worked downward to the bottom of the slab, and some of these will be studied to see whether a reactive sand-gravel material was used in them.

The water-reducing, set-retarding admixtures did not appear to influence the development of either map cracking or D-cracking. The pavement condition is approximately the same where either set retarder was used and where none was used. Therefore, they apparently neither contributed to nor hindered the development of deterioration.

The area in question has an average precipitation of 686 mm/year (27 in/year), but a pan evaporation rate of about 1626 mm/year (65 in/year) (4). It is subjected to an average of 5000 summer degree hours above 29.4°C (85°F) in a normal year (7). This high number of degree hours is experienced only in central and eastern Kansas, southeastern Nebraska, central and western Missouri, most of Oklahoma outside the panhandle, and north central Texas. The highest average number of such degree hours, more than 7000, is experienced only in portions of Kansas and Oklahoma. The maximum expected in these areas is more than 12 000 degree hours above 29.4°C (7).

The mean annual snowfall on the pavement is about 610 mm (24 in) (6, Figure 4), and more than 68 freeze-thaw cycles can be anticipated each year (9, Figure 2). In 1974, an average of 1500 passenger vehicles and 500 large trucks traveled the road daily (10).

It is reasonably certain that the high summer temperatures, the many freeze-thaw cycles, and the salt and melted snow all contributed to the deterioration. The daily pounding by heavy trucks would add to the problem by loosening and removing the cracked surface concrete. However, the occurrence of blowups because of internal expansion has done the most damage. The plane of splitting of the concrete in the blowups was the level of the load-transfer bars.

Thus, the Towanda limestone sweetener failed to prevent the reactive Republican River sand gravel from causing map cracking. The map cracking allowed the limestone coarse aggregate to become critically saturated, and freeze-thaw led to D-cracking. Together, these effects increased the process of pavement expansion, and with the help of water and hot weather, blowups at the joints soon followed.

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Publication of this paper sponsored by Committee on Performance of Concrete—Physical Aspects.

Resilient Response of Railway Ballast

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The resilient responses of five typical open-graded aggregate materials (dolomitic limestone, blast-furnace slag, granitic gneiss, basalt, and gravel) that are used for railway ballast were measured in a triaxial cell. Three levels of compaction and seven stress levels were used. The results were used in regression analyses to develop equations relating the resilient modulus of a specimen to its first stress invariant. They were also used in correlation analyses attempting to relate the resilient response to the physical properties (particle index, specific gravity, Los Angeles abrasion, gradation, flakiness, soundness, and crushing index), but no consistent relations were established. It is concluded that (a) the resilient response of a specimen is essentially independent of its stress history, (b) the resilient moduli of no. 4 and no. 5 ballast-gradation specimens are

usually lower than that of a well-graded aggregate, (c) the resilient moduli of open-graded ballast materials are virtually insensitive to changes in gradation or compaction level, and (d) the variable that most directly influences the resilient moduli of granular materials is stress level.

Although the concept of resilient modulus has gained acceptance and been widely applied to highway and airfield aggregates and soils, information is lacking about the resilient response of the typical open-graded aggregate materials that are used for railway ballast. This paper presents information about the resilient behavior of open-graded materials and relates the results to material and sample properties.

BACKGROUND

Railroads use ballast to support the rail-tie system and provide a free-draining medium. One of the problems related to the performance of ballast materials is the excessive elastic deformation caused by the rapid application and removal of heavy wheel loads.

Excessive elastic deformations in the ballast and subgrade can shorten the life of the rail tie because of the fatigue that results from increased bending stresses. In addition, the ride quality of both freight and passenger cars is reduced if the elastic deformations in the conventional railway-track support system (CRTSS) are excessive.

Modern analytical models can be used to improve the present experience-oriented design of rail-tie support systems. However, before these techniques can be applied, adequate input in the form of the response parameters of ballast materials must be obtained. Thus far, such information has not been available. The response of ballast materials depends on the applied state of stress, and to accurately predict the structural response of the CRTSS, the test method used to evaluate the granular materials should simulate in-service, dynamic stress conditions.

There have been several investigations (1, 2, 3, 4, 5) of the repeated-load behavior of granular materials, but little work has been done involving open-graded aggregates such as ballast.

Repeated-load triaxial testing of a variety of types of aggregates appears to be the most appropriate method for investigating the resilient behavior of ballast materials. Previous investigations in which actual loading conditions were closely simulated have given results that are excellent for convenient application to techniques of finite-element structural analysis.

MATERIALS

Five materials commonly used for ballast were studied, and comparisons of their repeated-load behavior and their natural properties were made. The materials selected were dolomitic limestone from Kankakee, Illinois; blast-furnace slag from Chicago; granitic gneiss from Columbus, Georgia; basalt from New Jersey; and gravel from McHenry, Illinois.

The materials were sieved, and the various size fractions were stored in separate containers for recombining into the desired gradations.

Characterization Tests

To relate the results of the repeated-load tests to the physical properties of the materials, the following standard tests (9, 10, 11, 12) were performed on each type of material.

Property	Test
Particle index	ASTM D 3398-75
Specific gravity	ASTM C 127, AASHTO T 85
Los Angeles abrasion	ASTM C 131, AASHTO T 96
Gradation parameter	Hudson and Waller
Flakiness index	British Standard 812-15
Soundness	ASTM C 88, AASHTO T 104
Crushing value	British Standard 812-34

The results of these tests are summarized in Table 1.

Gradation

To examine the effects of different gradations of ballast on the resilient response, three different ones were tested. Two standard American Railway Engineering Association gradations, no. 4 and no. 5, were selected by using the center values of the recommended gradation bands, and a third gradation was based on the use of the Talbot equation with an exponent of $^2/_3$. Because one of the main considerations of ballast is that it be free draining, the results obtained through the use of the Talbot equation were maintained only through the 4.75-mm (no. 4) sieve, and to ensure a high permeability, no material finer than the 1.18-mm (no. 16) sieve was used. This gradation was labeled well graded. A conservative estimate of the permeability of the well-graded material is 1500 m/d (5000 ft/d).

Figure 1 shows the three gradations used in the testing program.

EQUIPMENT

A U.S. Army Engineer Waterways Experiment Station triaxial cell design was modified, and the cell was fabricated at the University of Illinois. Because of the large size of the aggregate to be tested, the cell was constructed with an inside diameter of 279 mm (11 in) to provide the capability for testing 203-mm (8-in) diameter cylindrical specimens 406 mm (16 in) high.

The confining pressure was supplied by air pressure and was not cycled during the tests. The repeated deviator stress was applied by a hydraulically actuated piston; control was by a closed-loop electronic system. Input for the load control was provided by a function generator connected through electronic controls to the hydraulic actuator.

Several investigators (2, 4, 6) have experimented with changes in the duration of the repeated load and found no significant dependence of the resilient behavior on the duration of load, especially if the duration is of the order of 0.10 to 0.15 s. The effect on resilient behavior of the frequency of applied load has been studied by Seed and others (6), who found that so long as the frequency is in the expected in-service range, the effect on the resilient response is slight.

The spacing of trucks on conventional railroad rolling stock varies, and the pulse caused by the second truck on one car overlaps that of the first truck on the following car. These two factors cause problems in analyzing the in-service frequency and duration of loading of the ballast. Thus, to satisfy the constraints of the equipment and to approximate the in-service conditions, a frequency of 50 applications/min and a haversine load pulse of 0.15-s duration were used. These conditions are equivalent to a train speed of about 129 km/h (80 mph).

The triaxial chamber pressure was monitored by a gauge on the air supply line. The axial load was monitored by a load cell mounted between the hydraulic actuator and the loading rod. A two-channel high-speed strip-chart recorder was used to monitor the output of

Table 1. Characterization tests.

Material	Gradation	Particle Index	Specific Gravity	Los Angeles Abrasion Loss (%)	Gradation Parameter	Flakiness Index	Soundness Loss (%)	Crushing Value
Limestone	No. 5	13.80	2.626	34.2	1.846	17.52	12.3	22.7
	No. 4	13.75	2.626	34.2	1.074	16.78	18.5	22.7
	Well-graded	14.09	2.626	34.2	2.039	17.33	15.3	22.7
Granitic gneiss	No. 4	13.45	2.679	34.7	1.074	14.39	0.25	26.1
Blast-furnace slag	No. 4	15.68	2.133	37.8	1.074	3.59	0.75	37.3
Basalt	No. 5	15.10	2.775	12.3	1.846	19.69	6.14	12.4
	No. 4	15.40	2.775	12.3	1.074	17.33	4.93	12.4
	Well-graded	14.83	2.775	12.3	2.039	16.11	4.86	12.4
Gravel	No. 5	7.54	2.658	23.2	1.846	4.03	5.06	13.8
	No. 4	10.17	2.658	23.2	1.074	5.79	5.78	13.8
	Well-graded	8.86	2.658	23.2	2.039	6.58	5.84	13.8

Figure 1. Gradations of specimens tested.

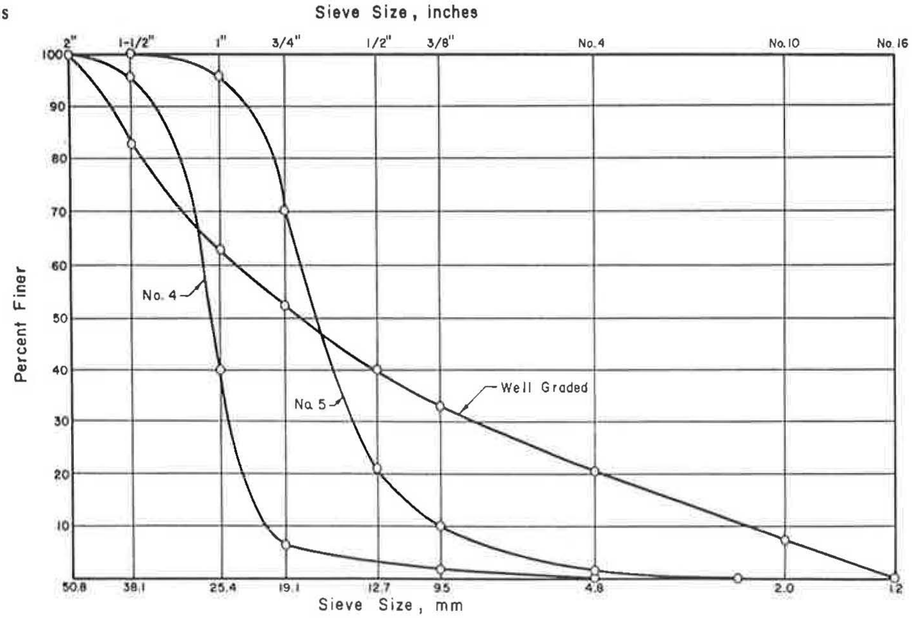


Table 2. Properties of test specimens.

Type of Material	Gradation	Compaction Level	Density (kg/m³)	Void Ratio
Limestone	No. 5	Medium	1653	0.59
	No. 4	Low	1424	0.84
	No. 4	Medium	1536	0.71
	No. 4	High	1586	0.66
	Well-graded	Medium	1792	0.46
Granitic gneiss	No. 4	Low	1490	0.76
	No. 4	Medium	1562	0.71
	No. 4	High	1639	0.63
Blast-furnace slag	No. 4	Low	1068	1.00
	No. 4	Medium	1137	0.87
	No. 4	High	1173	0.82
Basalt	No. 5	Medium	1722	0.63
	No. 4	Medium	1527	0.82
	Well-graded	Medium	1853	0.50
Gravel	No. 5	Medium	2030	0.31
	No. 4	Low	1640	0.62
	No. 4	Medium	1722	0.54
	No. 4	High	1796	0.48
	Well-graded	Medium	2110	0.26

Note: 1 kg/m³ = 0.062 lb/ft³.

the load cell.

Two methods were used to observe the axial deformations. The first was by the use of two electronic-optical scanners that measured the vertical motion of targets placed at the upper and lower quarter points of the specimen. These targets consisted of one black and one white rectangular strip, 32 by 64 mm (1.25 by 2.5 in) each, held to the specimen membrane by double-sided tape. The chamber pressure ensured that the membrane was molded firmly to the specimen, thereby eliminating slippage between specimen and targets. The movements of the targets were sensed by the optical heads and converted into an electrical signal; the difference in movements was recorded as output on the strip recorder.

A backup for measuring the axial deformations was provided by a linear variable differential transformer (LVDT) mounted at the top of the hydraulic actuator. The LVDT signal was recorded simultaneously with the collimator signal. The LVDT measured deformations over the entire specimen length; therefore, the output included specimen end effects.

TEST PROCEDURE

Because one of the objects of this study was to determine the effects of gradation and maximum size on ballast behavior, two different sample sizes were used. Samples 152 mm (6 in) in diameter were used for the no. 5 ballast-gradation specimens, which have a maximum particle size of 38 mm (1.5 in), and samples 203 mm (8 in) in diameter were used for the no. 4 ballast gradation, which has a maximum particle size of 51 mm (2 in). Thus, the ratio of the diameter of the sample to the maximum particle size was always four. All the prepared samples had a height to diameter ratio of 2 to 1 or more to minimize the end effects on the deformation measurements.

To minimize segregation and to ensure gradation control, each specimen was weighed out by thirds for each of the size fractions, and each third was placed in a separate container. The material was then washed to remove the fines, drained, and compacted.

Because of the open-graded nature of ballast, vibratory compaction similar to that described by Rostron and others (7) was used. To determine the compaction characteristics of the aggregate and whether it was degraded during compaction, no. 5 ballast-gradation limestone was compacted in the standard split mold for various times by using the vibratory compactor. The results showed that there was little increase in density for compaction times greater than 45 s and that the gradation change (aggregate degradation) due to compaction was extremely small. For example, the amount of material passing the 4.75-mm sieve increased from 2.5 to 4.0 percent after compaction for 45 s/layer, and the increase was less (less than 1 percent) for shorter compaction times.

Because densities are generally not specified when ballast is placed, there was no attempt to attain a predetermined density. Instead, three degrees of compaction were used. For low-density specimens, each layer of aggregate was placed and rodded 10 times; for medium-density specimens, each layer was compacted for 5 s with the vibratory hammer; and for high-density

Figure 2. Relation between E_r and θ for medium-density no. 5 gradation limestone.

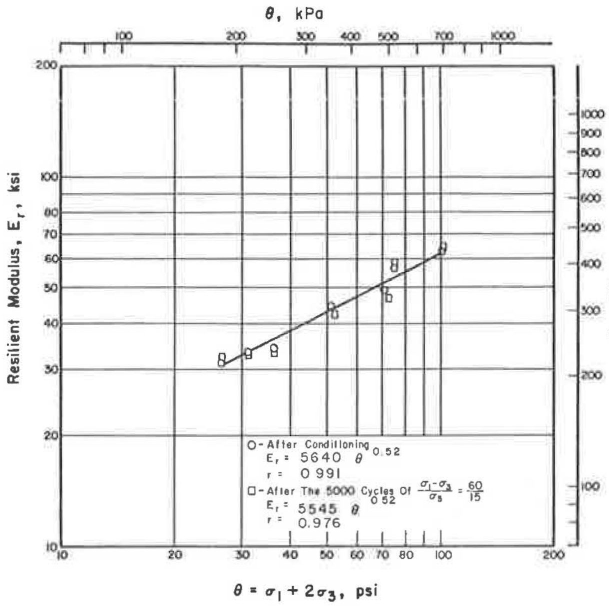


Figure 3. Relation between E_r and θ for low-density no. 4 gradation limestone.

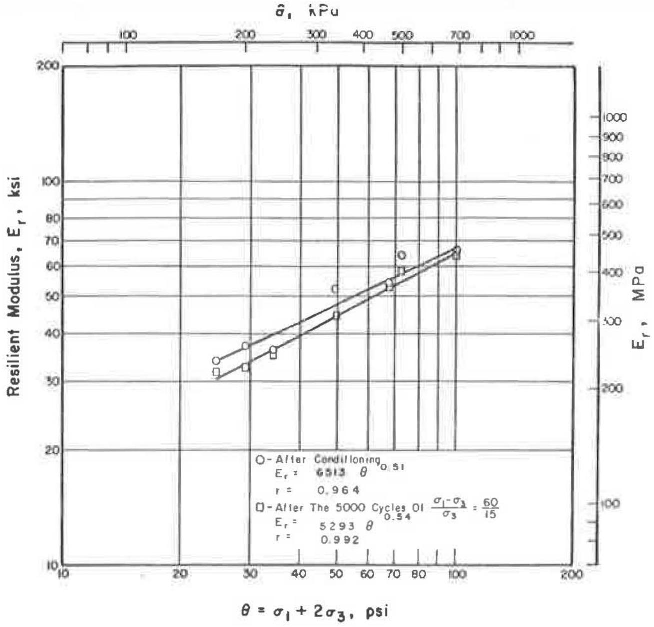


Figure 4. Relation between E_r and θ for medium-density no. 4 gradation limestone.

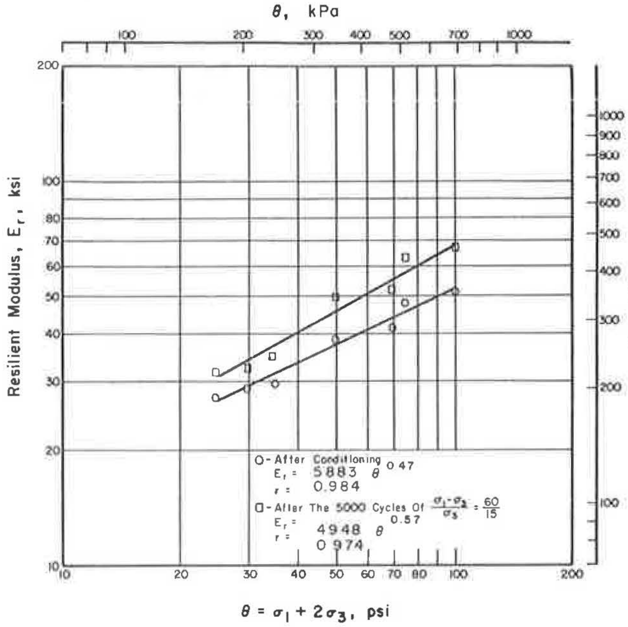
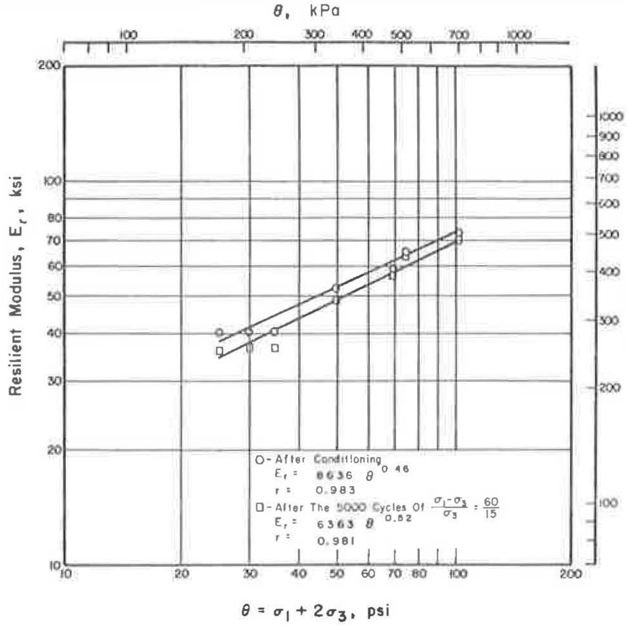


Figure 5. Relation between E_r and θ for high-density no. 4 gradation limestone.



specimens, each of the three layers was vibrated for 45 s.

The compaction was carried out in a split mold clamped to the sample base. A rubber membrane was used inside the mold, and a vacuum was applied through the attached tubing to hold the membrane against the mold. After compaction, the height of the specimen was recorded, the mold was removed, and a second membrane was placed over the specimen because (almost without exception) the original membrane was punctured during compaction.

From a finite-element analysis of CRTSS (8), values were obtained for the stress at various points in the ballast layer. A deviator stress of 310 kPa (45 lbf/in^2) and a confining pressure of 103 kPa (15 lbf/in^2) were selected as representative of the stresses occurring approximately 51 mm beneath a crosstie, and each specimen was conditioned for 5000 load applications. After conditioning, each specimen was tested for resilient modulus at each of seven stress levels as follows (1 kPa = 0.145 lbf/in^2):

Figure 6. Relation between E_r and θ for medium-density well-graded (n = 2/3) limestone.

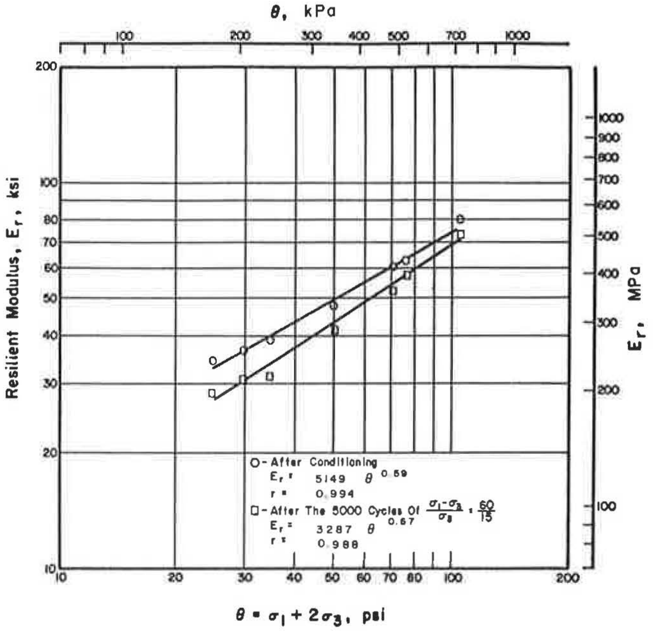


Figure 7. Relation between E_r and θ for low-density no. 4 gradation granitic gneiss.

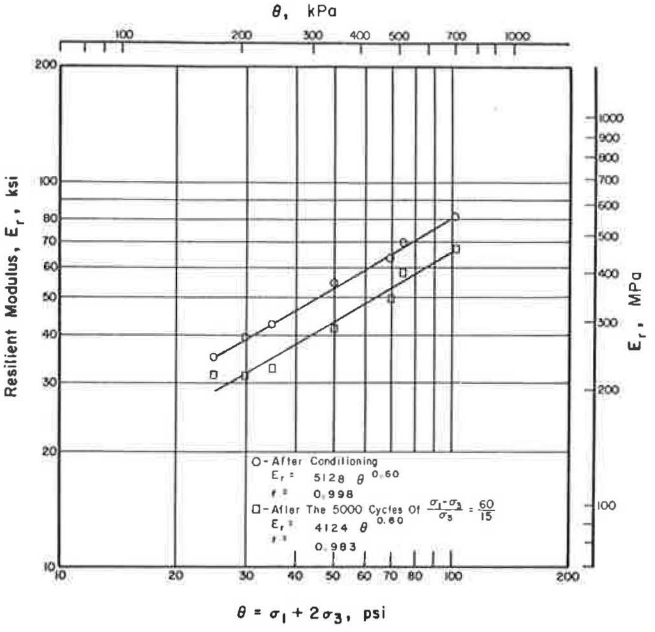


Figure 8. Relation between E_r and θ for medium-density no. 4 gradation granitic gneiss.

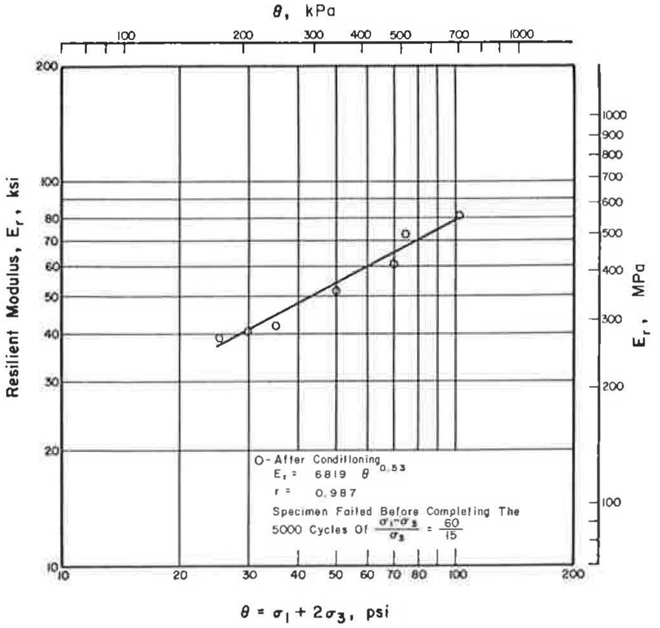
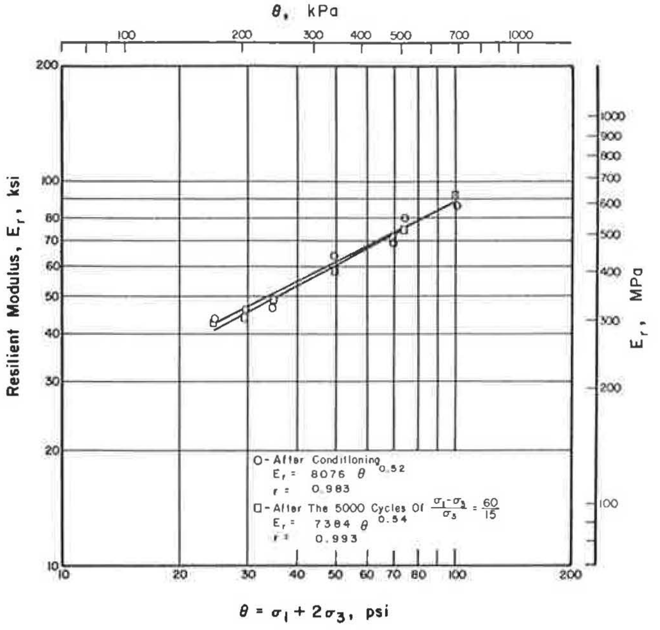


Figure 9. Relation between E_r and θ for high-density no. 4 gradation granitic gneiss.



Deviator Stress (kPa)	Confining Pressure (kPa)	Deviator Stress (kPa)	Confining Pressure (kPa)
414	103	138	34
207	103	103	34
276	69	69	34
138	69		

After the first test of resilient response, the specimens were loaded for 5000 cycles at a deviator stress of 138 kPa (20 lbf/in^2) and confining pressure of 34 kPa (5 lbf/in^2) and then for 5000 cycles at a deviator stress of 414 kPa (60 lbf/in^2) and a confining pressure of 103 kPa (15 lbf/in^2). A second resilient-response test was then performed to determine the effects of mixed loading and stress history.

RESULTS

Table 2 summarizes the physical properties of the specimens tested. The most dense specimen, the well-graded gravel, had a density almost twice that of the least dense, the low-compactive-effort blast-furnace slag.

The data collected in the resilient-response tests were used in regression analyses to develop equations

Figure 10. Relation between E_r and θ for low-density no. 4 gradation Chicago blast-furnace slag.

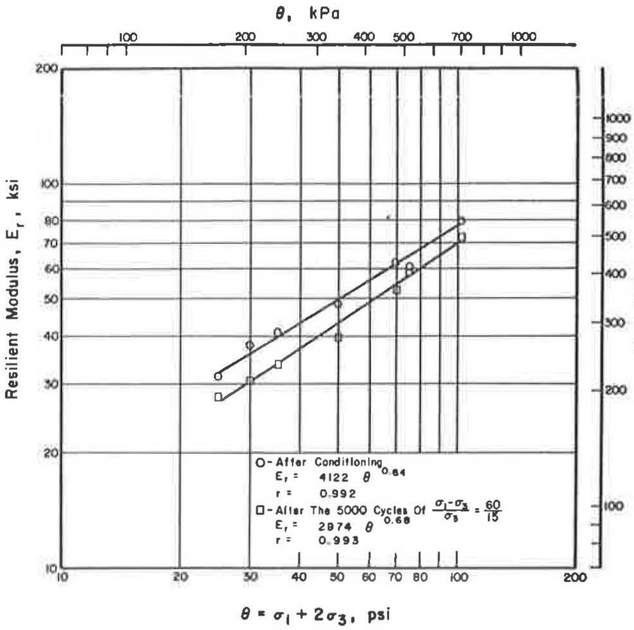


Figure 11. Relation between E_r and θ for medium-density no. 4 gradation Chicago blast-furnace slag.

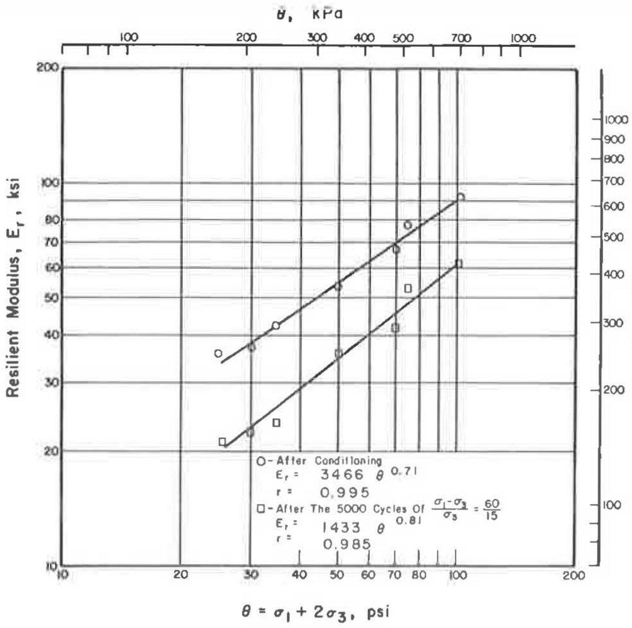


Figure 12. Relation between E_r and θ for high-density no. 4 gradation Chicago blast-furnace slag.

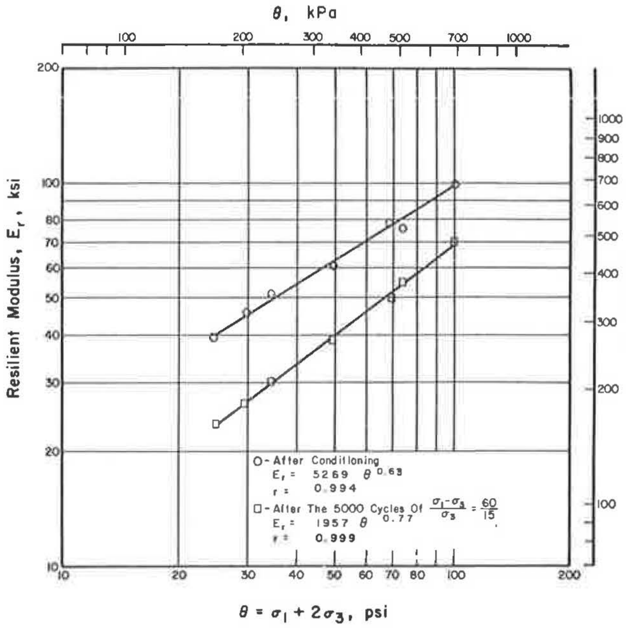
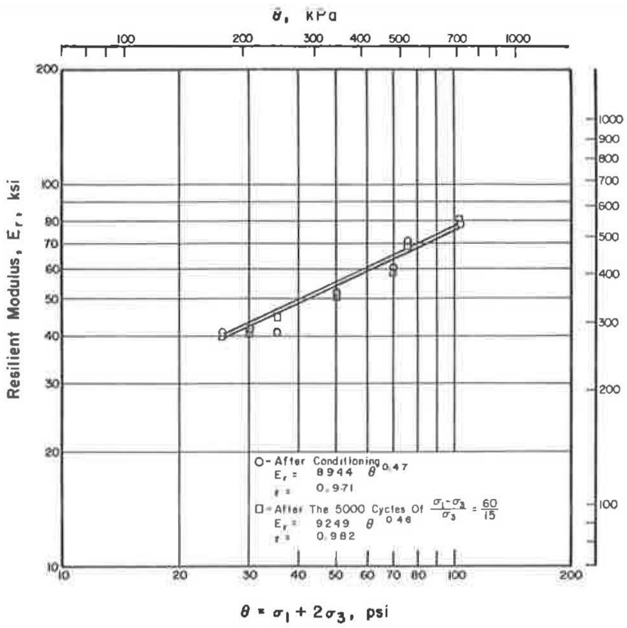


Figure 13. Relation between E_r and θ for medium-density no. 5 gradation basalt.



of the following type:

$$E_r = K\Theta^n \quad (1)$$

where

E_r = resilient modulus,
n and K = constants representing slope and intercept respectively on a log-log plot, and
Θ = first stress invariant, i.e., $\sigma_1 + \sigma_2 + \sigma_3$.

($\Theta = \sigma_1 + 2\sigma_3$ in the triaxial test.)

Figures 2 through 20 present the results, including the regression analyses, for the specimens tested. (SI units are not given for the coefficients in the regression results because the analyses were carried out in customary units only.) Two of the specimens failed before completion of the mixed loading sequence, and thus only one set of data is available for those two. All the regression analyses were significant at $\alpha = 0.01$.

The resilient-response data were also used in correlation analyses with the results of the standard characterization tests, but no consistent relations could be established between K or n and the material-

Figure 14. Relation between E_r and θ for medium-density no. 4 gradation basalt.

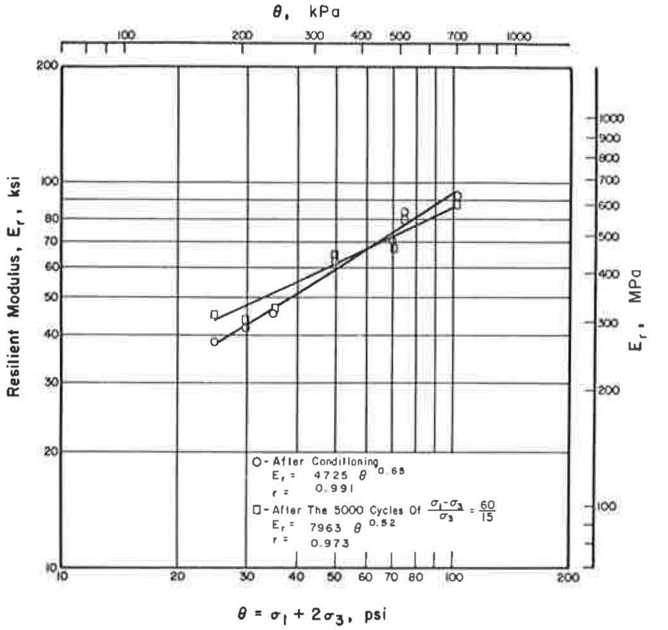


Figure 15. Relation between E_r and θ for medium-density well-graded (n = 2/3) basalt.

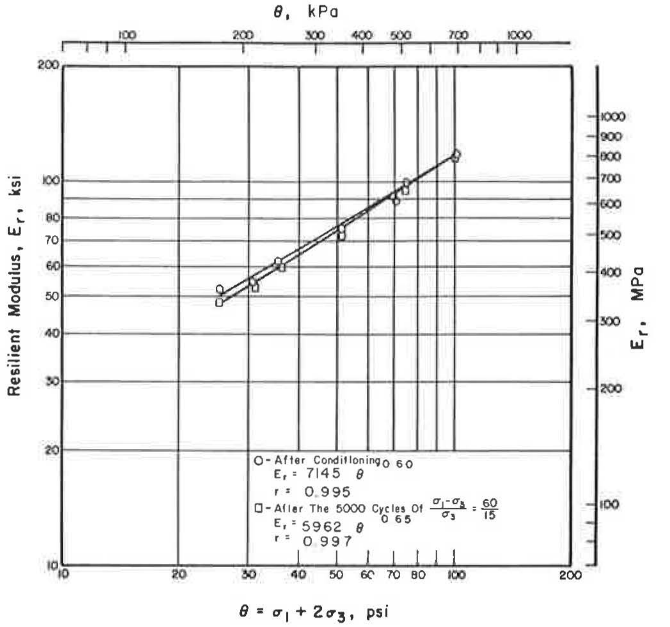


Figure 16. Relation between E_r and θ for medium-density no. 5 gradation gravel.

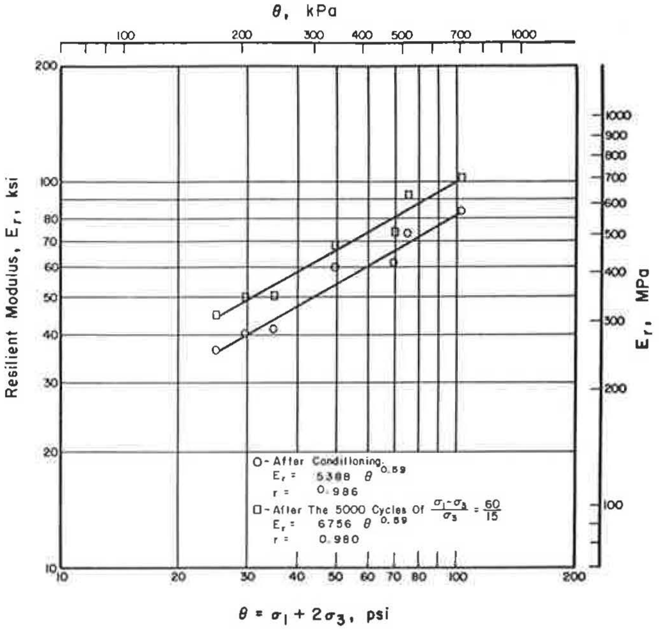
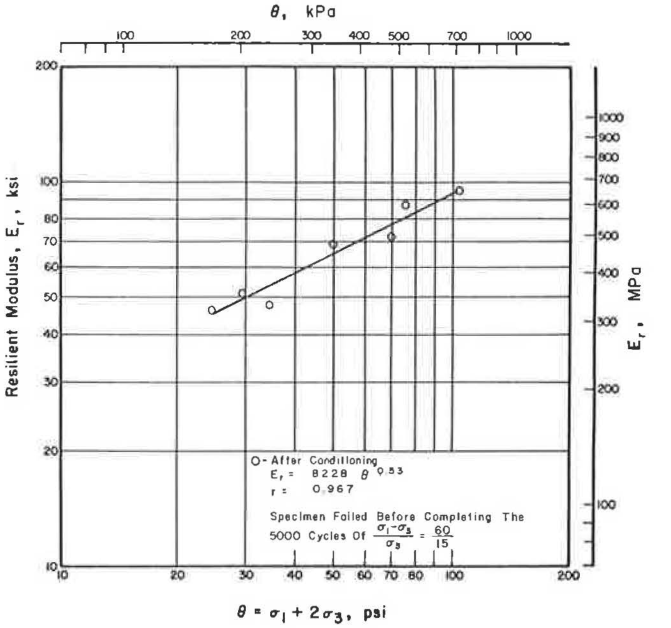


Figure 17. Relation between E_r and θ for low-density no. 4 gradation gravel.



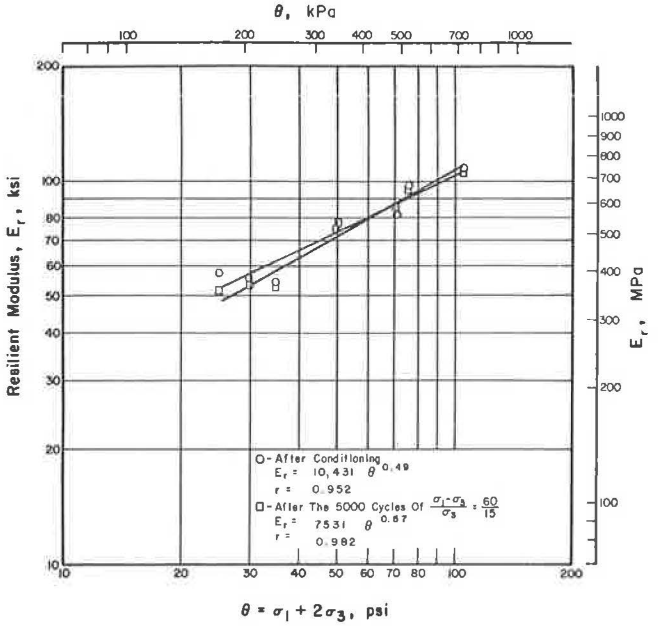
characterization data.

To ensure that the gradation parameter was included on an equal basis, three levels of gradation of three types of material (limestone, basalt, and gravel) were included in the correlation analyses, but neither K nor n were found to correlate significantly ($\alpha = 0.05$) with any of the material properties.

Attempts were also made to determine the effects on the resilient response of the type of material and the gradation through the use of randomized complete block analyses. The effects of loading history and relative density were also investigated.

Because previous research (4) has shown that variations in the values of n and K of the predictive equations for resilient modulus often cancel one another, two values of E_r were calculated at values of Θ of 241 kPa (35 lbf/in^2) and 620 kPa (90 lbf/in^2) and included in the analyses. Thus, the variables included were K, n, E_r at 241 kPa, and E_r at 620 kPa.

Figure 18. Relation between E_r and θ for medium-density no. 4 gradation gravel.



To further examine the effect of gradation, three levels of gradation (no. 4, no. 5, and well graded) of three types of material (limestone, basalt, and gravel) were included in the analysis. Only one of the four variables—E_r at 620 kPa—had significant ($\alpha = 0.05$) differences due to gradation. The values of E_r at 620 kPa were further analyzed by using Duncan's multiple range test. No difference was found between the values for the no. 4 and no. 5 ballast-gradation specimens, but both were significantly lower than the values for the well-graded specimens. In general, the effect on resilient modulus of changes in gradation was slight.

The effect of density was included by considering three density levels (low, medium, and high) of four different materials (limestone, granitic gneiss, blast-furnace slag, and gravel). There were no differences among the resilient responses of these materials.

Further analysis of the resilient responses of the specimens to determine the effect of loading history (resilient behavior after conditioning versus after additional loading) showed that none of the four variables (K, n, E_r at 241 kPa, and E_r at 620 kPa) had significant ($\alpha = 0.05$) differences between the two sets of data. Thus, the conclusion that the resilient response of granular materials remains essentially unchanged through a complex loading history is reinforced (2, 3, 4, 5).

To include the effect of type of material, an analysis was made of low, medium, and high-density no. 4 ballast-gradation specimens of limestone, granitic gneiss, gravel, and blast-furnace slag.

There were no differences in the values of K among the four materials considered, but there were significant ($\alpha = 0.05$) differences among the values of n, E_r at 620 kPa, and E_r at 241 kPa. A further analysis was made by using Duncan's multiple range test. Although there were differences among the values for the various types of material, there were no consistent trends. The slag had the highest value of n, and this value was signifi-

Figure 19. Relation between E_r and θ for high-density no. 4 gradation gravel.

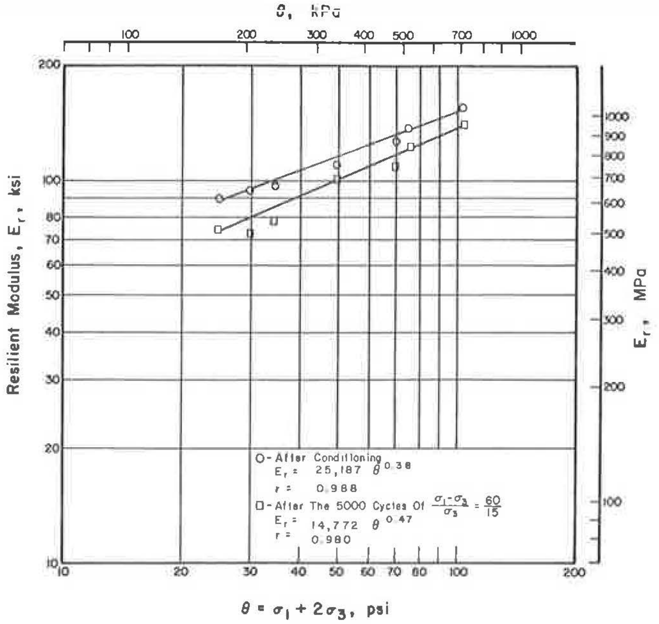
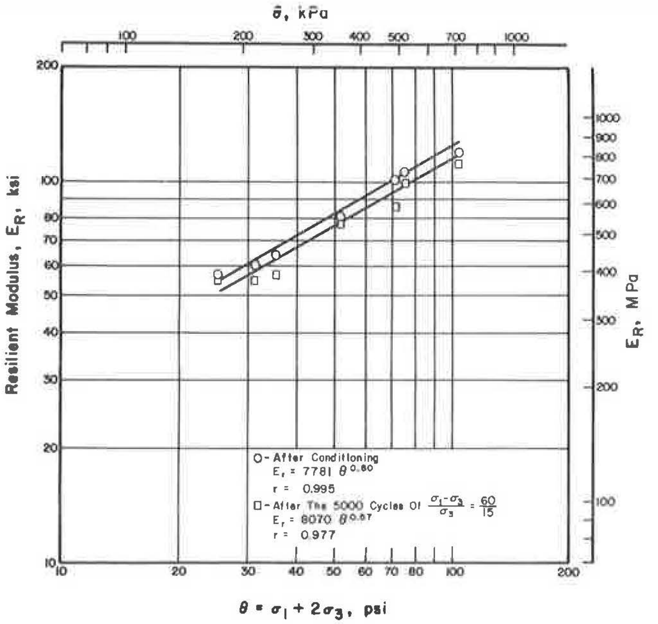


Figure 20. Relation between E_r and θ for medium-density well-graded (n = 2/3) gravel.



cantly different from that of the other three materials. The gravel specimens had the highest mean values of E_r at 241 kPa and at 620 kPa, and these values were significantly different from those of the other three types of material.

Although the resilient response depends somewhat on the type of material, the lack of consistency in the data prevents making any definite conclusions. The differences in resilient behavior were so slight as to be negligible from the standpoint of the structural response of a CRTSS.

SUMMARY AND CONCLUSIONS

Ballast materials from several sources were tested in the triaxial apparatus. In-service conditions were simulated by the use of a repeated deviator stress and a constant confining pressure. The resilient modulus characteristics were determined; the variables considered included the type of material and its gradation and density, and the stress level. Equations relating the resilient modulus to the first stress invariant were developed, and the results were analyzed with respect to the variables.

The following conclusions were reached:

1. The resilient response of a specimen of open-graded granular material is independent of its stress history so long as the specimen has not been subjected to a stress level that would cause failure.
2. The resilient moduli of no. 4 and no. 5 ballast-gradation specimens are usually slightly lower than that of a well-graded aggregate.
3. The resilient moduli of open-graded ballast materials are virtually insensitive to changes in gradation or compaction level. The dependence of resilient response on type of material is weak and inconsistent, and therefore, no conclusion is drawn with respect to material type.
4. Stress level is the variable most directly influencing the resilient modulus of granular materials. The stress-dependent nature of ballast materials can be characterized by the predictive equation:

$$E_r = K\Theta^n \qquad (1)$$

ACKNOWLEDGMENT

This paper is based on the results of a ballast and foundation materials research program conducted by the Transportation Research Laboratory of the Department of Civil Engineering, University of Illinois at Urbana-Champaign. The research was sponsored by a subcontract between the Research and Test Department, Association of American Railroads, and the University of Illinois. This subcontract is part of a larger contract that is a cooperative effort between the Federal Railroad Administration, U.S. Department of Transportation, and the Association of American Railroads on improved track structures. This paper represents our views and positions and does not necessarily reflect those of the U.S. Department of Transportation or the Association of American Railroads.

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Publication of this paper sponsored by Committee on Coatings, Signing, and Marking Materials.

Abridgment

Snowplowable Raised Pavement Markers in New Jersey

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Pavement markings are an important source of information to the motorist for safe vehicle control and guidance under almost all circumstances of driving. One of the most difficult problems in recent years has been that of