkable amount of particle-crushing occurs under relatively low stresses (The authors have used the word 'particle-crushing' before the 'particle-breakage' was adopted as a key word). As to the particle-crushing phenomenon, a few studies have been made concerning the compaction property and permeability (Fukumoto, 1972; Matsuo et al., 1977), but strictly limited information has been obtained on the particle-crushing phenomenon of decomposed granite soils under shear stresses.

* Assistant Professor, Department of Civil Engineering, Yamaguchi University, Tokiwadai, Ube 755.
** Professor, Department of Civil Engineering, Yamaguchi University, Tokiwadai, Ube, 755.

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For making a contribution to this problem, this paper deals with the particle-crushing phenomenon of a decomposed granite soil under both static and repeated deviator stresses. Concerning the problem of particle-crushing, Miura and Yamanouchi (1977) have investigated the effect of particle-crushing on the shear characteristics of a quartz-rich sand under high pressures and have come to the following conclusions: a) As a measure for the amount of particle-crushing surface area, $S$ is reasonable to use. b) The amount of particle-crushing is a function of the plastic work done $W$, c) The rate of increase of $S$ to $W (dS/dW)$ is a useful quantity for evaluating the effect of particle-crushing on the shear characteristics of the sand.

It is an intuitive inference that the particle-crushing phenomenon of a granular soil consisting of breakable particles under low stresses may substantially be the same as the particle-crushing phenomenon of a granular soil consisting of strong particles under high pressures. One of the purposes of this study is to examine whether or not the conclusions derived from the high pressure triaxial tests on the quartz-rich sand can apply to the particle-crushing phenomenon of a decomposed granite soil in both the static triaxial compression tests and the repeated triaxial tests at a confining pressure up to 3 kgf/cm$^2$ (≈294 kPa).

**SOIL AND PREPARATION OF SPECIMEN**

**Soil**

A sample of decomposed granite soil was taken from a borrowed pit in Ube city, containing a fine fraction ($<74\mu$m) of 15 percent and a coarse fraction ($>2000\mu$m) of 30 percent. From this original soil, the fine fraction and the coarse fraction were eliminated by sieving to obtain a sample for testing, of which grain size distribution is depicted in Fig. 1. Various properties of the sample are as follows: Specific gravity $G_S=2.62$; Maximum voids ratio $e_{\text{max}}=0.944$ and minimum voids ratio $e_{\text{min}}=0.505$; Fifty percent diameter $d_{50}=820\mu$m; Uniformity coefficient $U_0=d_{40}/d_{10}=6.0$. The shape of each particle of the sample was very angular as is seen in Photo. 1.

The particle-crushing of a soil consisting of very breakable particles does occur even in the process of sieving, and hence the amount of sample passing through a sieve actually increases with the time of sieving. Therefore, it is necessary to know beforehand the appropriate time for sieving.

According to a preliminary test to determine an appropriate sieving time for the sample tested, as illustrated in Fig. 2, the sieving time is insufficient when shorter than 4 minutes.

![Fig. 1. Grain size distributions of the tested sample](image1.png)

![Photo. 1. Typical grain shape of the tested sample](image2.png)
and excessive when longer than 10 minutes. Thus, sieving of the sample was performed for 5 minutes using a ro-tap sieve shaker.

**Specimen**

All specimens were prepared by the following method and were commonly used in standard triaxial compression tests and repeated triaxial tests. A dry sample of about 380 g provided for making a specimen was divided into four groups in beakers and these were submerged and boiled to eliminate trapped air. All the divided samples were used for making a specimen of a size 50 mm in diameter and 125 mm in height. The compaction of the sample was made by a vibration method to give a specimen of an initial voids ratio of 0.54 to 0.56, which is called the 'dense' state in this paper.

**MEASUREMENT OF SURFACE AREA**

To evaluate the particle-crushing numerically, several methods have been proposed. Marsal (1967) has used the "particle breakage B" that is calculated from the difference of the grain size distributions before and after testing. Fukumoto (1972) has defined an index "S. I." as the logarithm of ratio of specific surface areas (in cm²/g) before and after testing. Miura and Yamanouchi (1977) have shown that the increase in surface area ΔS (in cm²/cm³) is a reasonable measure for describing the amount of particle-crushing quantitatively. This study also uses the increase in surface area as the measure for the amount of particle-crushing. The surface area S is given by $S = S_w \cdot r_d$, where $r_d$ (g/cm³) is the current value of the dry density of the specimen being tested, and $S_w$ is the specific surface area (cm²/g). The value of a specific surface area of the sample finer than 74 μm is measured by the Blaine method, which is widely used for measuring the specific surface area of a cement powder. The Blaine method is not suitable for measuring the specific surface area of a sample coarser than 74 μm, thus, the specific surface area of the coarse fraction was evaluated by the following way: The sample was divided into ten grades of grain size by sieving (openings of sieves used: 1190, 840, 590, 420, 210, 177, 149, 105, and 74 in μm). For example, for the sample whose grain size $d$ is 2000 μm > $d$ > 1190 μm, the mean diameter $d_m$ is given by $d_m = \sqrt{2000 \times 1190} = 1543$ μm, and assuming that all particles are spherical, then the specific surface area can be calculated as 14.9 cm²/g. In the same way, the values of the specific surface areas of ten grades are calculated respectively, and are summed up to obtain the specific surface area of fraction coarser than 74 μm. The values obtained by these methods were summed up and the specific surface area of the sample is given.

In the evaluation of a specific surface area by the method mentioned above, the assumption that particles are spherical inevitably leads to an underestimation of the value of the specific surface area of a sample coarser than 74 μm. For the sample whose grain size $d$ is between 74 and 105 μm, for instance, the mean diameter is calculated as $d_m = \sqrt{74 \times 105} = 88$ μm, and thus the specific surface area is 260 cm²/g. On the other hand, the specific surface area of the same sample measured by the Blaine method was scattered between 350 and 450 cm²/g, even though the Blaine method is considered not appropriate for measuring.

**Fig. 2. Determination of the appropriate sieving period**
a specific surface area smaller than 1000 cm$^2$/g. Comparing the calculated value and measured value of specific surface area above stated, it may be said that the error due to the assumption that particles are spherical is at most several tens percent. A more reliable value for the specific surface area of the sample can be estimated by knowing the 'shape factor' (Kubo et al., 1973), but this study makes no further discussion on this problem.

PARTICLE-CRUSHING UNDER STATIC SHEAR STRESSES

Test
A series of triaxial compression tests under conditions of drained and constant confining pressures (CD test) were performed on specimens of the dense state. Consolidation under hydrostatic pressure was carried out for thirty minutes. The rate of loading in a shear stage was about 0.6 mm per minute. The volume change in a specimen during the test was measured by the amount of drained water into a buret. As a shear test under a condition such that particle-crushing is substantially negligible, a series of triaxial compression tests at a confining pressure of 0.1 k gf/cm$^2$ (=9.8 kPa) were carried out. A confining pressure of 0.1 k gf/cm$^2$ (=9.8 kPa) was generated by the water head from a water vessel. This water vessel could move up or down so as to hold the magnitude of confining pressure constant during the shear tests, corresponding to a change in the water level of the buret connected to a specimen whose volume change was to be measured.

Test Results
Typical stress-strain curves obtained in the triaxial compression tests on the saturated specimens of the dense state (initial voids ratio is about 0.55) are presented in Fig. 3, in which the axial strain $\varepsilon_{1}$ and volumetric strain $v$ are both expressed in natural strain. As

![Fig. 3. Stress-strain curves of the saturated dense sample in drained triaxial compression test](image-url)
the confining pressure $\sigma_3$ increases, the axial strain at failure $\varepsilon_{1f}$ increases and the volumetric strain at failure $\nu_f$ changes towards the volume contraction. The magnitude of $\sigma_3$ that makes the value of $\nu_f$ zero is about 3 kgf/cm$^2$ (=294 kPa). Fig. 4 illustrates the changes in the maximum principal stress ratio $(\sigma_{1f}/\sigma_3')_f$ and dilatancy rate $(d\nu/d\varepsilon_3)_f$ with increasing confining pressure. On this semilogarithmic diagram, curves of $(\sigma_{1f}/\sigma_3')_f$ versus $\sigma_3$ and $(d\nu/d\varepsilon_3)_f$ versus $\sigma_3$ may roughly be approximated by linear lines. Taking notice of the change in the maximum principal stress ratio, it is found that the value of $(\sigma_{1f}/\sigma_3')_f$ at $\sigma_3=3.0$ kgf/cm$^2$ (=294 kPa) is reduced to only 70 percent of the value of $(\sigma_{1f}/\sigma_3')_f$ at $\sigma_3=0.1$ kgf/cm$^2$ (=9.8 kPa). Such a significant reduction of the maximum principal stress ratio with an increase in the confining pressure is due mainly to the particle-crushing as explained later, and this inevitably brings about the non-linear characteristics of the Mohr envelope.

Mohr's circles are depicted in Fig. 5, which shows that the convex was the shape of a
failure envelope. Such a shape of the failure envelope is ordinarily obtained when a granular material of the dense state is sheared in a wide range of confining pressures large enough to cause particle-crushing (Miura et al., 1977). The relation between \((\sigma_1'/\sigma_3')_f\) and \((d\sigma_1/d\varepsilon_1)_f\) is represented in Fig. 6, which shows that there exists an approximately linear relation between the two values. A linear relation between the maximum principal stress ratio \((\sigma_1'/\sigma_3')_f\) and the dilatancy rate \((d\sigma_1/d\varepsilon_1)_f\) has also been found in high pressure triaxial compression tests on the Toyoura sand (Miura et al., 1977).

**Particle-Crushing Property**

As stated previously, an increase in surface area was adopted as the measure for particle-crushing, and the change in the amount of particle-crushing during the shear was investigated. Fig. 7 illustrates the change in surface area increase \(\Delta S\) with developing of the axial strain \(\varepsilon_1\) (natural strain) in the CD tests at various confining pressures. It seems curious that the surface area of a sample sheared at a confining pressure of 0.1 kgf/cm\(^2\) (=9.8 kPa) decreases with increasing axial strain. This is caused by the marked expansion in volume, and hence a decrease in dry density, during the shear. Namely, as stated previously, the surface area \(S\) (cm\(^2\)/cm\(^3\)) is given by the product of specific surface area \(S_w\) (cm\(^2\)/g) and the dry density \(\gamma_d\) (g/cm\(^3\)),

**Fig. 6. Relation between maximum principal stress ratio \((\sigma_1'/\sigma_3')_f\) and dilatancy rate \((d\sigma_1/d\varepsilon_1)_f\) in drained triaxial compression test at various confining pressures**

**Fig. 7. Relation between increase of surface area \(\Delta S\) and axial strain \(\varepsilon_1\) in drained triaxial compression test at various confining pressures**
and when the decrease in $\tau_d$ overcomes the increase in $S_o$ during the shear, the value of $S$ decreases. It is noted in Fig. 7 that the value of $\Delta S$ continues to increase as the axial strain increases even after the failure point is reached, where the stress increment is zero or negative. Similar results were obtained in previous studies for several kinds of granular materials (Miura et al., 1975, 1976). It is self-evident that an increase in surface area may be a function of the magnitude of stress. Thus the conclusion derived from the previous study that the value of $\Delta S$ is a function of work done $W$ to the specimen, should be applicable to the test results obtained here.

As the work done, we chose the plastic component of a total work, taking into account that particle-crushing is an irrecoverable phenomenon. An increment in plastic work per unit volume, $dW$ is given by the following equation:

$$dW = dE - dU$$  \hspace{1cm} (1)

where, $dE$ and $dU$ are increments of total work and recoverable work respectively. By using stresses $q$ and $p$, and strain increments $d\varepsilon$ and $dv$, Eq. (1) may be expressed for a triaxial compression test at a constant confining pressure, as,

$$dW = (q d\varepsilon + pdv) - (qd\varepsilon + pdv)_r$$  \hspace{1cm} (2)

where, $q = \sigma' - \sigma'_r$, $p = (\sigma'_r + 2\sigma'_s)/3$, $dv = d\varepsilon + 2d\varepsilon_u$, $d\varepsilon = d\varepsilon - (dv/3)$, and suffix ‘$r$’ means recoverable component. Incorporating Roscoe’s assumption (Roscoe et al., 1963) that $(q d\varepsilon)_r = 0$, then

$$W = \int (q d\varepsilon + pdv) - \int (pdv)_r$$  \hspace{1cm} (3)

Depicting $q - \varepsilon$ curve and $p - v$ curve, the plastic work done per unit volume of a sample can be obtained as the sum of the two areas enclosed in the $q - \varepsilon$ curve and the $p - v$ curve. Fig. 8 indicates the change in plastic work done $W$ during the shear testing with developing axial strain $\varepsilon_1$.

**Fig. 8.** Relation between plastic work $W$ and axial strain $\varepsilon_1$ in drained triaxial compression test at various confining pressures
From the two relation curves $\varepsilon_1 - \Delta S$ (Fig. 7) and $\varepsilon_1 - W$ (Fig. 8), the $\Delta S - W$ relation curve can be depicted as shown in Fig. 9. It is noted in this figure that the $\Delta S - W$ relation is represented by a unique line which is concaved, irrespective of the magnitude of confining pressure. In the case of the Toyoura sand under high pressures, the $\Delta S - W$ curve was also represented by a unique line, but it was an 'S' type curve (Miura and Yamanouchi, 1977). The $\Delta S - W$ curve shown in Fig. 9 may be an initial stage of the 'S' type curve; that is, if a large amount of plastic work is done additionally, the corresponding part of the $\Delta S - W$ curve will develop into an 'S' type curve. Inspecting the characteristics of the $\Delta S - W$ curve in the light of Tanaka's comminution equation, it may be derived a useful quantity for evaluating the particle-crushing property of a material under shear stresses. Tanaka (1954) has presented the following comminution equation in which the final value of the surface area $S_w$ is taken into consideration, as follows:

$$\frac{dS}{dE} = K(S_w - S)$$

where, $E$ is grinding energy, $dS/dE$ is energy efficiency and $K$ is comminution coefficient.

Eq. (4) implies that the comminution efficiency of a material subjected to grinding is successively changed with developing of grinding. Taking notice of the analogous characteristics of $\Delta S - W$ curve to Tanaka's equation, it may be reasonable to consider that the slope of the $\Delta S - W$ curve ($dS/dW$), corresponding to the energy efficiency ($dS/dE$) in Eq. (4), is an appropriate quantity by which we can evaluate the particle-crushing property of a sample under triaxial compression stresses. In the following, therefore, the relation between shear characteristics and the value of $dS/dW$, called the "particle-crushing rate" hereafter, are investigated.

![Graph showing the relation between increase of surface area $\Delta S$ and plastic work $W$ in drained triaxial compression test](image)

**Fig. 9.** Relation between increase of surface area $\Delta S$ and plastic work $W$ in drained triaxial compression test
Effect of Particle-Crushing on Shear Characteristics

As a result of particle-crushing, void of a sample is filled with crushed particles to some extent and the sample is densified. Accordingly, it is expected that an intimate relation between the particle-crushing property and the volume change characteristics of the sample under shear stresses can be found. The volume change characteristics under shear stress, especially at the time of failure, can be represented by a dilatancy rate at the failure, \((dv/d\varepsilon_e)_f\). On consideration of this, the authors examined in what way the particle-crushing property defined by \((dS/dW)_f\) is related to the volume change characteristics at failure \((dv/d\varepsilon_e)_f\).

The relation between the particle-crushing rate at the failure \((dS/dW)_f\) and the dilatancy rate \((dv/d\varepsilon_e)_f\) is presented in Fig. 10, which shows that there exists a direct relation between these two rates. It can be seen in Fig. 10 that the value of the dilatancy rate corresponding to \((dS/dW)_f = 0\) is \(-0.8\). Plotting this value, \((dv/d\varepsilon_e)_f = -0.8\) in Fig. 4 and we can see the magnitude of confining pressure \(\sigma_s\) at which the particle-crushing rate becomes zero, that is, \(\sigma_s = 0.65\text{kgf/cm}^2 (= 64\text{kPa})\). From the relation curve \((dS/dW)_f\) versus \((dv/d\varepsilon_e)_f\), the following may be said: At a confining pressures lower than 0.65 \text{kgf/cm}^2 (= 64 \text{kPa}), the value of \((dS/dW)_f\) is substantially zero, meaning that no particles are crushed at the time of a failure under the conditions of these confining pressures; At a confining pressure higher than 0.65 \text{kgf/cm}^2 (= 64 \text{kPa}), both particle-crushing rate and dilatancy rate increase with increasing confining pressure; in other words, as the particle-crushing rate \((dS/dW)_f\) becomes larger due to particle-crushing, the dilatancy rate \((dv/d\varepsilon_e)_f\) changes towards volume contraction. Now, as was shown in Fig. 6, there is a linear relation between the maximum principal stress ratio \((\sigma_1/\sigma_3)_f\) and dilatancy rate \((dv/d\varepsilon_e)_f\). This relation is combined with the relation between the particle-crushing rate and the dilatancy rate, and thereby it can be seen that there exists a direct relation between the particle-crushing rate and the maximum principal stress ratio, as indicated in Fig. 11. The same result was found for the Toyoura sand during high pressure triaxial compression tests.

It should be emphasized from the results above—mentioned that the factor responsible for decreasing the shear strength of a sample is not the total amount of particle-crushing, but

![Fig. 10. Relation between dilatancy rate \((dv/d\varepsilon_e)_f\) and particle-crushing rate \((dS/dW)_f\) in drained triaxial compression test](image-url)
the rate of particle-crushing at the time of failure. Thus the particle-crushing phenomenon of the decomposed granite soil during standard triaxial compression tests can be interpreted in much the same way as the particle-crushing phenomenon of the Toyoura sand during high pressure triaxial tests (Miura and Yamanouchi, 1977). From this, it may be concluded that the particle-crushing phenomenon, under low stress, of a soil consisting of breakable particles is substantially the same as the particle-crushing phenomenon, under high pressures, of a soil consisting of strong particles.

PARTICLE-CRUSHING UNDER REPEATED SHEAR STRESSES

The foregoing section made clear that the amount of particle-crushing of decomposed granite soil under static shear stress has an intimate relation with plastic work done to the specimen. As a contrast to the particle-crushing under static shear stresses, the authors investigated the particle-crushing of a sample subjected to repeated shear stress. Such an investigation may be significant for making clear the behavior of decomposed granite soils as subgrade materials.

Test

Repeated triaxial tests were carried out using a dynamic triaxial test apparatus (O-hara, 1972) under conditions of drained and constant confining pressures. A saturated specimen in the dense state ($\varepsilon_0 \approx 0.55$) was consolidated at a specific confining pressure, and then was subjected to a repeated deviator stress of a given amplitude at a specific frequency. To give a repeated deviator stress to the specimen, an upper pressure plate was connected to a spindle jointed to a piston rod from an air-cylinder of bello-phram type. To the upper and lower chambers of the air-cylinder, compressed air was fed alternately to move the piston rod up and down. The repeated deviator stress was regurated by air pressures induced into the bello-phram air-cylinder, and the magnitude of the stress was measured by a transducer of a wire strain gage type. An axial strain of the sample was observed through the displacement of the spindle using a displacement meter of a differential transformer type.
The deviator stress was applied in square waves and its frequency was 0.5 Hz.

**Test Results**

The relation between the volume strain \(v\) and the number of cycles in the repeated triaxial test under various stress ratio \(\sigma_d/2\sigma_s\) is illustrated in Fig. 12. The stress ratio \(\sigma_d/2\sigma_s\) is the ratio of shear stress on a plane inclined at 45 degrees to the \(\sigma_s\) direction, \(\sigma_d/2\) to a confining pressure \(\sigma_s\). The changes in volume strain \(v\) and axial strain \(\varepsilon_i\) with increasing loading number up to 500 cycles are shown in Fig. 13. It can be seen in this figure that a significant part of the total changes in \(v\) and \(\varepsilon_i\) occur during repeated stress of the initial 200 cycles. In order to investigate the particle-crushing under repeated loading, the surface area was measured for the specimens subjected to repeated deviator stress of a prescribed number of cycles. The typical relation curve between the increase in surface area \(\Delta S\) and the number of cycles in repeated loading \(N\) is presented in Fig. 14. According to this figure, the increase of surface area \(\Delta S\) under repeated deviator stress rapidly develops during the initial loading of 100 to 200 cycles, and after that, the rate of surface area increase gradually lessens. The amount of plastic work done per unit volume during
one cycle of a repeated deviator stress is given from the area of the hysteresis loop of $\sigma_d - \varepsilon_1$ and the value of the $\sigma_d dv_p$, where $dv_p$ is an increment of the plastic volume strain. A typical diagram of the changes of the plastic work done per one cycle and the accumulated plastic work with increasing of the number of cycles is shown in Fig. 15.

The relation between the increase of surface area $\Delta S$ and plastic work done $W$ was as shown in Fig. 16. The experimental data are limited in number, but the $\Delta S - W$ curve seems capable of being represented by a unique curve independent of the magnitude of the stress ratio $\sigma_d/2\sigma_3$ or the confining pressure $\sigma_3$. The shape of $\Delta S - W$ curve from the repeated triaxial tests is convex and it is somewhat different from the $\Delta S - W$ curve from the static triaxial tests (Fig. 9). Such a different tendency may be caused by the differences of particle-crushing property of the sample under dynamic and static stresses. Further investigation is needed to obtain a more definite conclusion on the particle-crushing during repeated deviator stresses. However, the experimental results above give significant suggestions that the amount of particle-crushing during a repeated triaxial test may be a function of the plastic work done in the same manner as the amount of particle-crushing during a static triaxial compression is a function of plastic work done.

![Figure 16. Relation between increase of surface area $\Delta S$ and plastic work $W$ in repeated triaxial test in various conditions of stress ratio and confining pressure](image)

**CONCLUSIONS**

On a decomposed granite soil consisting of breakable particles, particle-crushing phenomena during both static triaxial compression tests and repeated triaxial tests were investigated and the following conclusions were derived.

1) The increase in surface area of the sample $\Delta S$ ($cm^2/cm^3$) is useful as a measure for the amount of particle-crushing under shear stress.

2) The amount of particle-crushing under triaxial stress was found to be a function of plastic work done, $W$.

3) The relation between $\Delta S$ and $W$ was represented by a concaved unique curve irrespective of the magnitude of confining pressures.

4) The slope of $\Delta S - W$ curve is defined as a quantity of particle-crushing property,
and it has been shown that this value, the particle-crushing rate, has a close relation with volume change characteristics and hence with the strength of the sample tested.

5) Conclusions 1)—4) are identical with the conclusions derived from the previous study on the particle-crushing phenomenon for the Toyoura sand during high pressure triaxial compression tests (Miura et al., 1977).

6) Hence it can be concluded that the particle-crushing phenomenon, under low stress, of a soil consisting of breakable particles is substantially the same as the particle-crushing phenomenon under high pressure of a soil consisting of strong particles.

7) It is suggested that the amount of particle-crushing during a repeated triaxial test may also be a function of the plastic work done.

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NOTATION

\[ d = \text{diameter of particles} \]
\[ d_{10}, d_{30}, d_{60} = \text{ten, thirty, sixty percent diameter} \]
\[ E = \text{grinding energy or total work done} \]
\[ U = \text{recoverable work done} \]
\[ W = \text{plastic work done} \]
\[ K = \text{comminution coefficient} \]
\[ S = \text{surface area (cm}^2/\text{cm}^3) \]
\[ \Delta S = \text{increase of surface area (cm}^2/\text{cm}^3) \]
\[ S_e = \text{final value of surface area (cm}^2/\text{g}) \]
\[ S_s = \text{specific surface area (cm}^2/\text{g}) \]
\[ p = \text{effective mean principal stress} \left( = \left( \sigma_1' + 2\sigma_3' \right)/3 \right) \]
\[ q = \text{deviator stress} \left( = \sigma_1' - \sigma_3' \right) \]
\[ \nu = \text{volumetric strain} \]
\[ \epsilon = \text{shear strain} \left( = \epsilon_1 - (\nu/3) \right) \]
\[ \epsilon_1, \epsilon_3 = \text{maximum and minimum axial strains} \]
\[ \sigma_1', \sigma_3' = \text{maximum and minimum effective principal stresses} \]
\[ \sigma_d = \text{deviator stress in repeated triaxial test} \]

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