that pressures predicted elsewhere in the roadbed will be sufficiently accurate for track-design evaluations. Predictions of soil behavior are limited by the assumptions of linear elasticity in the MULTA model; thus, inelastic behavior of highly loaded soils could not be predicted accurately.

The major difficulty in using MULTA (or any other track-analysis program) is in the accurate modeling of the ballast and subgrade. The elastic continuum used in the MULTA model does show that the transfer of shear in the roadbed produces appreciable tie-to-tie coupling in displacements. This effect is also observed in track-response measurements, but it is not included in conventional beam-on-elastic-foundation models. However, the real difficulty is in establishing the material properties for a layered model of the ballast and subgrade that match the overall track-modulus measurements. The plate-bearing tests on the ballast and subgrade and independent vibroseismic measurements of subgrade properties did not give sufficiently accurate predictions of track modulus for the prediction of track loads under heavy-car wheel loads even though pressures greater than the maximum pressures under traffic were used for the plate-bearing tests. This difficulty cannot be explained at this time. In the meantime, it is recommended that the ballast and subgrade properties be adjusted to match the experimental measurements of track modulus under heavy-car wheel loads by using representative soil data for the relative ballast-soil stiffness. Predictions of tie loads, track deflections, and roadbed pressures will not be greatly influenced by changes in the relative ballast and soil stiffnesses as long as the track modulus is matched. Inaccurate estimates of these parameters will have their greatest effect on predictions of relative deflections in the ballast and subgrade layers.

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Permanent-Deformation Behavior of Railway Ballast

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Ballast materials were tested in the triaxial apparatus by using a repeated deviator stress and a constant confining pressure. Permanent deformation (plastic) characteristics at several stress levels were determined for a variety of types and gradations of material. Correlation analyses were made between the plastic response and the results of standard material-characterization tests. The results indicate that the most important factor influencing the repeated-load plastic-strain behavior of ballast is the degree of compaction. The stress level was also found to be an important factor; there was some indication that permanent deformation was less for the more nearly well graded specimens. Finally, unlike the resilient response, the permanent-deformation behavior of ballast is dependent on loading history.

One of the major problems of rail track support systems is the continual need for realignment of the rail-tie system by addition of ballast. Present maintenance practice dictates that only the portion of the ballast near the rail be tamped; the center is left undisturbed. This practice results in the addition of ballast primarily in the proximity of the rails; ballast pockets result (1).

Before the experience-oriented design of rail-tie support systems can be improved, the plastic-deformation behavior of ballast subjected to repeated loading must be investigated so that an understanding of its nature can be obtained. To accurately predict the deformation characteristics of ballast, the test method should simulate the in-service dynamic stress conditions.

BACKGROUND

There have been several investigations (2, 3, 4, 5) of the repeated-load behavior of granular materials. Both rigid-confinement and triaxial equipment have been used to study dense-graded aggregates and sand, but little work has been done that involved open-graded aggregates such as ballast. In addition, most of these investigations have been directed toward studies of the elastic (resilient) properties of the material; little attention has been paid to the plastic (permanent-deformation) behavior of aggregates subjected to repeated-load conditions.

Repeated-load triaxial testing of a variety of types of aggregate would appear to be the most appropriate method for the investigation of the plastic behavior of ballast materials. Previous investigations in which actual loading conditions were closely simulated have given excellent results.

Among the factors that affect the repeated-load permanent-deformation characteristics of granular materials are the confining pressure, the number of cycles, the load, and the stress history.

Lade and Duncan (6) have offered an explanation for the effects of stress history on permanent-deformation behavior. When a triaxial specimen (constant confining pressure) of a cohesionless material is subjected to an initial load, there is a large plastic deformation caused by the rearrangement of particles. This plastic deformation is accompanied by a smaller elastic deformation. When the specimen is unloaded and then reloaded to the previous stress level, theoretically only an elastic deformation will be observed. However, in the actual case, some additional plastic strain accumulates with each loading cycle. If, after several repeated loading cycles, the specimen is subjected to a deviator stress greater than that previously experienced, the stress-strain curve will continue in the direction of the original curve. Thus, the maximum load to which a material has previously been subjected becomes extremely important.

Field evidence of the effect of the maximum loading conditions (or primary loading) on the permanent deformation of ballast has been given in a report by the Office for Research and Experiments of the International Union of Railways (7). They concluded that smaller loads cause "negligible settlement" and that "small numbers of large dynamic loads ... determine the deterioration of the track level, rather than the general level of the axle loads."

MATERIALS

Six materials commonly used for ballast were chosen so that their repeated-load behavior and natural properties could be compared. The materials selected were dolomitic limestone from Kankakee, Illinois; blast-furnace slag from Chicago; granitic gneiss from Columbus, Georgia; basalt from New Jersey; gravel (crushed and uncrushed) from McHenry, Illinois; and the type of slag used in the Kansas test track.

The materials were sieved, and the various size fractions of each 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 were performed.

1. Particle index: ASTM D3398 (8),
2. Specific gravity: ASTM C127 (8) and AASHTO T85 (9),
3. Los Angeles abrasion: ASTM C131 (8) and AASHTO T96 (9),
4. Gradation parameter: that developed by Hudson and Waller (10),
5. Flakiness index: British standard 812-815 (11),
6. Soundness: ASTM C88 (8) and AASHTO T104 (9), and
7. Crushing value: British standard 812-34 (11).

The results of the characterization tests are summarized in Table 1.

Gradation

To examine the effects of different gradations on the resilient response, three different ones were included in the testing program. Two standard American Railway Engineering Association (AREA) gradations, nos. 4 and 5, were selected by using the center values of the recommended gradation bands. A third gradation was based on the use of the Talbot equation with an exponent of two-thirds. Because one of the main considerations of ballast is that it be free draining, the Talbot-equation gradation was maintained only through the 4.75-mm (no. 4) sieve. To ensure a high permeability, no material finer than that passing the 1.18-mm (no. 16) sieve was used. The gradation determined by using this analysis was labeled "well graded." A conservative estimate of the permeability of the well-graded material is 1500 m/d (5000 ft/d).

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 maximum size of the aggregate to be tested, the cell was constructed to have an inside diameter of 279 mm (11 in) so that 203-mm (8-in) diameter cylindrical specimens 406-mm (16-in) high could be tested.

Air was used to supply the confining 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.

To satisfy the constraints of the equipment and to approximate actual in-service conditions, a frequency of 50 cycles/min and a haversine load pulse of 0.15-s duration were selected.

The spacing of trucks on conventional railroad rolling stock varies, and the pulse caused by the second truck of 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 ballast. The frequency (50 cycles/min) and duration of load (0.15 s) selected are equivalent to a train speed of approximately 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 high-speed strip chart recorder was used to record the output of the load-cell amplifier.

Two methods were used to monitor the axial deformations. The primary method was provided by a linear variable differential transformer (LVDT) mounted at the top of the hydraulic actuator. The LVDT signal was observed on a strip chart recorder. In addition, two electronic-optical scanners were used to measure the vertical motion of targets placed at the upper and lower quarter points of the specimen. The targets consisted of one black and one white rectangular strip, 32×64 mm (1.5×2.5 in) each, that were 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 the specimen and the targets. The optical scanners were rezeroed periodically, and the change in the distance between the two heads was observed on a dial indicator and thus provided a backup for the LVDT.

TEST PROCEDURE

Because one of the objectives of this study was the determination of 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 had a maximum particle size of 38 mm (1.5 in), and samples 203 mm in diameter were used for the no. 4 ballast-gradation specimens, which had 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 4. All samples had a height-to-diameter ratio of 2:1 or more to minimize the end effects on 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 then was 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 (12) was used. To determine the compaction characteristics of the aggregates and whether they were 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 percent to 4.0 percent after compaction of 45 s/layer, and the increase was less (less than 1 percent) for shorter compaction times.

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

The test specimen properties are given in Table 2.

All of the test specimens were conditioned for 5000 cycles at a deviator stress of 310 kPa (45 lbf/in^2) and a confining pressure of 103 kPa (15 lbf/in^2). The permanent deformations recorded by the LVDT method were divided by the specimen height to obtain the strains at 10, 100, 1000, and 5000 cycles. The plastic-strain data obtained during this conditioning phase have not been influenced by any stress-history effects and are probably the most representative results for making direct comparisons.

After the conditioning phase, the stress ratio was increased and 5000 additional load cycles were applied. Typical stress levels applied are given below (1 kPa = 0.145 lbf/in^2).

Deviator Stress (kPa)	Confining Pressure (kPa)
138	34
414	103
207	34
620	103
827	103

The stress state was increased until the sample failed or showed noticeable lateral bulging. The sample height at the beginning of each 5000 load cycles was taken as the gauge length for the strain determination.

RESULTS

The purpose of this part of the research was to determine the effects of material type and gradation on the plastic-strain behavior under repeated-load conditions of a variety of types of aggregates. The effects of stress history, degree of compaction, and stress level were also considered. [A more detailed description of these results has been given by Knutson and others (13).]

Linear regression analyses were used to develop relationships between the plastic strain and the corresponding number of loading cycles. Three types of regression analyses were used: arithmetic (strain versus number of cycles), semilog (strain versus logarithm of number of cycles), and log-log (logarithm of strain versus logarithm of number of cycles). In general, the best results

Table 1. Results of 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
Crushed gravel	No. 4	11.85	2.678	28.0	1.074	10.12	7.45	20.0
Kansas test-track blast-furnace slag	No. 5	14.10	2.521	26.7	1.846	5.39	0.87	25.2

Table 2. Properties of test specimens.

Material	Gradation	Compaction		Void Ratio
		Level	Density (kg/m^3)	
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	1976	0.48
	Well graded	Medium	2110	0.26
Crushed gravel	No. 4	Medium	1615	0.66
Kansas test-track blast-furnace slag	No. 5	Medium	1585	0.59

Note: 1 kg/m^3 = 0.062 lb/ft^3.

were those obtained for plastic strain versus the logarithm of number of cycles. The slopes obtained from the linear regression equations were used in attempts to further analyze plastic-strain behavior. Because strain is zero at the beginning of testing and because only the trend of plastic strain is of practical importance, the equation intercepts were not included in the analyses.

The slopes and correlation coefficients of the data obtained at a repeated deviator stress of 310 kPa and a confining pressure of 103 kPa are summarized in Table 3. The slopes and correlation coefficients of the semilog analyses of the data obtained at the other stress levels are summarized in Table 4.

In all cases, an increase in the stress ratio (repeated deviator stress divided by confining pressure) resulted in an additional plastic-strain accumulation during the 5000 cycles. However, the stress ratio by itself cannot be used to predict adequately the plastic-strain behavior of ballast materials. Both the repeated deviator stress and the confining pressure must be considered together; for example, the application of a stress ratio of 4 and a confining pressure of 34 kPa (5 lbf/in^2) is usually much less severe than is the same stress ratio and a confining pressure of 103 kPa.

The possibility of links between plastic-strain behavior and material properties was investigated by correlation analyses between the various plastic-strain parameters and the results of the material characterization tests.

There were significant ($\alpha = 0.05$) correlations between the four plastic strain values (10, 100, 1000, 5000 cycles) and both the initial density (inverse) and the void ratio. The strain value recorded after 5000 cycles also showed a significant correlation with the results of the crushing value tests. None of the other variables showed any significant level of correlation. The dependency of plastic strain on initial void ratio or on density (or porosity) reported by ORE (7) thus is reinforced.

To eliminate the effects of gradation, a correlation analysis was performed using only the results for the no. 4 ballast-gradation specimens. The significant correlations were much the same as in the previous analysis.

In the analysis of the no. 4 ballast-gradation specimens, not all of the material types were weighted equally; another analysis therefore was conducted that used only the six medium-density no. 4 gradation specimens. In this analysis, the particle index correlated significantly with two of the strain readings, but the results were not consistent. The results of the analysis, in general, were too erratic to draw any conclusions.

To include the effects of gradation, three gradation levels of each of three types of material (limestone, basalt, and gravel) were used in another correlation analysis. The results showed significant ($\alpha = 0.05$) correlations between the gradation and the recorded strain values. The relationship was inverse [which means that the strains were highest for the more uniformly graded (no. 4) specimens]. The slopes of the semilog relationships for all of the specimens (for a stress level of 310/103) showed significant ($\alpha = 0.05$) correlations between the strain and the Los Angeles abrasion number, density, void ratio, crushing value, and gradation parameter.

In general, none of the analyses considered resulted in consistently significant ($\alpha = 0.05$) correlations between the various strain parameters and the specimen properties. However, there was an inverse relationship between plastic strain and initial void ratio in several of the analyses. Because of the lack of consistent results and because of the difficulty in establishing causal relationships through correlation studies, an analysis of variance was used to assess possible differences among the plastic-strain responses of the samples due to gradation, compaction, and material effects.

Because changes in gradation affect both the compaction characteristics and the maximum theoretical density of aggregates, gradation effects on plastic-strain behavior are difficult to demonstrate quantitatively.

To show quantitatively the effects of gradation, a randomized complete block analysis was made of the plastic-strain data recorded at 10, 100, 1000, and 5000 cycles for several stress levels. Three types of material (limestone, basalt, and gravel) and three gradation levels of each were included. In only two cases were the strains significantly different.

Because of economic considerations, a ranking of ballast according to type of material (slag, granite, etc.) is desirable. The plastic-strain results of two no. 4 gradation gravel specimens compacted with the same effort—one containing rounded material and the other containing crushed particles—showed that the crushed gravel sample accumulated more plastic strain. However, for the same compactive effort, the uncrushed gravel attained a density 1.1 kN/m^3 (7 lbf/ft^3) greater than did the crushed material, which makes a direct comparison difficult.

A randomized complete block analysis was made to evaluate the effects of the material properties on the plastic strain after 10, 100, 1000, and 5000 cycles for various stress levels. Three materials (limestone, basalt, and gravel) and three gradations of each were considered in the analysis. No significant ($\alpha = 0.05$) differences were found among the strain readings with regard to material type.

A completely randomized design analysis was made to evaluate the effects of the various material properties on plastic-strain behavior. The stress-level values and the material properties (particle index, specific gravity, Los Angeles abrasion number, flakiness index, soundness loss, and crushing value) were included as the variables. The results show no significant differences for the effects of any of the material properties between the two stress level groups.

The effects on plastic-strain behavior of various levels of compaction were evaluated through the use of a randomized complete block analysis of the semilog regression equation slopes of five material types (limestone, basalt, granite, slag, and gravel) and three levels each of compactive effort. There were significant ($\alpha = 0.05$)

Table 3. Regression analyses of plastic strain during conditioning phase.

			Type of Regression Analysis						
			Arithmetic		Semilog			Log-Log	
Material	Gradation	Compaction Level	Slope	Correlation Coefficient	Slope	Correlation Coefficient	Standard Error of Estimate	Slope	Correlation Coefficient
Limestone	No. 5	Medium	0.0001	0.999[a]	0.219	0.943[a]	0.042	0.209	0.977[a]
	No. 4	Low	0.0008	0.612	1.470	0.981[a]	0.382	0.372	0.874[a]
	No. 4	Medium	0.0003	0.845[a]	0.678	0.995[a]	0.075	0.304	0.984[a]
	No. 4	High	0.0000	0.902[a]	0.088	0.967[a]	0.028	0.162	0.996[a]
	Well graded	Medium	0.0002	0.767	0.619	0.996[a]	0.057	0.284	0.932[a]
Granitic gneiss	No. 4	Low	0.0004	0.715	1.120	0.982[a]	0.210	0.296	0.942[a]
	No. 4	Medium	0.0002	0.800[a]	0.632	0.999[a]	0.029	0.276	0.969[a]
	No. 4	High	0.0001	0.942[a]	0.218	0.952[a]	0.077	0.177	0.991[a]
Blast-furnace slag	No. 4	Low	0.0005	0.727	1.260	0.964[a]	0.348	0.127	0.930[a]
	No. 4	Medium	0.0004	0.876[a]	0.797	0.985[a]	0.153	0.304	0.994[a]
	No. 4	High	0.0005	0.963[a]	0.936	0.879[a]	0.557	0.501	0.957[a]
Basalt	No. 4	Medium	0.0001	0.657	0.171	0.988[a]	0.107	0.168	0.938[a]
	No. 4	Medium	0.0003	0.791	0.668	0.999[a]	0.028	0.221	0.981[a]
	Well graded	Medium	0.0001	0.773[a]	0.327	0.997[a]	0.029	0.224	0.979[a]
Crushed gravel	No. 4	Medium	0.0002	0.846[a]	0.513	0.995[a]	0.058	0.202	0.995[a]
Gravel	No. 5	Medium	0.0001	0.795	0.297	0.995[a]	0.033	0.248	0.984[a]
	No. 4	Low	0.0003	0.796[a]	0.727	0.998[a]	0.045	0.160	0.988[a]
	No. 4	Medium	0.0002	0.923[a]	0.391	0.984[a]	0.089	0.265	0.997[a]
	No. 4	High	0.0000	0.854[a]	0.023	0.994[a]	0.003	0.111	0.999[a]
	Well graded	Medium	0.0000	0.840[a]	0.152	0.994[a]	0.018	0.128	0.999[a]
Kansas test-track blast-furnace slag	No. 5	Medium	0.0001	0.732[a]	0.151	0.999[a]	0.066	0.205	0.969[a]

[a] Significant at $\alpha = 0.05$.

Table 4. Regression analyses of plastic strain at stress levels other than conditioning.

				Semilog Regression Results		
Material	Gradation	Compaction Level	Stress Level (kPa/kPa)	Slope	Correlation Coefficient	Standard Error of Estimate
Limestone	No. 5	Medium	414/103	0.044	0.832	0.042
			207/34	0.021	0.901	0.014
			276/34	0.123	0.875[a]	0.090
			620/103	2.876	0.860[a]	1.716
	No. 4	Low	207/103	0.010	0.945[a]	0.004
			138/34	0.045	0.931[a]	0.019
			414/103	2.207	0.935[a]	0.969
			207/34	0.164	0.908[a]	0.083
		Medium	207/103	0.005	0.984[a]	0.001
			138/34	0.020	0.997[a]	0.002
			414/103	0.776	0.970[a]	0.232
			207/34	0.150	0.837[a]	0.117
		High	138/34	0.005	0.977[a]	0.001
			414/103	0.256	0.895[a]	0.126
			207/34	0.068	0.976[a]	0.017
			276/34	3.436	0.826[a]	1.985
	Well graded	Medium	138/34	0.014	0.932	0.006
			414/103	0.399	0.907[a]	0.202
			207/34	0.043	0.893[a]	0.024
			276/34	0.288	0.856[a]	0.190
			620/103	1.911	0.947[a]	0.698
			827/103	3.169	0.804	1.537
Granitic gneiss	No. 4	Low	138/34	0.052	0.998[a]	0.004
			414/103	0.107	0.967[a]	0.031
			207/34	0.016	0.993[a]	0.002
			276/34	0.452	0.883[a]	0.264
			620/103	7.500	0.777	3.924
		Medium	138/34	0.016	0.962[a]	0.005
			414/103	0.233	0.933[a]	0.079
		High	207/103	0.028	0.984[a]	0.004
			138/34	0.036	0.937	0.020
			414/103	0.243	0.902[a]	0.118
			207/34	0.051	0.897[a]	0.027
			276/34	0.125	0.892[a]	0.070
			620/103	2.478	0.930[a]	0.942
Chicago blast-furnace slag	No. 4	Low	138/34	0.061	0.843[a]	0.043
			414/103	1.444	0.872[a]	0.881
			207/34	0.163	0.811[a]	0.128
			276/34	0.461	0.778[a]	0.365
			620/103	2.706	0.849	1.458
		Medium	138/34	0.036	0.821[a]	0.027
			414/103	2.091	0.848	1.421
			207/34	0.231	0.819[a]	0.185
			276/34	0.514	0.792	0.430
			620/103	5.878	0.828[a]	2.742
		High	138/34	0.020	0.915[a]	0.010
			414/103	0.956	0.897[a]	0.512
			207/34	0.088	0.830[a]	0.064
			276/34	0.441	0.778	0.390
			620/103	3.298	0.876[a]	1.397

Note: 1 kPa = 0.145 lbf/in^2.

[a] Significant at $\alpha = 0.05$.

Table 4. Continued.

				Semilog Regression Results		
Material	Gradation	Compaction Level	Stress Level (kPa/kPa)	Slope	Correlation Coefficient	Standard Error of Estimate
Basalt	No. 5	Medium	414/103	0.076	0.921[a]	0.035
			207/34	0.015	0.996[a]	0.001
			276/34	0.104	0.958[a]	0.034
			620/103	0.547	0.962[a]	0.169
			827/103	0.936	0.959[a]	0.303
	No. 4	Medium	138/34	0.019	0.947[a]	0.008
			414/103	0.361	0.858[a]	0.235
			207/34	0.104	0.930[a]	0.049
			276/34	1.118	0.932[a]	0.478
			620/103	2.157	0.990[a]	0.313
	Well graded	Medium	138/34	0.010	0.939[a]	0.004
			414/103	0.135	0.948[a]	0.049
			207/34	0.018	0.945[a]	0.007
			276/34	0.048	0.910[a]	0.024
			620/103	0.691	0.965[a]	0.205
			827/103	0.745	0.940[a]	0.299
Crushed gravel	No. 4	Medium	138/34	0.023	0.934[a]	0.010
			414/103	0.451	0.890[a]	0.252
			207/34	0.116	0.903[a]	0.061
			276/34	2.064	0.850[a]	1.223
Gravel	No. 5	Medium	414/103	0.019	0.920[a]	0.009
			207/34	0.210	0.788	0.180
			276/34	3.075	0.793	1.501
	No. 4	Low	207/103	0.005	0.989[a]	0.001
			138/34	0.068	0.882[a]	0.039
			414/103	0.557	0.930[a]	0.203
		Medium	207/103	0.004	0.960[a]	0.001
			138/34	0.039	0.930[a]	0.017
			414/103	0.467	0.871[a]	0.286
			207/34	0.415	0.811[a]	0.326
			276/34	2.156	0.788	1.217
		High	138/34	0.011	0.974[a]	0.003
			414/103	0.058	0.941[a]	0.023
			207/34	0.992	0.866[a]	0.552
			276/34	5.063	0.946	1.098
	Well graded	Medium	138/34	0.008	0.915[a]	0.005
			414/103	0.102	0.907[a]	0.052
			207/34	0.034	0.912[a]	0.017
			276/34	1.244	0.700	1.368
			620/103	0.739	0.965[a]	0.216
			827/103	1.963	0.845[a]	1.141
Kansas test-track blast-furnace slag	No. 5	Medium	414/103	0.015	0.910[a]	0.007
			207/34	0.035	0.957[a]	0.010
			241/34	0.057	0.864[a]	0.036
			276/34	0.046	0.822[a]	0.035
			345/34	0.306	0.895[a]	0.169
			517/103	0.036	0.838[a]	0.031
			620/103	0.081	0.794[a]	0.068
			723/103	0.361	0.804[a]	0.260

Note: 1 kPa = 0.145 $\mathrm{lbf/in^2}$.

[a] Significant at $\alpha = 0.05$.

differences among the slopes for the three levels of compaction. Further analysis by using Duncan's multiple range test showed that there was no significant ($\alpha = 0.05$) difference in slope between the high- and medium-compactive-effort samples, but both were significantly different from the low-compactive-effort samples. The lowest slope values were those obtained for the high-density samples.

SUMMARY

These analyses have shown that the most important factors influencing the permanent-deformation behavior of ballast are the number of repetitions, the degree of compaction, and the stress level. As previous studies have also shown, the increase in plastic strain is generally inversely proportional to the number of loading cycles. In every case, the permanent deformation was least for the specimens compacted by using the greatest effort. The stress-level effects are more difficult to discern because both the deviator stress and the confining pressure, not merely the ratio of the two, must be considered. However, the permanent-strain results agree well with the concepts of Lade and Duncan (6); large strains accumulated during primary loading, but almost no plastic strain occurred during reloading or during loading at reduced stress levels.

The effects on permanent deformation of gradation are less important than are those of the parameters discussed above. In general, the no. 4 ballast-gradation specimens tended to resist permanent deformation less than did the no. 5 specimens or the "well-graded" materials.

The effects of material properties (such as particle index and flakiness index) were not consistent, and therefore no conclusions are made with respect to such properties.

No other specimen parameter is as important in influencing the permanent strain behavior as is degree of compaction.

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Ballast and Subgrade Response to Train Loads

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Ballast and subgrade play major roles in the maintenance life of track structures because they are the source of the cumulative permanent deformation associated with the deterioration of surface and line. Ballast is also the principal means of correcting for this deterioration, which is caused by traffic and environmental factors. Better methods are still needed for the prediction of the effects of the controlling parameters on track performance for more rational track design and maintenance planning. The purpose of this paper is to provide a better understanding of these problems and describe progress being made toward their solution. The functions of ballast and subgrade are briefly discussed, and the mechanisms of permanent deformation are described. Newly developed or improved methods to measure the in situ physical state of ballast are presented, and examples of results from field tests are given. The capabilities of existing analytical track structure models for the prediction of track deterioration are assessed. New instrumentation techniques used for measuring the dynamic and permanent strains and deformations in ballast and subgrade are described. Finally, the characteristics of the stress, strain, and deformation in ballast and subgrade are illustrated with results of both analytical and experimental studies.

The type and condition of the ballast and the subgrade are key factors in the performance of a track structure. During the service life of a track, permanent strains accumulate in its substructure and cause permanent deformation that is visible as deterioration of surface and line. This deterioration of the track geometry leads to decreased safety (including increased potential for derailments) and increased damage to equipment and lading unless additional track maintenance is provided or train speed (and hence service level) is reduced. During the past few decades, traffic loads have increased and, at the same time, economic factors have restricted the amount of maintenance that can be done each year. In practice, the maintenance cycle frequency is often dictated by factors such as the availability of money and equipment to do the required work rather than by the amount of track deterioration. Thus, U.S. railroads have had increasing difficulty in maintaining the high service level desired. A recent estimate of the dollar value of the maintenance deficit for all of U.S. railroads was reported by Ward (1) to be $10 billion.

Raymond (2) has reported that approximately 40 percent of the $100 million that Canadian railroads spend on track-structure maintenance relates to ballast maintenance alone. Therefore, it is a safe assumption that, at least in dollar value, both the ballast and the subgrade parts of the track substructure are important in the upkeep of the service level of the track.

Ballast maintenance is the means by which the deterioration of track geometry is controlled, irrespective of the driving forces behind the geometry changes. Whether the structural deficiency is in the ballast, the subgrade, or the track superstructure (the crossties