Effects of Particle Characteristics on Behavior of Granular Material

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The stress-strain and strength characteristics of railroad ballast are known to be functions of particle shape, size, and gradation. However, the nature and extent of these effects are only partly understood, and opinions are sometimes contradictory. For this reason a review was undertaken of available literature on granular materials relevant to this subject. To supplement this information, triaxial tests were conducted on specimens of crushed granular material with varying sizes and shapes of particles to observe the effects on the strength of the assembly particles. Any amount of flaky particles added to a specimen or crushed granular material, either randomly placed or oriented, increased the shearing resistance except when the particles were oriented generally parallel to the shear plane. However, the presence of flaky materials resulted in greater particle abrasion and breakage, larger permanent strain under repeated loading, and lower stiffness. Increasing particle angularity increased shearing resistance, but particle breakage also increased. Increasing particle surface roughness increased shear strength. Broadening the gradation of the specimen increased shear strength. However, this effect may be primarily because the void ratio typically decreases as the range of particle sizes increases. For the gradations tested, shear strength was independent of gradation for common void ratios. Similarly, particle size had no significant effect on shear strength within the range tested for common void ratios. Broadening the gradation also decreased permanent strain under repeated loading and decreased particle degradation.

Industry specifications for railroad ballast contain some criteria related to particle size, shape, angularity, and grading. However, the functions of ballast impose conflicting requirements on these parameters. Furthermore, the influence of these parameters is only partly understood. This leads to uncertainty about what the most appropriate ballast particle specifications might be. Results of a study to provide a better understanding of some of the related issues are presented.

A literature review was first conducted to assemble available information on effects of particle size, shape, angularity, and gradation on the mechanical behavior of crushed angular material. Emphasis was on shear strength characteristics of assemblies of particles and associated particle breakage. In most cases only a single loading or a few load cycles were involved so that wear and abrasion often were not a significant consideration.

To supplement information in the literature, triaxial tests to failure were performed on ballast specimens with varying particle sizes, shapes, and gradings. Information was obtained on the relationship of these factors to shear strength and volume change behavior.

PAST WORK

Particle Shape

Parameters that have been used to define particle shape include flakiness or flatness (*1,2*), elongation, (*1,2*), sphericity (*3,4*), and roundness or angularity (*3,4*). Flakiness or flatness refers to the ratio of particle thickness to width (intermediate dimension), and elongation refers to the ratio of length to width. Sphericity is a measure of how much the shape of a particle deviates from a sphere. Finally, roundness or its inverse, angularity, is a measure of the sharpness of the edges or corners of an individual particle. Some information was found in the literature on the effects of each of these factors except elongation.

Dunn and Bora (*5*) tested a hard, crushed limestone aggregate in a special triaxial device. The particle size ranged from 3/16 in. (4.8 mm) to 1 1/2 in. (38 mm) and the percentage of flaky particles (*1*) was varied from zero to 100 percent of the specimen. Any amount of flaky particles increased the shear strength, but the results suggest that the range of 25 to 75 percent flaky particles is better than 100 percent.

Gur et al. (*6*) used several different tests to evaluate the effect of flakiness on crushed material (type not indicated) ranging in size from 1/4 in. (6.3 mm) to 3/4 in. (19 mm). The aggregate crushing value (*1*) increased 2 1/2 times as the amount of flaky particles increased from zero to 100 percent. Over the same range the Los Angeles abrasion resistance value increased four times. Increasing the percentage of flaky particles also increased the amount of breakage during compaction. Shear strength from triaxial tests was greater with flaky material than with nonflaky material. As a final test the aggregate was compacted in a box and then subjected on the surface to 9,000 coverages with a rubber wheel. Rutting of the flaky material was roughly twice that of the nonflaky material. The increased rutting was attributed to particle alignment of the flaky material.

Siller (*7*) found that the apparent cohesion intercept from triaxial tests on railroad ballast increased with increasing flakiness. He attributed this to increased particle interlock.

Eerola and Ylosjoki (*8*) found that the triaxial shear strength of aggregate specimens increased in proportion to the ratio of particle length to thickness.

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In a European study (*9*) modulus of elasticity was calculated from loading tests on ballast specimens confined by steel rings. Ballast with flat particles generally gave a lower modulus of elasticity than did ballast with equidimensional particles.

Chen (*10*) conducted triaxial tests on various sands and gravels with density ranging from loose to compact. Modulus was determined from the 25th cycle with loading to 30 percent of estimated strength. Strength was subsequently measured by loading to failure. The modulus decreased with increasing angularity, but the strength increased.

Holtz and Gibbs (*11*) conducted triaxial tests on subangular to subrounded gravel and on sharp, angular, crushed quartz rock with similar grading curves. As expected, the angular material had a higher strength.

Vallerga et al. (*12*) conducted triaxial tests on both subrounded and angular sandstone aggregate at various void ratios. The strength of the angular aggregate was significantly higher than that of the subrounded aggregate. At the same void ratios the difference in angle of internal friction was 4 to 8 degrees. However, at the same compaction effort the difference was reduced to about 1 degree. These authors also conducted triaxial tests on glass beads etched to provide a range of surface roughness. With increasing surface roughness, strength, as measured by angle of internal friction, increased by about 8 degrees.

Pike (*13*) conducted shear-box tests on 17 aggregates ranging in particle size from fine sand to coarse gravel. Increased angularity or surface roughness generally resulted in reduced dry density for the same compactive effort, but strength still increased.

Holubec and D'Appolonia (*14*) showed that increasing angularity of sands significantly increased shear strength.

Edil and Luh (*15*) showed that the shear modulus of sands, determined in the resonant column test, increased with increasing roundness (decreasing angularity).

Norris (*16*) showed that the shear strength of sand decreased significantly with increasing roundness. The same trend was shown by Frossard (*17*).

Koerner (*18*) conducted triaxial tests on sands of equal grading but different particle angularity and sphericity. He separated the measured effective angle of internal friction into frictional and dilational components. The dilational component was approximately independent of angularity whereas the frictional component increased significantly with increasing angularity or decreasing sphericity for common relative densities. The same trends had been previously shown by Kolbuszewski and Frederick (*19*).

George and Shah (*20*) compared triaxial test results on rounded gravel with the results on the same gravel after waxing the particles. The waxed particles produced a substantially lower strength. These researchers also compared the triaxial results for platy crushed limestone with results for chunky crushed limestone. Although the same peak strength was obtained, the stiffness was less for the platy specimens. The authors did not indicate whether these comparisons were made at common void ratios.

Particle Gradation and Size

Roenfeld (*21*) conducted repeated load triaxial tests on limestone ballast. One set of specimens had a narrow range of particle sizes [coefficient of uniformity (CU) = 1.14]; the other set had a broader grading (CU = 4.1) but a slightly smaller mean size. The cumulative plastic strain for the uniform ballast was almost double that for the more broadly graded ballast. Furthermore, the particle degradation for the uniform ballast was four to five times greater than that for the more broadly graded ballast.

Klugar (*22*) reported that replacing a small amount (<15 percent) of large particles in a ballast specimen by smaller particles increased the friction angle in shear-box tests and that replacing a greater amount (>20 percent) caused a significant reduction in the friction angle mobilized at a given displacement.

Rico et al. (*23*) tested three different gradations of crushed basalt in a Texas triaxial cell. The comparisons were made at equal compactive effort. Thus void ratio and unit weight were not identical. A relatively uniform gravel size specimen gave a much higher strength that did a relatively uniform sand size. For the same top particle size (1.5 in. or 38 mm), a more broadly graded specimen gave a higher strength than did a narrowly graded specimen.

Marsal (*24*) tested rockfill dam materials with a maximum particle size of about 6 in. using a large, high-pressure triaxial cell. He showed that shear strength increased as the gradation became broader for the same top size, even though the mean size decreased. Marachi et al. (*25*) came to the same conclusion after making tests with common compactive efforts, although mineral composition and void ratio were not identical for all specimens.

Chen (*10*), in tests previously described, found that increasing the coefficient of uniformity increased shear strength but did not affect stiffness.

Kirkpatrick (*26*) conducted triaxial tests on a sand with three different gradings in which the top and bottom sizes were kept constant while the mean size was varied. In general, shear strength increased as mean size decreased.

Leslie (*27*) conducted triaxial tests on gravelly soils in which the minimum particle size was kept constant while the maximum size was increased, which increased the mean size and broadened the gradation. For comparable compactive effort, as mean size increased shear strength decreased.

Triaxial tests on sands by Koerner (*18*) showed little effect on shear strength of changes in coefficient of uniformity for common void ratios. In some cases increasing the coefficient of uniformity at common relative densities increased shear strength. However, strength increased as particle size decreased.

Triaxial tests by Marachi et al. (*25*) showed that strength increases as particle size decreases. However, Dunn and Bora (*5*), in triaxial tests previously described, found that shear strength increased with increasing particle size. Finally, triaxial tests by Vallerga et al. (*12*) and by Holtz and Gibbs (*11*) showed little effect of particle size on strength. Thus the effect of particle size on strength is unclear. The same conclusion was indicated by results of direct shear tests summarized by Roner (*3*).

DESCRIPTION OF TEST

To supplement results available in the literature, triaxial tests were conducted by Roner (*3*) on nonflaky specimens of several sizes and gradings and on flaky specimens with both random and parallel particle orientations. The triaxial tests used specimens 8 in. (203 mm) in diameter by 20 in. (508 mm) high. Although a larger size would have been preferable, this was the largest size that could be used with available apparatus.

The specimens were contained in a rubber membrane, and a constant confining pressure was applied through water. The ballast voids were also filled with water under constant back pressure so that volume change could be determined from the amount of water flowing into or out of the specimen during the test. The effective confining pressure for all tests was 5 psi (34 kPa). Loading was provided by a compression machine at a constant rate of deformation of about 0.1 in./min (2.5 mm/min).

The primary ballast used in the tests was a crushed quartzite. Its Los Angeles abrasion resistance was 20 and its mill abrasion value was 1.9. Because the quartzite did not contain sufficient flaky particles, additional flaky particles were obtained from a sample of gneiss that had a Los Angeles abrasion resistance of 23 and a mill abrasion value of 2.0. Four ballast gradings were prepared:

	Size Range		
Grading	*Inches*	*Millimeters*	*Coefficient of Uniformity*
1	1 1/2-1/2	38-13	1.47
2	1 1/2-1 1/8	38-29	1.03
3	1 1/8-3/4	29-19	1.03
4	3/4-1/2	19-13	1.03

Gradings 2, 3, and 4 are parallel and connected. Grading 1 consists of equal parts by weight of the other three gradings.

The regular (nonflaky) ballast specimens had 6 percent by weight of flaky particles according to British Standard 812 (*1*) but none according to the Corps of Engineers (*2*), which was representative of the composition of the quartzite ballast as received. The first method defines flaky particles as having a width-to-thickness ratio greater than 1.7, and the second method uses a width-to-thickness ratio greater than 3. Thus the second is about twice as flat as the first.

The flaky ballast tested was composed of 96 percent by weight of flaky particles according to British Standard 812 (*1*) but only 4 percent by weight of flaky particles according to the Corps of Engineers (*2*). The American Railway Engineering Association, before 1986, combined flat and elongated particles into a single definition that required the length-to-thickness ratio to be greater than 5. The flaky specimen had only about 3 percent by weight of flat and elongated particles by this definition. Only Grading 1 was used for the flaky specimens because of the limited amount of flaky material available.

A range of void ratios was achieved by hand placing the particles and tamping, as needed, using a rubber-tipped falling-weight device (*28*). The flaky particles were placed either randomly or all parallel. The parallel plane was oriented at zero, 45, and 65 degrees from horizontal, the latter representing the approximate orientation of the failure plane. Little variation in the void ratio could be obtained with the oriented specimens.

The void ratio of the completed specimens was obtained by determining the volume of water required to fill the voids while the specimen was still in the forming mold. The error caused by water adsorption by the ballast particles was sufficiently small to be neglected. However, a large error is introduced because the specimen is formed in a smooth-walled cylinder. This results in the boundary voids being too large and hence an overestimate of the true in situ void ratio. Because no procedure has been developed for boundary voids correction, this error was ignored. However, this is largely a systematic error that should not significantly affect comparisons done with the same sized mold for the ranges of particle sizes considered. The details of the test apparatus and procedures are given elsewhere (*3*).

TEST RESULTS

The maximum deviator stress (failure state) and corresponding angle of internal friction are shown as a function of initial void ratio in Figures 1 and 2, respectively. No significant

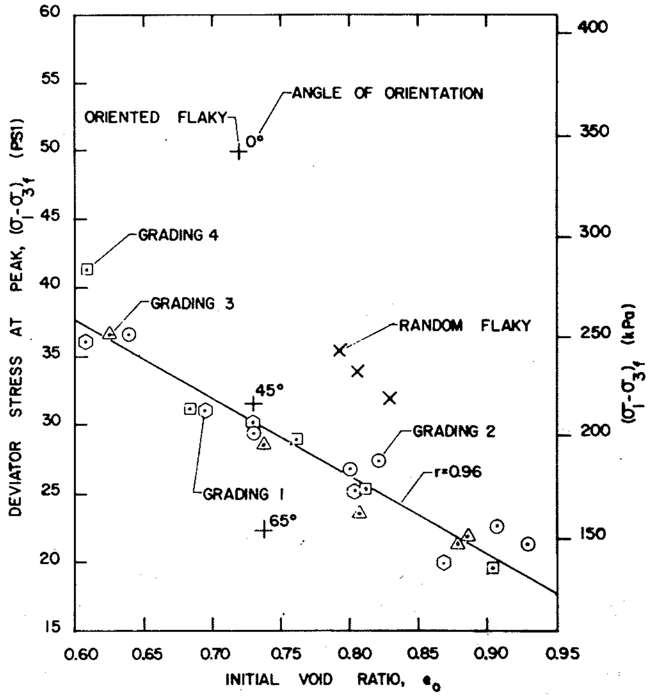

FIGURE 1 Effect of initial void ratio on deviator stress at failure.

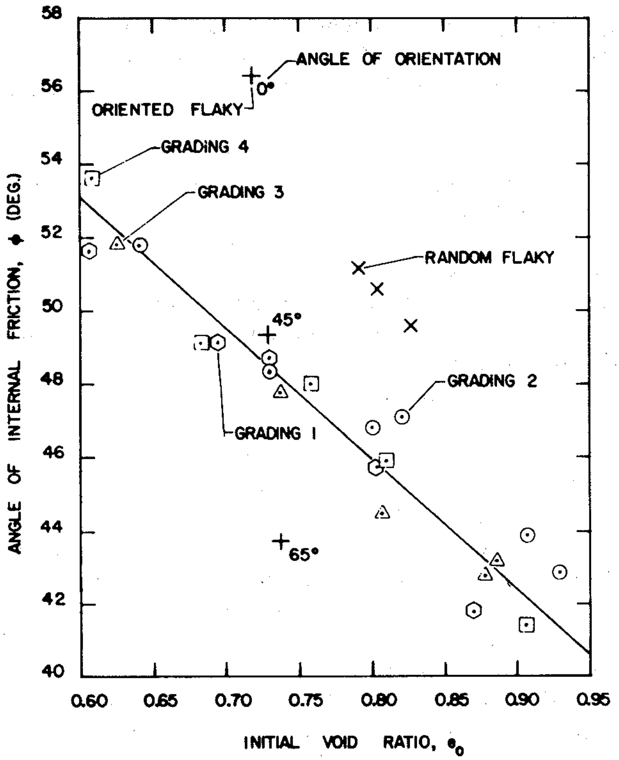

FIGURE 2 Effect of initial void ratio on angle of internal friction.

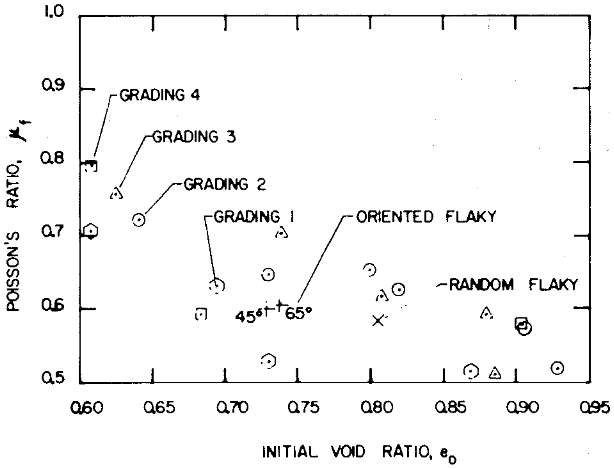

FIGURE 3 Effect of initial void ratio on Poisson's ratio at failure.

influence of particle size or gradation is evident for the nonflaky specimens within the range represented.

Volume change and axial strain at failure were used to calculate the secant Poisson's ratio at failure. The resulting values are shown as a function of initial void ratio in Figure 3. Poisson's ratio decreases with increasing void ratio. All values exceed 0.5, signifying dilation even for the uncompacted specimens (highest void ratios).

The maximum deviator stress and angle of internal friction for the flaky specimens are also shown in Figures 1 and 2. The random flaky specimens had a strength that is significantly greater than the strength at the corresponding void ratios for the nonflaky specimens. The flaky specimen with horizontally oriented particles had by far the greatest strength of all specimens. Only when the particles were oriented parallel to the failure plane did a substantially lower strength occur for the flaky specimens.

The Poisson's ratio values for all of the flaky specimens were consistent with those for the nonflaky specimens at the same void ratio (Figure 3). Three flaky specimens are missing because of problems with volume measurement. It is presumed that these values would also have been consistent.

SUMMARY AND CONCLUSIONS

The main problem in drawing conclusions about the individual effects of particle size, shape, texture, and gradation on aggregate specimen performance is that tests to determine these trends often involved simultaneous changes in several significant variables. For example, changes in size may also have included changes in particle composition, void ratio, gradation, or angularity. In the following summary the effects of these independent factors are separated as well as possible by considering the conditions associated with all of the reviewed data as well as the supplemental tests conducted in this study. Some of the trends need further verification.

Shape

Any quantity of flaky particles, either randomly oriented or oriented other than generally parallel to the failure plane, increases the shear strength of the granular specimen. Orientation parallel to the failure plane, when a significant proportion of the particles is flaky, will cause a substantial reduction in strength. The disadvantage of increased flakiness appears to be increased abrasion, increased breakage, increased permanent strain accumulation under repeated load, and decreased stiffness. A further study of these factors is needed.

Increased particle angularity, as is well known, increases shear strength. However, particle breakage increases and specimen stiffness decreases as well. At the same compactive effort, a more angular material will tend to form a higher void ratio that will result in less strength increase than at a common void ratio.

Increasing particle surface roughness increases the shear strength of the assembly of particles. As is the case with angularity, this effect is greater at a common void ratio than at a common compactive effort.

No conclusions about the effects of elongation could be drawn from the literature.

Gradation

Strength was not affected by the gradation changes investigated by the writers for common void ratios. However, broadening the gradation by increasing the range of particle sizes with the same mean size should increase shear strength as a result of decreased void ratio that would exist with a broader grading.

Additional benefits of broadening gradation are decreased cumulative plastic strain under repeated loading and decreased particle degradation.

Size

The literature gives contradictory information about the effects of particle size on shear strength. Available results in some cases show an increase, in some cases a decrease, and in some cases no effect with increase in particle size. For the range tested by the writers, mean particle size did not appear to affect strength when compared at common void ratios.

Volume Change

For all cases tested by the writers, the ballast specimens expanded in volume as a result of shearing to failure. This means that the secant Poisson's ratio at failure exceeded 0.5 even for the uncompacted specimens. No distinctive effect on the relationship between Poisson's ratio and initial void ratio was detected as a result of changes in particle size, shape, or gradation.

Application to Ballast

On the basis of strength considerations, broader ballast gradations are better than narrow gradations. However, other factors such as durability, fines storage volume, and size segregation must also be considered in selecting gradation. More research on these factors is needed before an optimum grading can be established. Available information does not provide a basis for choosing an optimum ballast size. Factors other than stress-strain and strength characteristics may therefore govern the choice of size. Such factors include particle durability and the movement and storage of fines within voids.

Until 1986 the AREA specifications (*29*) for ballast limited the amount of flat or elongated particles (length-to-thickness ratio greater than 5) to 5 percent by weight. The flaky ballast tested by the writers is acceptable by this standard. However, only extremely distorted shapes would be eliminated by this specification. In 1986 the AREA adopted the Corps of Engineers definitions (*2*) for defining flat (width-to-thickness ratio greater than 3) and elongated (length-to-width ratio greater than 3) particles. The percentage of such particles allowed remains 5 percent by weight. This requirement appears to be more restrictive, and hence better, than the previous AREA requirement, but the flaky ballast tested still is acceptable under this standard.

More research is needed to determine the important reasons for limiting the use of flaky ballast particles in track. Until such research is completed, the best shape criteria and proper limits will not be known. However, if the effects of particle orientation on strength and the effects of shape on stiffness that were indicated in this paper for flaky ballast are to be avoided, an even more restrictive definition of shape will be required. The British standard should then be adopted although perhaps a larger amount of such particles than 5 percent by weight could be allowed.

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