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A Study of the Rockfill Material Behavior in Large-Scale Tests

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ABSTRACT: Inspecting the behavior of the rockfill materials is of significant importance in analysis of rockfill dams. Since the dimensions of grains in such materials are greater than the conventional sizes suitable for soil mechanics tests, it is necessary to experimentally study them in specific large-scale apparatuses. In this research, the behavior of rockfill materials in two large rockfill dams constructed in northwest of Iran were studied using large-scale direct shear and triaxial tests. Various indices regarding the quantity of particle breakage in rockfill materials were assessed for both dams and an experimental correlation has been proposed between the Los Angeles Abrasion Value and internal friction angle of rockfill material. Also, the effect of surcharge intensity, grain size distribution and degree of compaction on the shear strength of rockfill material for both dams was studied. The findings indicate that increase in particle breakage leads to reduction of internal friction angle. Also, for a specific sample the particle breakage index increases with an increase in surcharge, percentage of gravel and degree of compaction.

Keywords: Direct Shear Test, Los Angeles Abrasion, Particle Breakage, Rockfill, Triaxial Test.

INTRODUCTION

Rockfill materials, which are used as the shell in rockfill dams and also in construction of breakwaters, constitute a considerable volume of embankment operations, carrying much of the costs of such projects. Therefore, in order to optimize the volume of rockfill-related operations and also to achieve a safe and economic design, investigating the real behavior of this material is crucial. Research shows that shear strength of rockfill material is a function of the degree of angularity, size of the largest particles, volume of fine grains, energy of compaction and grain size distribution of samples.

One of the oldest experimental studies on rockfill material has been conducted by Marsal (1967). According to his research, for crushed grains of basalt with 175 mm diameter and under pressures from 69 to 138 kPa the friction angles are 10 to 15 degrees greater than rounded gravel particles. Also, the findings of Hamidi (2011) advocate a considerable increase in friction angle by an increase in the size of particles. Based on the mentioned studies for a specimen with the maximum diameter of gravel size is 1.0 in, the friction angle is up to 5 degrees greater

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than the sample with the maximum gravel diameter of 0.5 inches.

Performing experiments on rockfill samples of 300 mm in diameter, Charles and Watts (1980) showed that the friction angle in material with the maximum grain size of 75 mm is 3 degrees greater than the friction angle in material with maximum diameter of 10 mm. Also, the experiments of Vustel (1983) revealed that the friction angle in coarse-grained material whose 30 to 40 percent of particles are smaller than 5 mm is 5 degrees greater than coarse-grained materials. The bulk modulus of this material was about two times greater than coarse-grained materials. Generally, the material with 30 to 40 percent of fine grains is more appropriate for rockfill because of their strength and stiffness.

Findings of Brauns and Kast (1991) regarding rockfill material show that such materials have non-linear, non-elastic and stress-dependant behavior which by increasing the confining pressure, the amount of maximum deviatoric stress, axial strain and volumetric strain in failure are increased. Even if the rocks have the same mineralogy, still the difference in texture and structure of particles has been found to have an important influence on their behavior.

In his studies, Parkin (1991) concluded that in dense well-graded material the interparticle forces are very small and thus the breakage decreases. He further argued that in general an increase in the size of grains leads to a decrease in the shear strength. Dilation and breakage are both dependent on the size of grains. Thus the variations in size between real grains and those in laboratory triaxial specimens may give misleading deformations.

The studies of Lade et al. (1996) on compacted sands showed that by increase in the confining pressure, the amount of particle breakage increases as well and that the material after being sheared tends to be more well-graded. Also, in drained tests with the same confining pressures, the amount of particle breakage is less than in undrained tests. Indraratna et al. (1998, 2002) demonstrated that compared to the material which are more well-graded, in material where the gradation curve has a narrower distribution, the friction angle decreases with a lower rate. Experimental studies of Varadarajan and Sharma (2003) in triaxial tests on angular and rounded aggregates revealed that high breakage of Purulia dam material is due to weakness of particles and that angular material are more prone to breakage than rounded aggregates.

New experimental studies on coarse material have been presented by Bum-Joo et al. (2005), Ghanbari et al. (2008), Cambridge (2008), Hamidi et al. (2009) and Gupa (2009). Hamidi et al. (2009) showed that an increase in gravel content and relative density results to an increase in the shear strength and dilation of the mixture. The studies of Bum-joo et al. (2005) showed that in rockfill material, increase of the compaction from 85% to 90% results in a two degree increase in internal friction angle and also that rockfill material are more compressible when they are wet. Ghanbari et al. (2008) showed that the internal friction angle obtained from rockfill material in direct shear tests is about two to three degrees greater than those obtained from triaxial tests. Also, the difference between friction angles of well-graded rockfill material with poorly-graded ones has been reported to be two to three degrees.

Conducting experiments on angular and rounded aggregates, Gupta (2009) showed that in both cases the amount of breakage increases by an increase in the confining pressure and that the friction angle in rounded material also increases with an increase in particle diameter while opposite results are found in angular material.

In this research, the behavior of rockfill material employed in two rockfill dams, namely Madani and Mianeh, has been experimentally studied. These two dams are constructed in northwest of Iran which are 93 and 67 meters high, respectively. Various indices related to the degree of breakage in rockfill material have been evaluated for both dams and their applicability has been discussed. Furthermore, a correlation between the Los Angeles Abrasion Value and internal friction angle of rockfill material has been also presented and the effects of surcharge intensity, gradation, and degree of compaction on the shear strength of rockfill material dams have been studied for both.

PROPERTIES OF THE SAMPLES

Specimens employed in this research have been provided from the same sources which served the required material for Madani and Mianeh dams. The properties of the specimens are provided in Table 1. Also, Table 2 provides the results of Los Angeles Abrasion Value from the two mentioned dams, letters V and I were used for Madani and Mianeh dams, respectively. Also, the first two numbers show the gravel percent and the next numbers are indicators of the percentage of compaction for samples.

The experiments were conducted in consolidated drained (CD) conditions and the confining pressures ranged from 100 to 700 kPa for triaxial test and 50 to 450 kPa for shear test. The lateral loading rate, with respect to the relative similarity of samples conditions, was considered 0.5 mm/min. In this study, all experimental samples of triaxial and direct shear tests were remolded samples prepared from the modified standard compaction method and optimum water content.

Table 1. Properties of tested specimens.

Surcharge (kPa)	Unified Gradation	C_u	C_c	D_{60} (mm)	D_{30} (mm)	D_{10} (mm)	Tested Material*	Dam	Rate of Loading (mm/min)	Sample Dimensions (mm)	Test
100,200,300,400	SP	5.77	0.65	1.05	0.35	0.18	V1895	Madani	0.5	300*300*160	Direct Shear
	SW	15.6	1.7	5.45	1.8	0.345	V439543100				
	GW	9.6	1.72	16.6	7.0	1.72	V8092				
50,150,300,450	SP	5.77	0.65	1.05	0.35	0.18	I1895	Mianeh			
	SW	15.6	1.7	5.45	1.8	0.345	I4395 I43100				
	GW	9.6	1.72	16.6	7.0	1.72	I8092				
100,200,400,700	SW	15.6	1.7	5.45	1.8	0.345	V4395	Madani	0.5	200*400	Triaxial
100,200,300,500,700	SW	15.6	1.7	5.45	1.8	0.345	I4395	Mianeh			
100,300,700	SP	5.77	0.65	1.05	0.35	0.18	I1895				

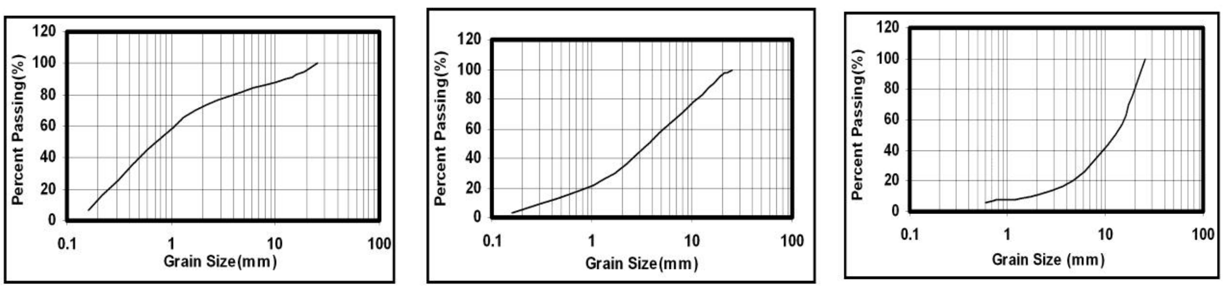
*The letters V and I have been used for Madani and Mianeh dams, respectively. Also, the first two numbers show the gravel percent and the next numbers are indicators of the percentage of compaction for samples.

Table 2. Results obtained from Los Angeles abrasion tests (numbers are in percent).

	Test No. 1	Test No. 2	Test No. 3	Test No. 4	Average
Mianeh	15	15.6	15.4	15.8	15.2
Madani	23.4	23.3	20.8	24.5	23

As far as number of experiments is concerned, a number of tests were conducted, including 12 large scales triaxial tests of 400 mm in height, 24 large scales direct shear tests of 300 mm in dimensions, and 8 Los Angeles tests. Among these tests, 8 large scale triaxial tests were performed on Mianeh dam Materials, 4 tests were carried out on Madani dam materials, and 4 abrasion Los Angeles tests and 12 large scale shear tests were performed on each dam.

In order to convert field grading to laboratory grading, the parallel scale method has been used. In this case, the grading curve of real material is transferred to the left with a constant shift so that the maximum sizes of particles are decreased to the minimum laboratory sizes. In Figures 1 and 2 grading curves and photograph of tested material are given. The maximum dry densities of Madani and Mianeh material are 1.99 and 2.2 tons/m^3, respectively.



A **B** **C**

Fig. 1. Gradation curve for employed material in Madani and Mianeh dams
A) 22% gravel with 92% compaction
B) 61% gravel with 95% and 100% compactions
C) 81% gravel with 95% compaction.

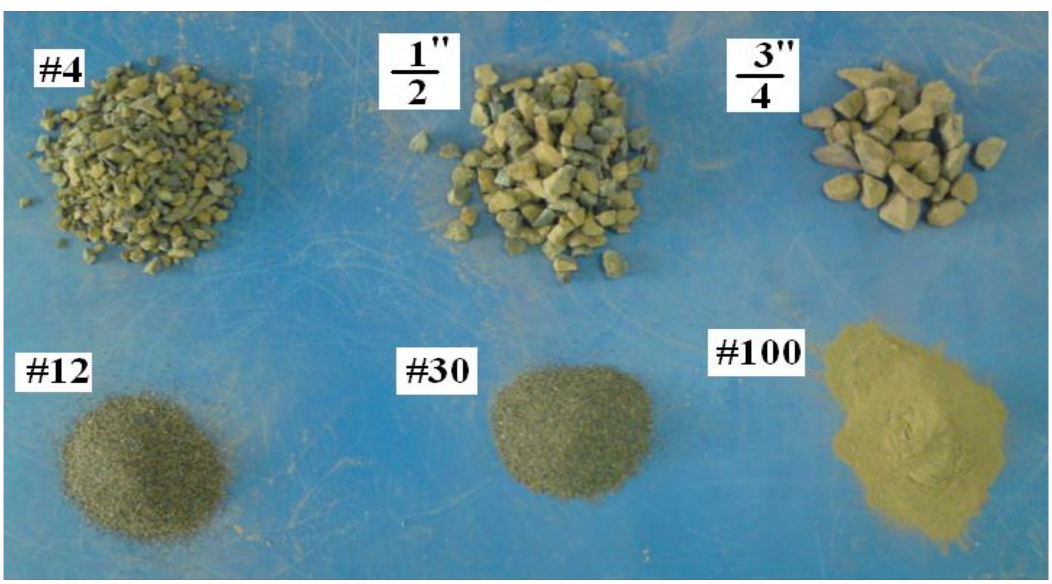


Fig. 2. Madani dam material.

INVESTIGATING THE RESULTS OBTAINED FROM DIRECT SHEAR TESTS

Large-scale direct shear tests of 160×300×300 mm dimensions were conducted on the rockfill material of Madani and Mianeh dams in soil mechanics laboratory of Kharazmi University. For testing, a compaction ranging from 92% and 100% of the maximum laboratory compaction was adopted. Four confining pressures in the range between 50 and 450 kPa were used for modeled rockfill material. The sample was sheared to failure with a loading rate of 0.5 mm/min.

As examples, shear stresses versus horizontal deformations and vertical deformations versus horizontal deformations for V8092 and I8092 specimens are illustrated in Figure 3. According to the results, failure of the specimens under smaller surcharges has occurred in smaller deformations while the failure of samples with greater surcharges is observed in horizontal deformations greater than 18 mm. Also, by increase in surcharge, the maximum shear strength has increased. The left side curve in Figure 3 which shows the variations of vertical deformations versus horizontal deformations, demonstrates that these material have been of considerable dilation in low surcharges. It further shows that by enhancing surcharge, the amount of dilation has decreased. It is worth mentioning that in low surcharges, the amount of dilation has been greater than 10 mm.

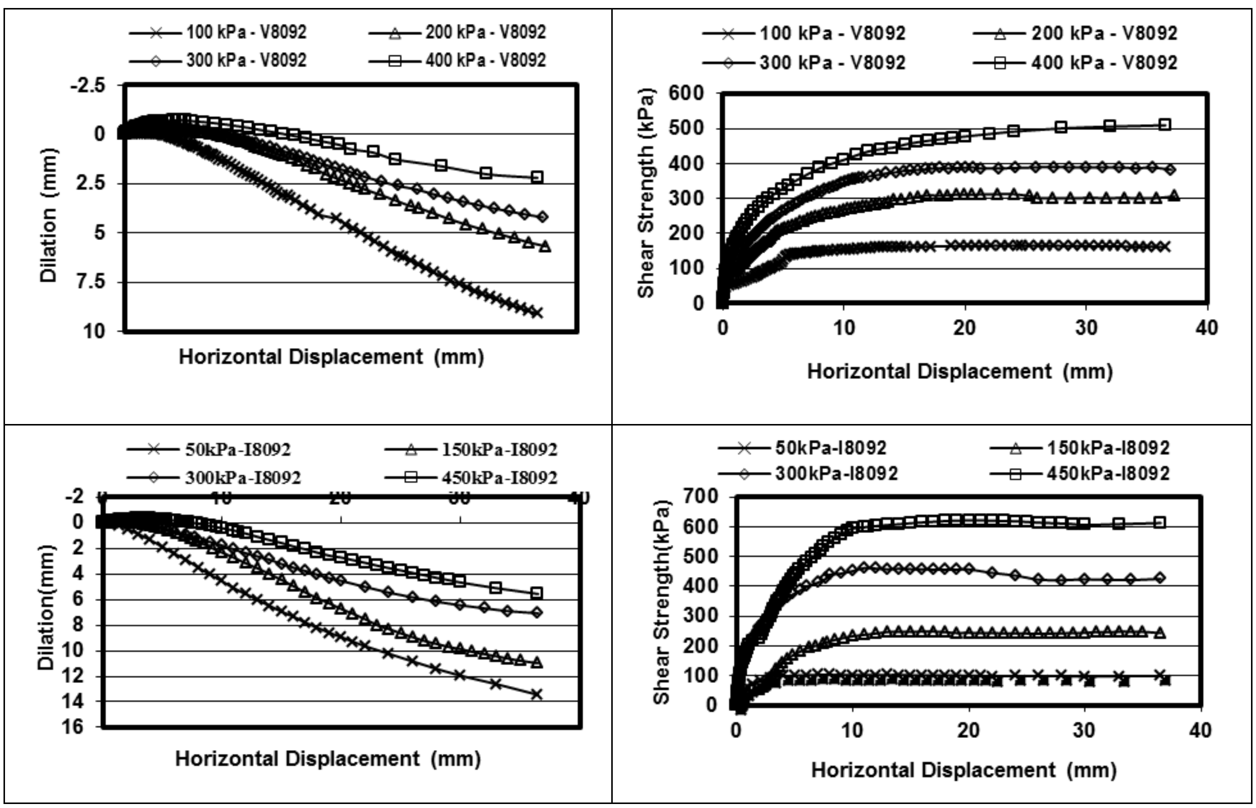


Fig. 3. Variations of shear stress versus horizontal deformation and vertical deformation versus horizontal deformation in direct shear for V8092 and I8092 specimens.

Figure 4 illustrates the variations of shear stress against shear displacement in rockfill material of Madani and Mianeh dams with 100% and 95% compactions and for different surcharges. The obtained results show that the initial slope of stress-strain curves, which is indicative of stiffness and shear modulus of soil, increases as compaction increases. Further, by enhancing compaction from 95% to 100%, the shear strength has increased due to increase of the interlocking particles and the failure has reached greater deformations. In other words, they have demonstrated more ductile behavior.

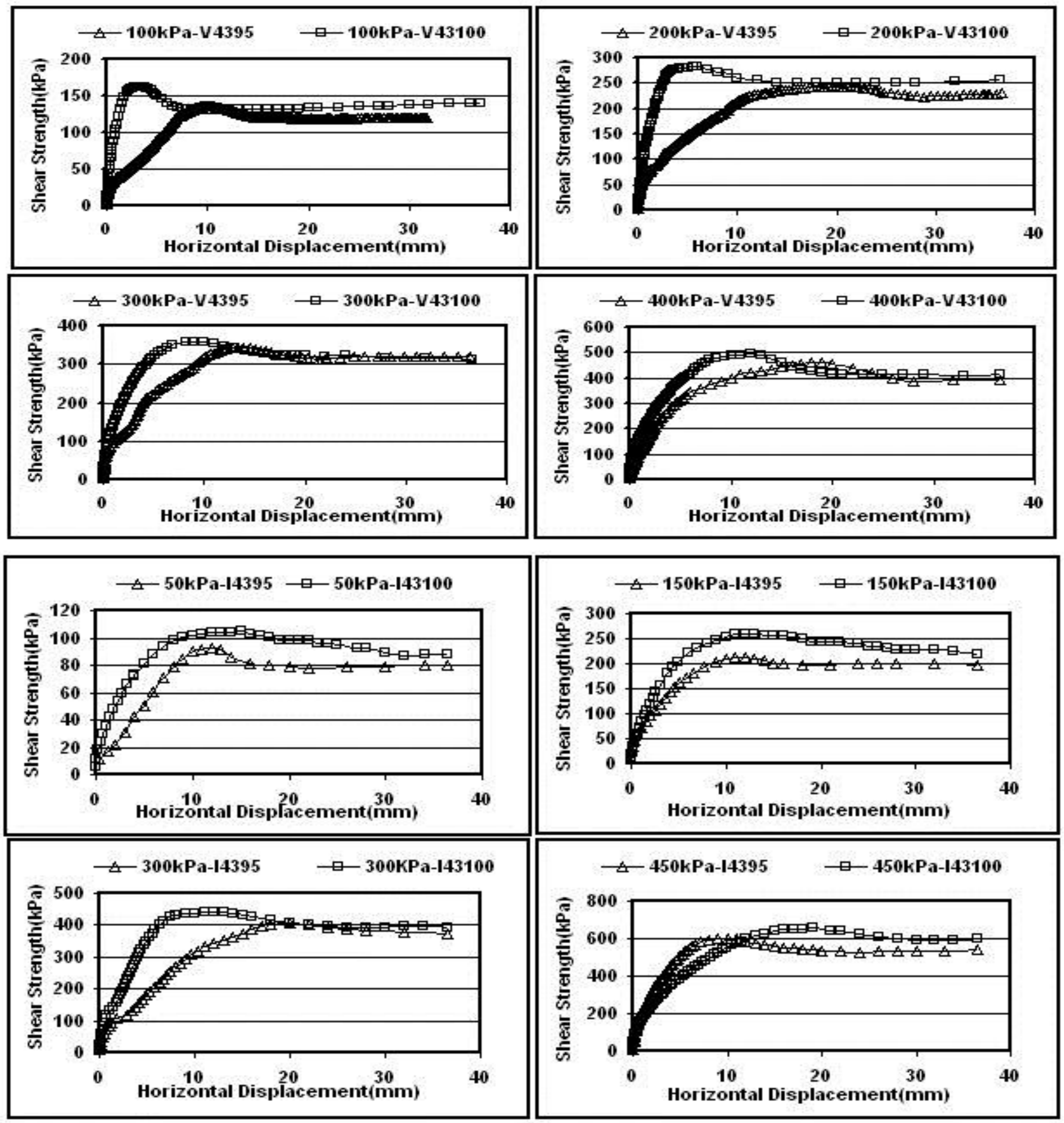


Fig. 4. Variations of shear stress versus shear displacement for different levels of compaction and surcharge in direct shear of the Madani and Mianeh material.

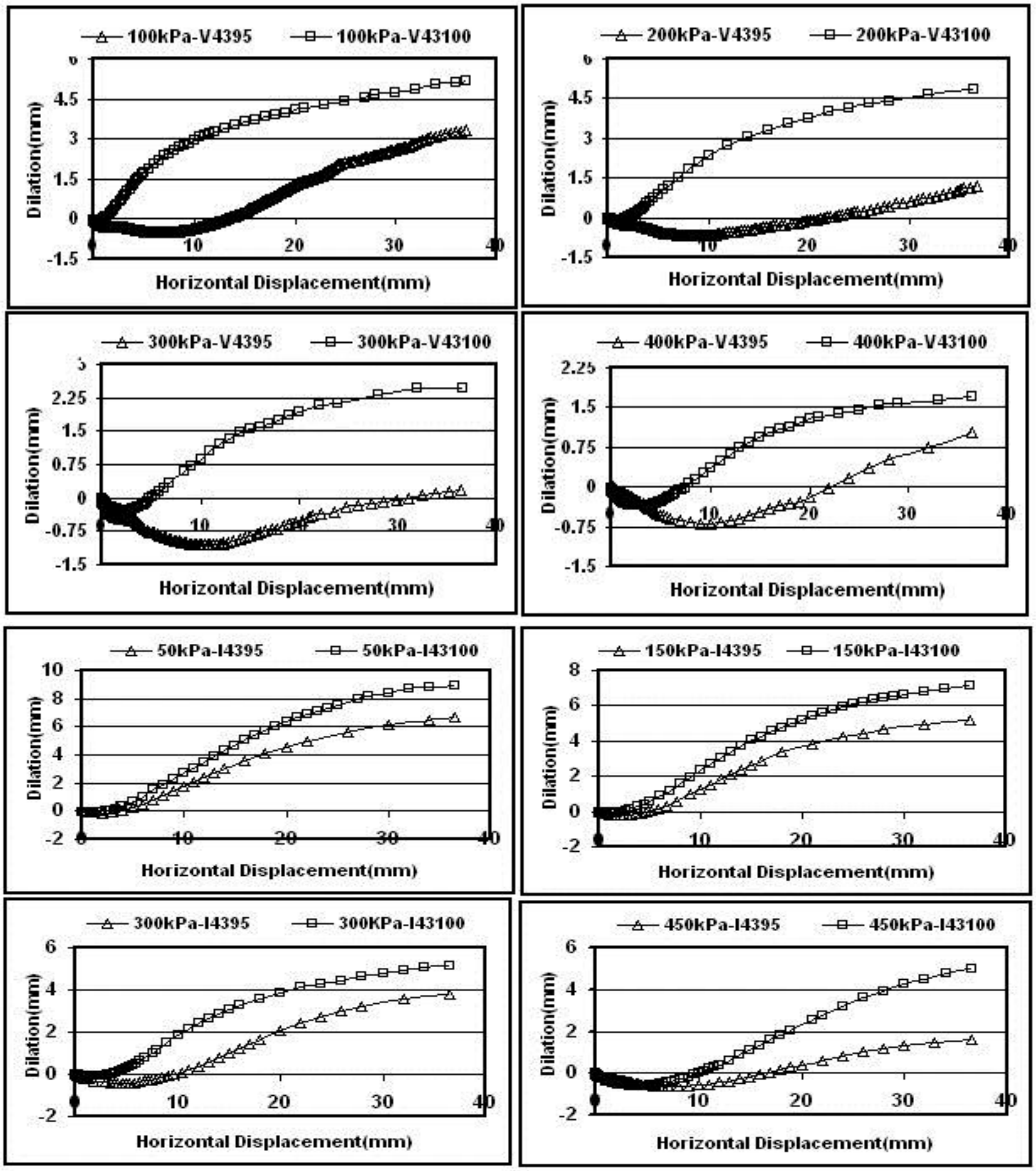


Fig. 5. Variations of vertical deformation versus shear displacement for different levels of compaction and surcharge in direct shear of the Madani and Mianeh material.

Variations of vertical deformations versus shear displacements for different degrees of compaction and surcharges are shown in Figure 5. Based on the results, by increasing compaction, dilation and shear strength of soil are increased. To put it differently, in the specimens under identical surcharges, the required energy for displacement of grains has increased by increase in the compaction. In order to investigate the effect of particle size distribution on behavior of rockfill material, variations of shear stress against horizontal displacement have been depicted in Figure 6 for the Madani and Mianeh material with three different grading properties. The obtained results show that samples with higher percentages of gravel enjoy greater shear strength. Moreover, although the degree of compaction and gradation are two controlling parameters for shear strength of rockfill material, the influence of particle size distribution has been much more significant than the degree of compaction.

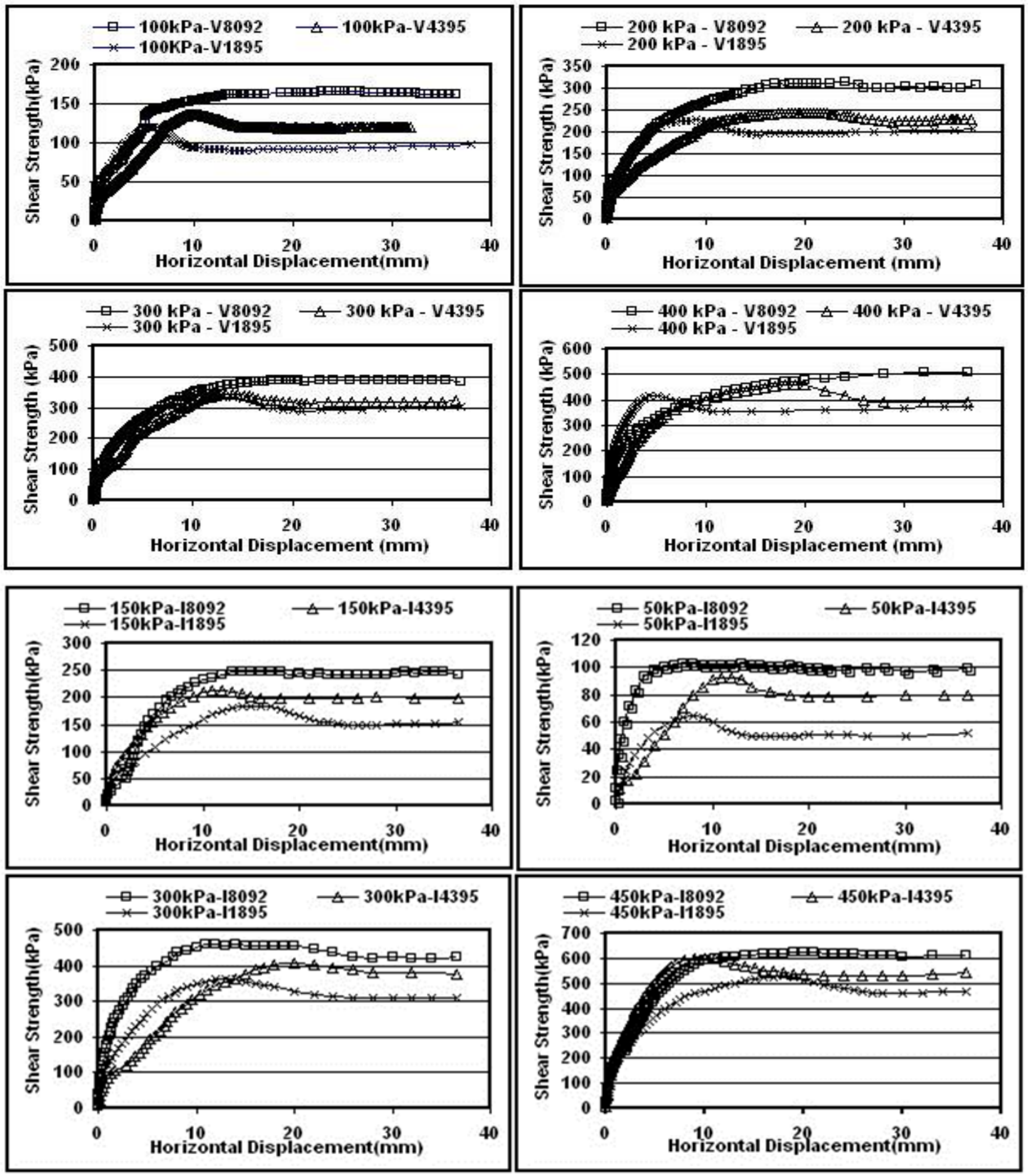


Fig. 6. Variations of shear stress versus horizontal displacement for the rockfill material with different gradations and surcharges in the Mianeh material.

Figure 7 illustrates the variations of vertical displacements versus horizontal displacements for Madani and Mianeh dams' material with three different gradations and surcharges. The results show that dilation of samples has increased by increase in the percentage of gravel. Also, comparing these curves with those demonstrating stresses versus horizontal deformations reveals that specimens with greater dilation enjoy greater shear strength as well. Consequently, the amount of dilation is one of the parameters controlling the shear strength of rockfill material.

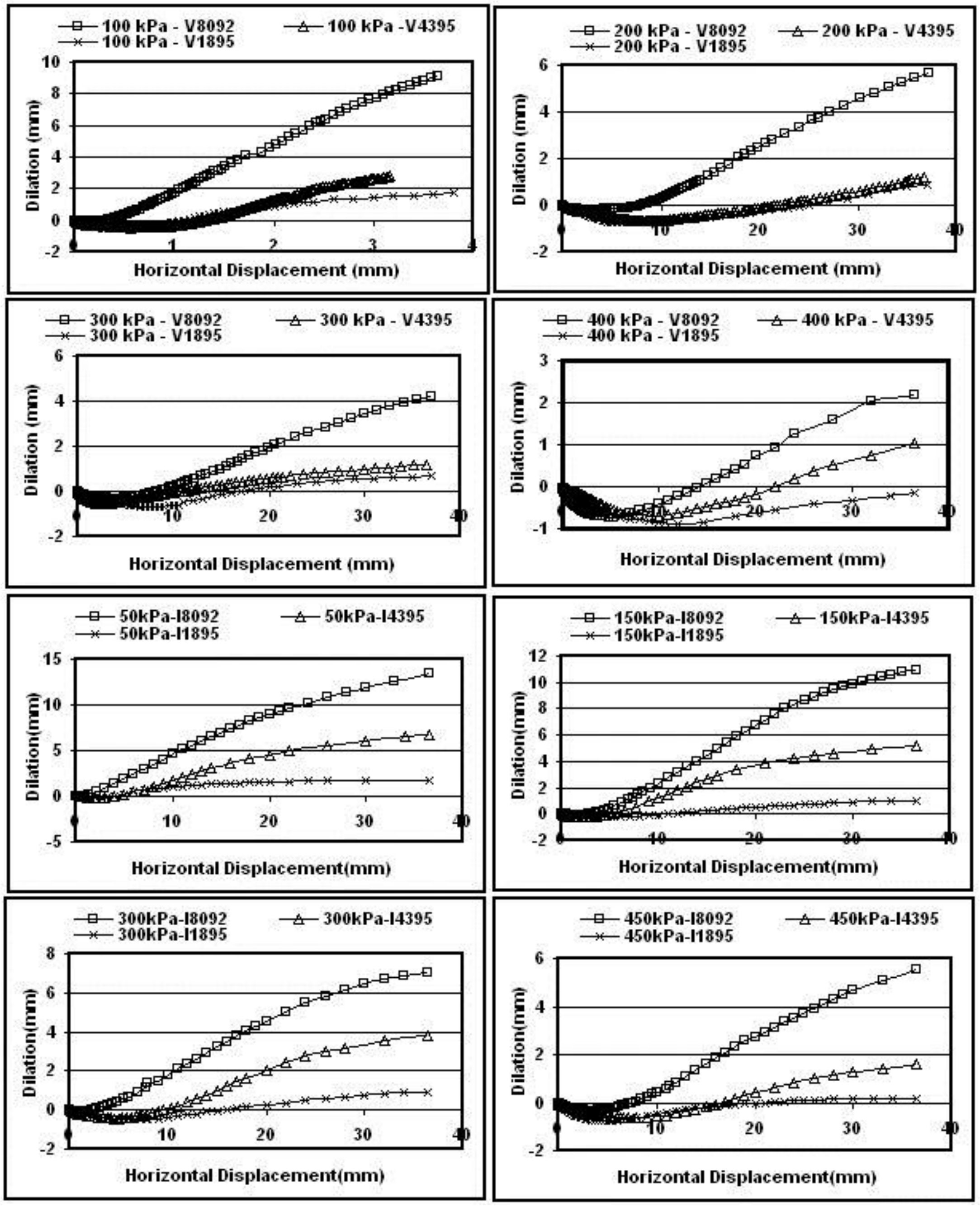


Fig. 7. Variations of shear stress versus horizontal displacement for the rockfill material with different gradations and surcharges in the Mianeh material.

INVESTIGATING THE RESULTS OBTAINED FROM LARGE-SCALE TRIAXIAL TESTS

Large-scale triaxial tests were conducted on rockfill materials of Madani and Mianeh dams in Building and Housing Research Center (BHRC). A specimen of 200 mm diameter size and 400 mm length was utilized for testing. For testing, a compaction corresponding to 95% of the maximum laboratory compaction was employed. Different confining pressures ranging from 0.1 and 0.7 MPa were used for the modeled rockfill material.

Variations of deviatoric stress versus axial strain for the I4395 specimen are shown in Figure 8. The obtained results indicate that the yield stress increases as confining pressure increases. The linear behavior continues from the initial status of loading to deformations of about 2 percent in confining stress of 700 kPa. The failure point or the peak of stress-strain curve, particularly in confining pressures of 500 and 700 kPa is clearly distinguished. Figure 8 further shows the variations of volumetric strain versus axial strains for the I4395 specimen. The results indicate that by decreasing the confining pressures, dilation (increase in volume) increases in the specimens so that for 15% deformations the dilation of specimen in confining pressure of 700 kPa has been less than 1 percent while in the confining pressure of 100 kPa this value has reached to the strains greater than 3.5%.

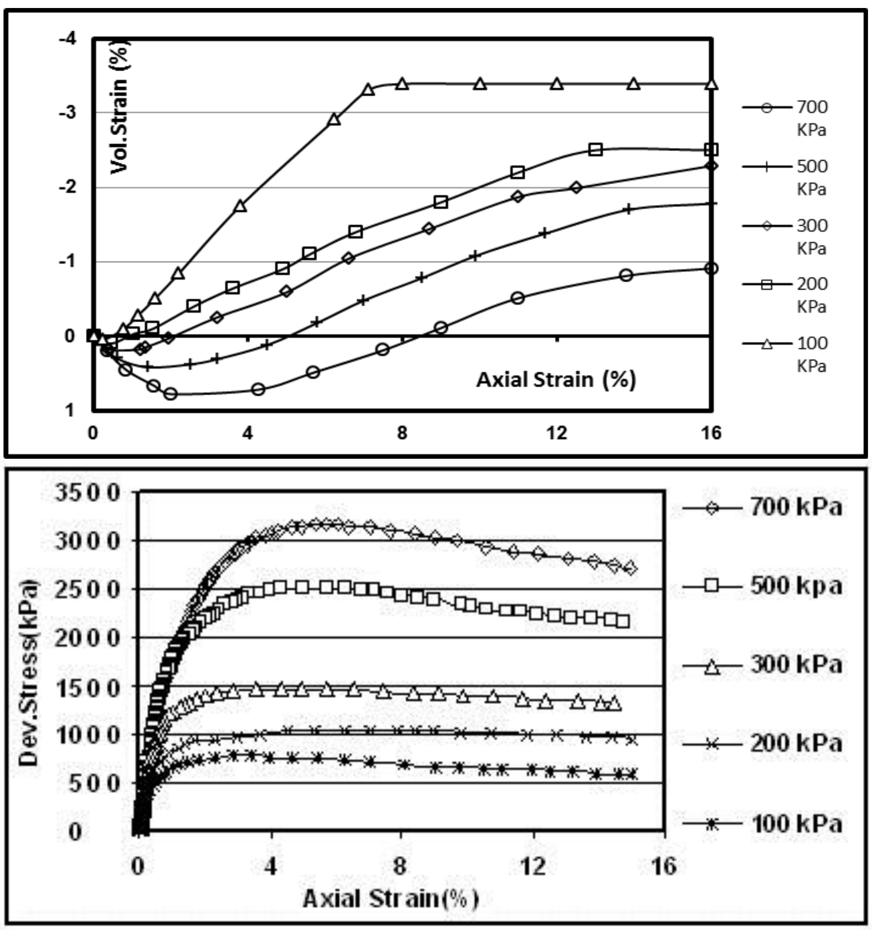


Fig. 8. Variations of deviatoric stress and volumetric strain versus axial strain for I4395 in triaxial test with different confining stresses.

Figure 9 illustrates the variations of differential stress versus axial strain for the I1895 specimen. The results show that failure of samples at confining pressure of 100 kPa has occurred in an axial strain less than 2%. While in the confining pressures greater than 300 kPa, the peak of curves has shifted to the right. Figure 9 also shows the variations of volumetric strain versus axial strain for I1895 specimen. The results indicate that in the confining pressure of 300 kPa, the sample has contracted to about 4%; they further show that subsequent to this contraction, there has been no increase in the volume of the sample. Moreover, according to the results, the specimen has been in its most compacted condition in the horizontal deformation of 8 to 10 percent in the confining pressure of 700 kPa, and the contraction of the specimen has decreased after this zone.

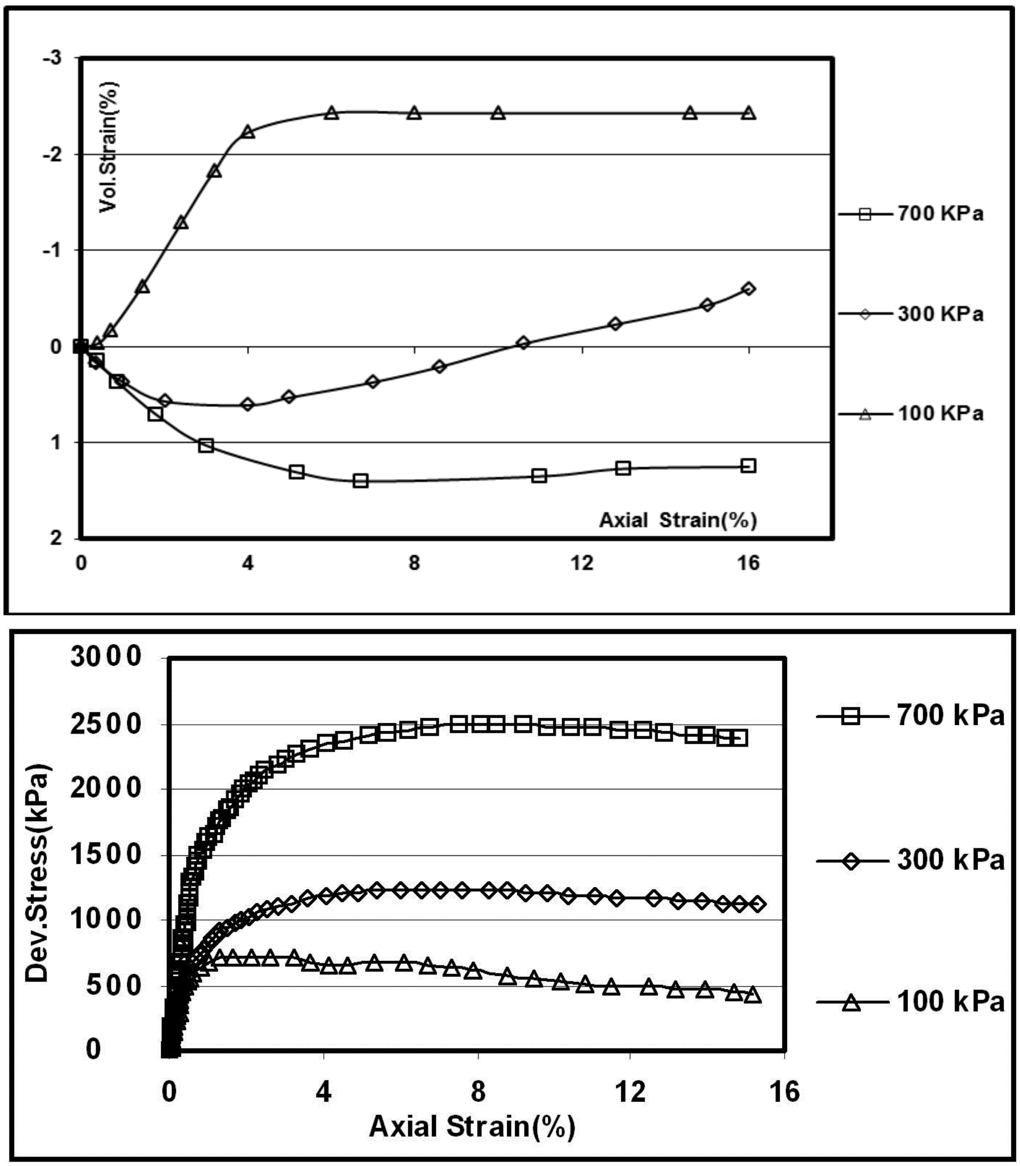


Fig. 9. Variations of deviatoric stress and volumetric strain versus axial strain for I1895 in triaxial test with different confining stresses.

Figure 10 shows the variations of deviatoric stress against axial strain for V4395 specimen. Based on the results, failure has occurred in confining pressures of 100 and 200 kPa in deformations ranging from 2 to 5 percent, respectively. According to the figure, the failure is observed in deformations greater than 10% for the confining pressures of 400 and 700 kPa. It also indicates not so much decrease in the applied stresses exhibit after the peak point; accordingly, stress-strain curves do not have a clear maximum point. Also, variations of volumetric strain against axial strain during loading are depicted in Figure 10 for V4395 specimen. The results show a drop in the volume of specimens in confining stresses of 400 and 700 kPa. They further indicate that in the confining stress of 100 kPa and after 0.5% axial strain, the sample has experienced dilation with increase in volume to more than 4%.

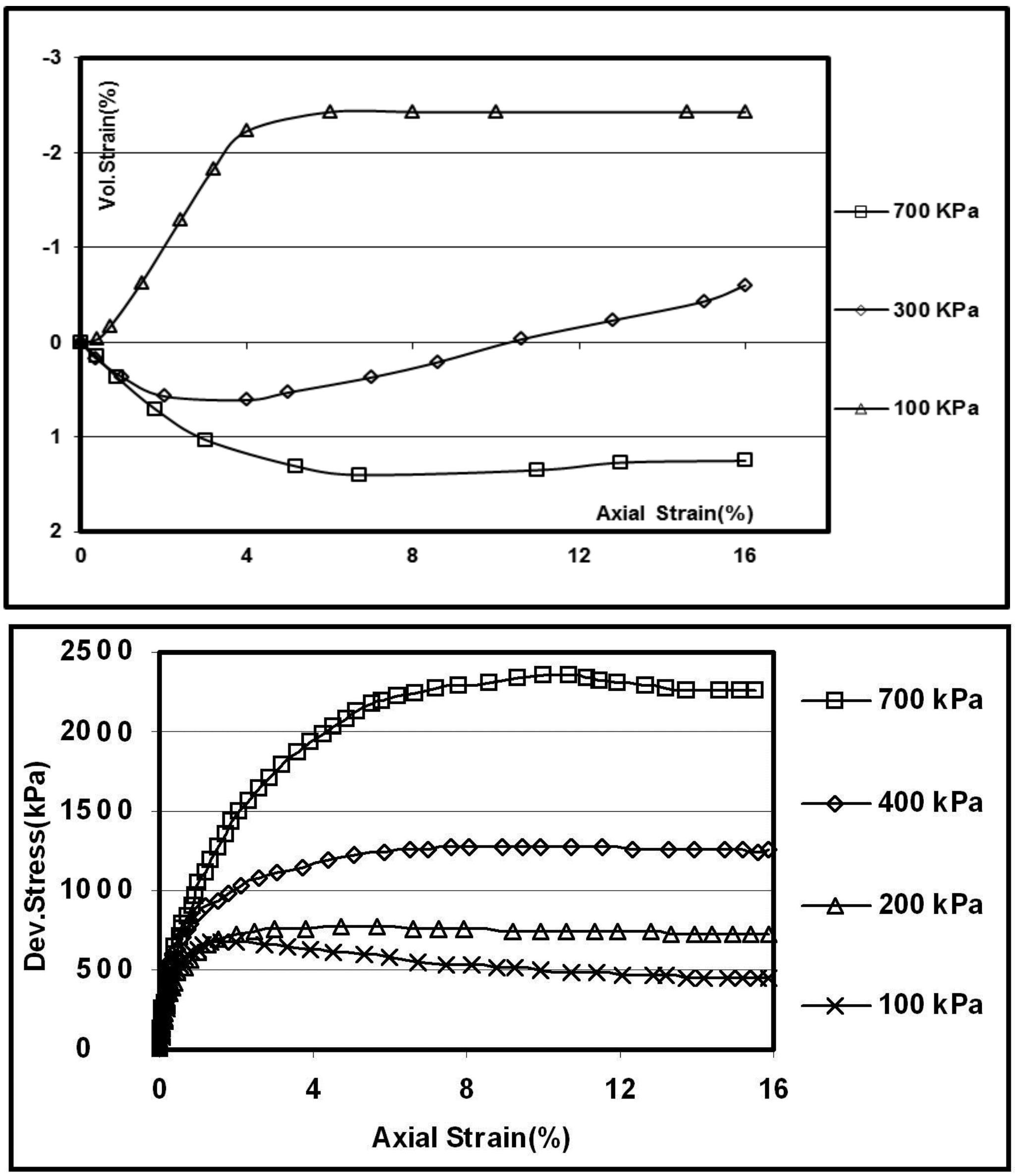


Fig. 10. Variations of deviatoric stress and volumetric strain versus axial strain for V4395 in triaxial test with different confining stresses.

STUDY OF INTERNAL FRICTION ANGLE FOR ROCKFILL MATERIAL

Table 3 compares the values of internal friction angle obtained from the present research in with the results reported by Ghanbari et al. (2008) conducted on direct shear apparatus of 300×300×160 mm dimensions on the same material as utilized in the current study. The cohesion in the rockfill is equal to zero. Table 3 shows that the observed internal friction angle in Ghanbari et al.'s (2008) direct shear test is comparable to the direct shear result presented in this paper. However the data from triaxial tests yielded an internal friction angle 2 or 3 degrees less. This difference might be due to the imposed failure path in the direct shear test. The table further shows an increase in the internal friction angle in one of the specimens by increase in the percentage of gravel. Also by increase in the level of compaction from 95% to 100% due to promotion of the interlocking between the grains, the value of the internal friction angle in both materials obtained from Madani and Mianeh dams has increased to about 2 degrees.

Figure 11 shows the relation between Los Angeles Abrasion Value and internal friction angle of rockfill material. Based on this figure, the internal friction angle of rockfill material can be determined with an acceptable precision given the Los Angeles Abrasion Value. Eqs. (1) to (3) have been deduced from the results of large-scale triaxial and direct shear tests conducted, respectively.

$$\phi_{Triaxial} = -0.42(S)+57.5 \qquad R^2 = 0.95 \tag{1}$$

$$\phi_{Direct\ Shear} = -0.40(S)+56.7 \qquad R^2 = 0.99 \tag{2}$$

$$\phi_{General} = -0.41(S)+57 \tag{3}$$

where ϕ and S represent internal friction angle and Los Angeles Abrasion Value, respectively.

Table 3. Values of internal friction angle obtained from various tests.

Dam	Type of Material	Direct Shear	Triaxial Test	Direct Shear (Ghanbari et al., 2008)
Madani	V1895	45	-	-
	V4395	47	44.1	47.5
	V8092	47.6	-	-
	V43100	49.2	-	-
Mianeh	I1895	49.3	47.1	49.1
	I4395	51.5	49.1	51.3
	I8092	52.5	-	-
	I43100	53.5	-	-

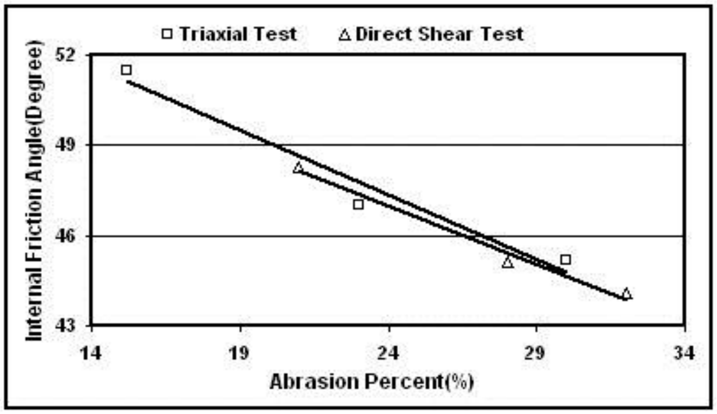


Fig. 11. Variations of internal friction angle versus Los Angeles Abrasion Value for rockfill material.

ANALYSIS OF THE CONSEQUENCES ARISEN BY PARTICLES BREAKAGE

Increase in the in-situ stress of soil and consequently increase in the concentrated stresses in the contact area of soil particles lead to the particle breakage which in turn results in an increase in the settlement of soil and its overlaying structures. Subsequently, soil's drainage capacity is reduced and thus the pore water pressure due to loading might increase and eventually endanger the stability of the soil, Leslie (1963) concluded that the passing percent of the aggregates from the sieve, on which the main portion of particles is retained, can be an appropriate index for demonstrating the amount of particle breakage. As he puts, breakage index is the vertical distance between the passing percentage of 10 in the two grading curves prior and subsequent to the conduction of the test. Hazen (1911) proposed the following empirical correlation in order to determine the amount of particles' breakage:

$$B_{10} = 1 - \frac{D_{10}^{f}}{D_{10}^{i}} \tag{4}$$

where B10 is the breakage index, D_{10}^{i} and D_{10}^{f} are the effective diameter of particles after and before loading, respectively.

Lee and Farhoodmand (1967) put up a breakage index as the ratio between D_{15} of material before loading to this value after finishing the test, that is:

$$B_{15} = \frac{D_{15}^{i}}{D_{15}^{f}} \tag{5}$$

Also, Indraratna et al. (1993) considered the variations of D_{50} during the test as an index for the amount of particle breakage:

$$B_{50} = \frac{D_{50}^{i}}{D_{50}^{f}} \tag{6}$$

On the other hand, according to Hardin's (1985) definition, the overall breakage of particles for a sample is equal to the area between two grading curves before and after the test. This area is limited to the vertical line corresponding to 0.075 mm (#200 sieve). Therefore, his proposed index is defined as below:

$$B_{Area} = A_i - A_f \tag{7}$$

Regarding the obtained results from this research, a new index $B_{50/15}$ is defined as following:

$$B_{50/15} = \frac{B_{50}}{B_{15}} \quad (8)$$

The pronounced advantages of the suggested index will be discussed later in this paper. Values of particle breakage in direct shear test are calculated based on various indices and are summarized in Tables 4 and 5.

Table 4. Particle breakage in direct shear test for rockfill material of the Madani dam.

Sample No.	Surcharge (kPa)	B_{10}	B_{15}	B_{50}	B_{Area}	$B_{50/15}$
V8092	100	0	1.0011	1.0384	0.0695	1.0372
V4395	100	0	1.0	1.0307	0.0644	1.0307
V43100	100	0.0570	1.0311	1.06017	0.1173	1.03
V8092	200	0.1261	1.0841	1.06	0.1204	0.98
V4395	200	0.0576	1.0503	1.0504	0.1885	1.0
V43100	200	0.1387	1.1085	1.075	0.2699	0.97
V8092	300	0.1569	1.1298	1.127	0.2425	0.99
V4395	300	0.15	1.0982	1.0925	0.2261	0.99
V43100	300	0.1623	1.1658	1.1517	0.4003	0.988
V1895	300	0.0612	1.0827	1.03565	0.0726	0.957
V8092	400	0.206	1.1521	1.1448	0.3632	0.993
V4395	400	0.1782	1.1466	1.1129	0.3126	0.971
V43100	400	0.2032	1.1953	1.1775	0.471	0.985
V1895	400	0.0957	1.0966	1.056	0.1569	0.963

Table 5. Particle breakage in direct shear test for rockfill material of the Mianeh dam.

Sample No.	Surcharge (kPa)	B_{10}	B_{15}	B_{50}	B_{Area}	$B_{50/15}$
I8092	150	0.0120	1.0466	1.0325	0.1135	0.986
I4395	150	0.0	1.0315	1.0383	0.0681	1.006
I43100	150	0.0552	1.0947	1.0693	0.2032	0.977
I8092	300	0.0337	1.072	1.0392	0.1881	0.969
I4395	300	0.0179	1.0596	1.0372	0.1608	0.979
I43100	300	0.1129	1.1227	1.0839	0.2207	0.965
I1895	300	0.0399	1.0256	1.0125	0.0578	0.987
I8092	450	0.0475	1.0860	1.0794	0.2926	0.994
I4395	450	0.0179	1.0793	1.0615	0.2575	0.983
I43100	450	0.156	1.1549	1.0985	0.309	0.95
I1895	450	0.0888	1.0458	1.0458	0.1066	1.0

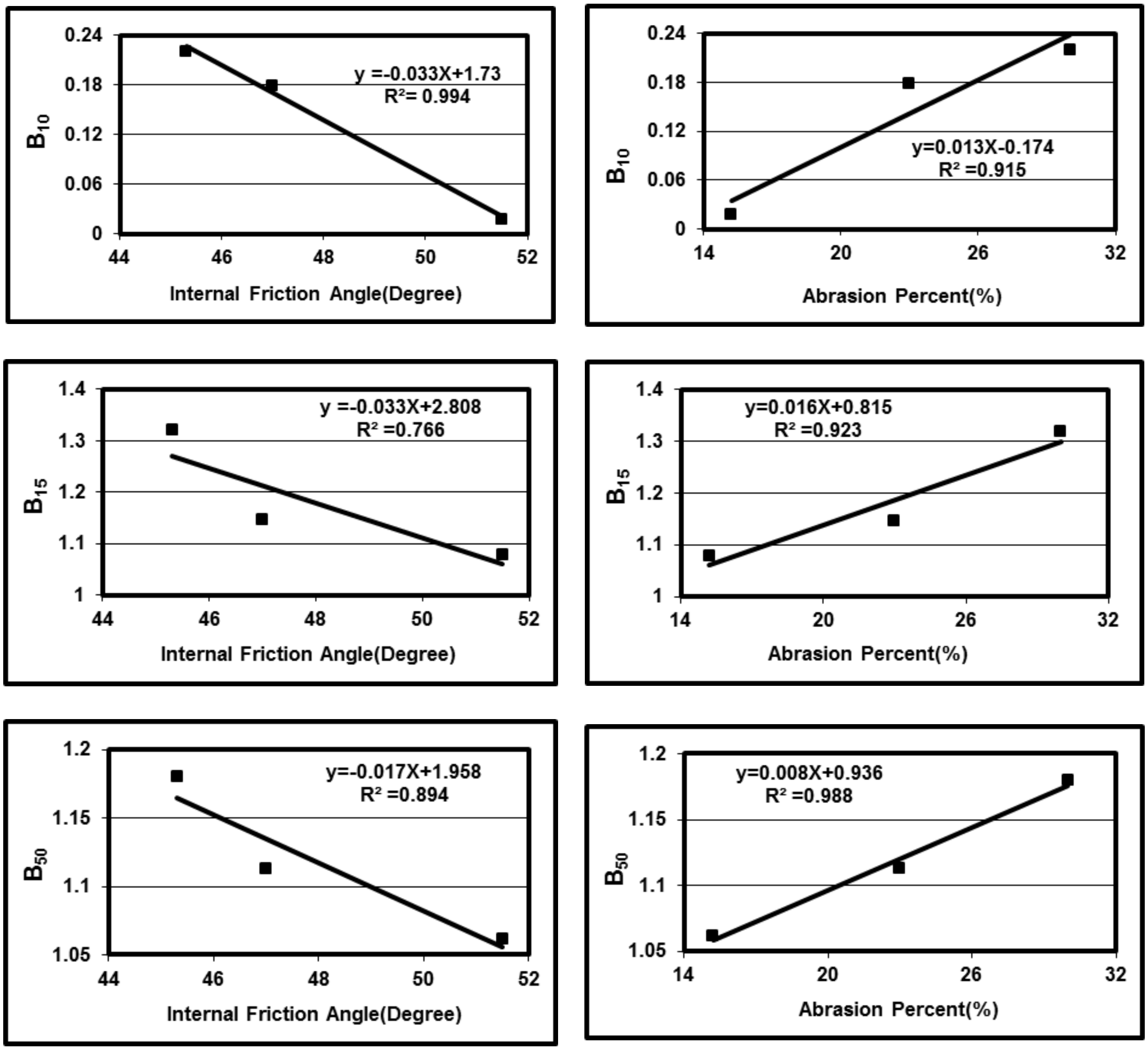


Fig. 12. Variations of different indices for particle breakage with Los Angeles Abrasion and internal friction angle in direct shear test.

In order to investigate the capability of various indices for particle breakage, it is imperative to study the mechanism by which breakage initiates in particles with regard to the type of rockfill material. In angular strong rockfills, the probability of cracking and breakage of grains is much less than the probability of abrasion and disappearance of the angularity of particles. Therefore, for this rockfill material, the B10 and B15 can be more appropriate indices to calculate the amount of particle breakage. On the other hand, comparison of B15 and B50 indices in Tables 4 and 5 shows the B15 index has been greater than B50 that in more than 95% of cases. Hence the particle breakage and halving in this material have been more than abrasion resulted from the above boundary.

Using $B_{50/15}$ index, the boundary between abrasion and particle breakage can be determined such that if the index is greater than unity, the amount of breakage will be more than the abrasion and if it is smaller than unity, abrasion will be more significant.

A careful inspection of the Tables 4 and 5 reveals that in most of the cases this ratio has been smaller than unity and thus the B15 index is recommended for this material. In most angular materials the breakage is due to both abrasion and splitting. So in angular material B_{Area} index which represents the average breakage of all the particles can be a useful criterion for particle breakage. Yet, in alluvial angular materials which were tested, abrasion was not significant and the breakage of particles was mainly due to splitting of rockfill particles. Therefore, B50 index is a suitable criterion for assessing the amount of particle breakage.

On the other hand, studying the influence of compaction on the amount of particle breakage is possible considering the data presented in Tables 4 and 5. Results show that for both of the rockfill materials in Madani and Mianeh dams, when degree of compaction increases from 95% to 100%, the amount of particle breakage in both indices is increased as well. In fact, by enhancing the degree of compaction, the volume of voids between the grains is reduced and consequently the interlocking between particles and also their breakage is enhanced too. The data in Tables 4 and 5 shows that based on all the indices, by increasing confining pressure, particle breakage increases. Investigation of volumetric changes during loading reveals that the dilation of the sample decreased as the confining pressure increased. Although this behavior is mainly due to the restriction in movement of grains and their over-topping, however the breakage phenomenon and decrease in the size of grains are also of considerable influence to the extent that they resulted in reduction in dilation and expansion of specimen.

What is more, investigation of the results shows that for all the samples with an increase in the percentage of big boulders, the amount of particle breakage increased as well. In other words, the amount of particle breakage in well-graded specimens in which the big boulders are more available has been greater than poorly-graded specimens. In fact, by increase in the size of grains, the number of bulges and depressions on the specimen would result more in increase of interlocking between the grains and promotion of the particle breakage too. Also, by increase in the size of grains, developments of microscopic cracks and eventually particle breakage have both increased.

Comparison of the results for both dams shows that the specimen with 80% gravel and 92% compaction has been of greater overall breakage compared with the material with 43% gravel and 95% compaction. To put it differently, the sample with lower compaction has demonstrated more breakage due to its grading type. The values related to particle breakage in great surcharges are presented in Table 6. The results indicate that based on all the indices, the amount of particle breakage in Madani material was greater than that from Mianeh dam.

Table 6. The amount of particle breakage in triaxial test for various tested material in this research.

	Surcharge (kPa)	B_{10}	B_{15}	B_{50}	$B_{50/15}$
Mianeh	500	0.07	1.08	1.09	1.0
Madani	400	0.25	1.48	1.14	0.77

Variations of different indices have been depicted in Figure 12 against internal friction angle and Los Angeles Abrasion Value. The data obtained from the present research has been used to draw these curves coupled with reported data by Ghanbari et al. (2008) from Sahand dam. The results show that the studied indices demonstrate a linear relationship between the internal friction angle and Los Angeles Abrasion Value.

CONCLUSIONS

Shear strength of rockfill material in two large dams, Madani and Mianeh, which are being constructed in North-West of Iran have been studied in large-scale tests. Investigation of the results shows a linear relationship between internal friction angle of rockfill material and Los Angeles Abrasion Value. Thus, for cases in which conducting the large-scale tests is not feasible due to practical or economical limitations, the suggested correlations can be employed for estimation of internal friction angle in rockfill material.

On the other hand, suggested indices by previous researchers for evaluation of particle breakage have been put together and a new index has been then proposed to determine the boundary between abrasion and breakage in rockfill material. Investigation of the proposed correlations between aforementioned indices and Los Angeles Abrasion Value revealed the existence of a linear relationship between mentioned properties. Hence the Los Angeles Test can be presented as a fundamental experiment in studies of rockfill material behavior.

Studying the influence of compaction on the behavior of rockfill material shows that by increase in the degree of compaction the particle breakage and the internal friction angle also increase. The results further indicate that by enhancing the level of compaction from 95% to 100% the value of internal friction angle enhances to about 2 degrees. On the other hand, increase in the surcharge leads to increase in breakage index of particles.

Moreover, the grain size distribution is of significant influence on the shear strength of rockfill material. Based on the obtained results, the difference between internal friction angle of a well-graded sample and a poorly-graded one was found to be 2 to 3 degrees. On the other hand, by increase in the percentage of big grains in the rockfill material, the amount of particle breakage as well as the shear strength of specimen increased.

Comparison of the results of triaxial and direct shear tests on similar material shows that the observed internal friction angle in direct shear test is 2 to 3 degrees greater than the same value obtained from triaxial test. The results further indicate that by decreasing the Los Angeles Abrasion Value, the shear strength and dilation of samples increases.

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