Performance of Large-Scale Model Single Tie-Ballast Systems

GERALD P. RAYMOND AND RICHARD J. BATHURST

Large-scale models of a single tie-ballast system were constructed over artificial ballast support that had variable compressibility ranging from rigid to very flexible (California bearing ratio = 10). Test configurations included a 0.45-m depth of crushed limestone ballast conforming to an American Railway Engineering Association grading No. 4. A steel footing 920 mm long by 250 mm wide by 150 mm deep was used to model the bearing area of a typical tie below the rail seat (i.e., one rail). Each rail seat was subjected to a repeated load of between 20 and 150 kN for a (typical) duration equivalent to 12 million gross tonnes in track. The principal objectives of the experimental work were to investigate the influence of load level and ballast support compressibility on the rate of accumulation of permanent deformations and ballast degradation. The test results show that at a given load level the rate of tie settlement is quite sensitive to ballast support compressibility. A competent ballast support resulted in a deformation-log tonnage response that was essentially linear. However, progressively weaker supports gave increasing semilogarithmic rates of settlement with tonnage. For a given support compressibility, a critical load level was identified that, if exceeded, led to a dramatic increase in settlement rate. The critical load level was also identified as a threshold level above which the generation of fines in the ballast directly below the tie was observed to increase markedly.

Under repeated tie loading, railway ballast undergoes nonrecoverable vertical deformations mostly due to ballast densification, aggregate degradation, and lateral spread of ballast beneath the ties. The current research is part of an ongoing Queen's University and Royal Military College research program directed at correlating aggregate quality, load level, and ballast support compressibility with track performance. The long-term goal of this research is to arrive at a design methodology that includes ballast quality in the forecasting of track performance. A parallel investigation by the authors related to geogrid-reinforced ballast models is reported elsewhere (*1*).

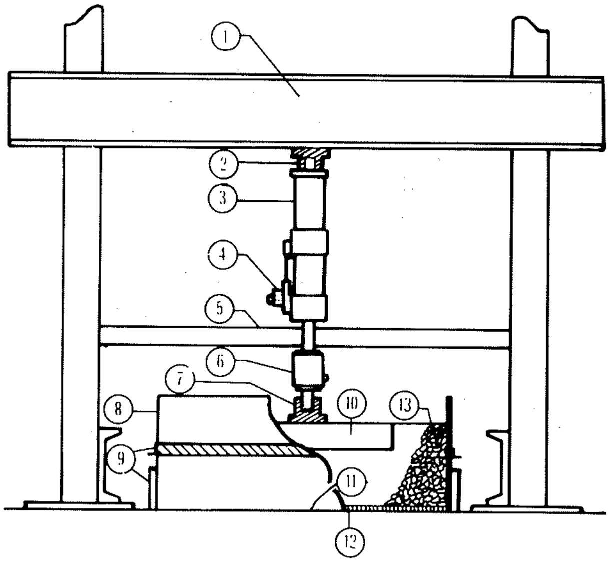
OBJECTIVES

Large-scale models of a single tie-ballast system over artificial subballast-subgrade support (hereafter referred to as artificial support) were built and subjected to a program of repeated loading. The principal objectives of this study were to

1. Investigate the influence of ballast support compressibility on the load-deformation response of a crushed limestone aggregate,
2. Examine the influence of peak load level on the deformation response of the ballast material, and
3. Determine the influence of both ballast support compressibility and peak load level on the degradation of the limestone ballast under repeated loading.

GENERAL TEST ARRANGEMENT

The general test arrangement is shown on Figure 1. A 450-mm depth of crushed limestone ballast was confined within a



1 LOADING CROSS BEAMS (2 MC 460 x 63.5)
2 UPPER SWIVEL JOINT
3 MTS HYDRAULIC ACTUATOR / INTERNAL LVDT
4 SERVO CONTROL VALVE
5 ACTUATOR GUIDE & INSTRUMENTATION SUPPORT BEAM
6 LOAD CELL
7 LOWER SWIVEL JOINT
8 PLYWOOD BULKHEAD
9 BULKHEAD SUPPORTS
10 STEEL LOADING TIE (920 mm x 250mm x 150 mm)
11 CONCRETE FLOOR
12 ARTIFICIAL SUPPORT
13 AREA #4 BALLAST

FIGURE 1 General test arrangement.

G. P. Raymond, Civil Engineering Department, Queen's University at Kingston, Ontario K7L 3N6, Canada. R. J. Bathurst, Civil Engineering Department, Royal Military College of Canada, Kingston, Ontario K7K 5L0, Canada.

rigid test box 3 m long by 1.5 m wide. A range of ballast support stiffnesses was incorporated into the test sections by placing ballast over different artificial support materials. A perfectly rigid condition was simulated by placing ballast material directly over a concrete floor. For compressible ballast support models, rubber mats of variable stiffness were placed over the concrete floor.

A steel footing 920 mm long by 250 mm wide by 150 mm deep was used to model the bearing area of a typical tie below the rail seat (i.e., one rail). The tie was placed within a compacted ballast layer to a depth of 150 mm to simulate typical track structure.

The footing was loaded by a computer-controlled closed-loop electrohydraulic actuator that applied a 20- to 150-kN repeated load to the rail seat for a (typical) duration equivalent to 12 million gross tonnes (MGTs) of axle loading in track. The equivalent axle tonnage was calculated by summing the number of load repetitions and multiplying by twice the applied load.

TEST DETAILS

Ballast

Crushed limestone aggregate (Sunbury limestone) was used for all test configurations. The aggregate was screened close to an American Railway Engineering Association (AREA) No. 4 grading and washed. The AREA No. 4 grading has a size distribution between about 50 mm (2 in.) and 10 mm (3/8 in.) (*2*). These gradation limits and the mean particle size distribution for the test ballast are shown in Figure 2. The ballast depth below the footing was 300 mm, which corresponds to the minimum recommended depth for new construction according to the AREA. The ballast was placed in 150-mm lifts and compacted using a vibrating plate tamper with a mass per unit area of 105 kg/m^2.

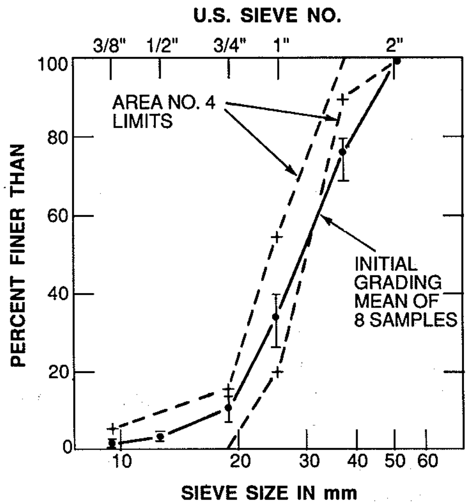


FIGURE 2 Ballast size distribution.

To qualify as railway ballast, aggregate must meet other criteria in addition to proper grading. These include specified limits for the Los Angeles abrasion (LAA), elongation factor, and sodium soundness tests. The results of these tests on the Sunbury aggregate showed that this material is acceptable according to AREA specifications. However, in terms of the more detailed ballast quality guidelines recently adopted by Canadian Pacific Railways (CP Rail), the selected ballast was deemed unlikely to be used in main-line track and marginal for use in branch-line track because of its inadequate abrasion resistance (*3*). The senior author (*4,5*) proposed a track class ranking based on a trade-off between the LAA and mill abrasion (MA) values involving limits on both tests and a combination of both tests (i.e., LAA + 5 MA). This quantity was named the aggregate index (I_a) in the development of a railroad track degradation model by Bing and Gross (*6*) and abrasion number (N_a) by CP Rail in the development of their ballast life model (*3*). Thus

$$I_a = N_a = LAA + 5\ MA \qquad (1)$$

The MA test is a nonstandard test that measures the hardness (resistance to abrasion) of a ballast material resulting from the autogeneous grinding of aggregate particles. The results of LAA and MA tests on the Sunbury limestone gave LAA = 27, MA = 8.5, and an abrasion number of 69.5. This abrasion number compares with a maximum value of 65 allowed by CP Rail. Research by CP Rail has related ballast life-cycle times to ballast quality (expressed as the N_a number) and traffic density. According to CP Rail criteria, the ballast used in this investigation would not be recommended for use on main-line track. However, because the same material was used for all tests reported in the current study, the quality of the ballast was not considered a factor that could influence the relative performance of test configurations.

At the time of writing, test sections comprising aggregate with a lower N_a-value are planned as part of the long-term goal to equate track performance with ballast quality (subject to obtaining financial support).

Footing

Footing dimensions were selected to model one-half of the total bearing area of a typical tie (i.e., the bearing area below one rail seat) as outlined in the AREA *Manual for Railway Engineering* (*2*). The footing length (920 mm) using the AREA approach also corresponds to about the tamper influence distance along the tie on either side of each rail. The footing was constructed from a rectangular hollow steel section 3.15 mm thick and closed at the end to prevent aggregate infilling.

Ballast Support

Test configurations reported in this paper were constructed with artificial subgrades that had three different compressibilities. The purpose of the artificial subgrades was to model ballast support (i.e., subballast-subgrade formation at the subballast-ballast interface) over a range of stiffnesses.

A rigid ballast support condition was simulated by placing ballast directly over the concrete laboratory floor. This condition models a field situation in which track traverses exposed bedrock faces or a chemically stabilized stiff subgrade.

A flexible ballast support condition was modeled using a closed-cell gum rubber mat. A ballast support modulus of 129 MN/m^3 was calculated for this material using a 762-mm-diameter plate and a maximum load of 85 kN. A California bearing ratio (CBR) value of 39 was determined for the same material using the test procedure outlined in ASTM D 1883-73. This condition may be considered to simulate ballast support due to a granular subballast over a competent cohesive subgrade.

A very flexible ballast support condition was modeled using a double layer of gum rubber. The ballast support modulus of this configuration was 62 MN/m^3 and gave a CBR value of 10. It should be noted that this low value indicates extreme subballast-subgrade formation compressibility, which would generally be avoided in the field although it might be encountered in cases in which poor drainage of subballast-subgrade formation exists. The principal reason for using this weak artificial support was to clearly establish trends in ballast load-deformation behavior and ballast degradation related to ballast support.

Loading System and Data Acquisition

Footing loads were applied through an MTS closed-loop electrohydraulic actuator controlled by a DEC PDP11/34 computer. A load cell and linear variable displacement transducer (LVDT) located above the actuator base were used to monitor footing load and vertical footing displacements at all test stages. At programmed intervals, the load-deformation response of the footing during a loading cycle was recorded and stored by the computer.

TEST PROGRAM

Results from 16 tests have been used in the current study to provide data with which to compare the relative performance of tie-ballast-support configurations subject to a range of load levels. A summary of the test program is given in Table 1.

Tests were carried out using the actuator in a load-controlled mode and each footing was subjected to a number of load repetitions equivalent to a typical loading of 12 million and a maximum of about 20 million cumulative axle tonnes in track. European railway experience has shown that, for conventional main-line track, the settlement rate expressed as deformation per log cycle cumulative tonnage is usually constant after about 2 million tones (*7*). In 1980 annual traffic of 10 million to 60 million gross tonnes (MGTs) was recorded for typical heavy branch-line and main-line track sections in Canada.

The applied maximum rail seat loads ranged from 20 to 150 kN. The lower load levels can be considered typical of loadings delivered to the tie rail seat by unloaded trucks or light passenger cars. The 150-kN load may be representative of a small percentage of dynamic impact defects associated with a wheel load delivered by a 100-tonne truck (*8*). Several tests were carried out using an 85-kN load; Figure 3 shows that an 85-kN load (tie bearing pressure = 370 kPa) represents a typical magnitude of dynamic load borne by ballast directly beneath the tie for a track modulus of between 14 and 84 MN/m/m of rail (*9*). Here the dynamic increment is generated by a 51-mm geometrically perfect square wheel flat and is added to the static load caused by two G75 bogies subject to 294-kN axle loads.

The rate of loading varied from 0.5 to 3 Hz depending on the test configuration. The frequency adopted for a particular test was a compromise between a desire to perform the test as quickly as possible and hardware constraints. Nevertheless, it is well documented that the magnitude of permanent deformations generated in track is insensitive to the magnitude of loading frequency when low rates of loading are employed (*10*). A sinusoidal compressive repeated loading waveform was used in the testing program. This waveform is thought to approximate the loading pulse applied to railway ties under actual field conditions (*11*). Finally, it should be noted that

TABLE 1 SUMMARY OF TEST PROGRAM

Test No.	Load Level (kN)	Subgrade Condition (CBR)
1	40	Rigid
2	85	Rigid
3	85 (repeat)	Rigid
4	85 (flooded)	Rigid
5	150	Rigid
6	20	39
7	40	39
8	60	39
9	70	39
10	85	39
11	20	10
12	40	10
13	50	10
14	60	10
15	70	10
16	85	10

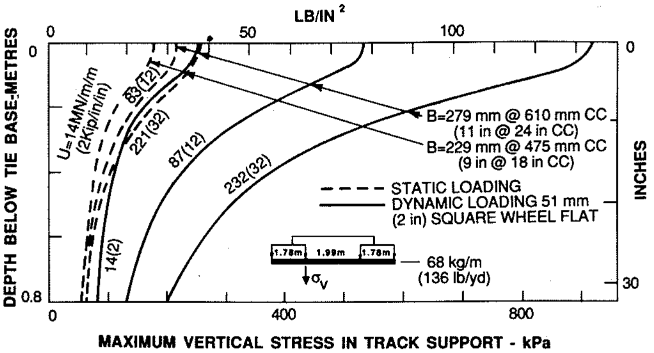


FIGURE 3 Relationships between maximum vertical track stress and depth below tie base for varying track modulus under static and dynamic loading conditions.

five initial load repetitions were applied to each test configuration to ensure that the footing was well seated. The seated position then became the reference datum for subsequent footing deformations.

TEST RESULTS

Ballast Support Compressibility

Figure 4 shows accumulated permanent deformation recorded for 85-kN tests as a function of equivalent cumulative axle tonnes. Permanent deformations shown in the figure are those measured at the base of the tie. The data illustrate that at a load level considered representative of heavy freight axles in track, the magnitude and rate of permanent deformation accumulation are sensitive to ballast support compressibility. For a rigid ballast support there is an essentially linear relationship between magnitude of permanent deformation and the log number of accumulated tonnage. Similar linear semilogarithmic settlement trends have been observed in full-scale tests in which ballast was placed over a firm subballast-subgrade formation (*12*) and by the European railways who have monitored conventional main-line track constructed over very competent subgrades (*7*). The CBR = 10 test shows that there is a dramatic increase in the semilogarithmic rate of accumulated settlement after about 2 MGT. Qualitatively similar trends have been reported by the European railways for main-line track in need of ballast maintenance (*7*). The 85-kN test with a CBR = 39 support likely represents a transition between a very competent ballast support and a weak subballast-subgrade formation.

Load Level

Figures 5-7 show permanent deformations recorded from tests with variable peak loads but identical artificial ballast support.

The rigid support tests (Figure 5) show that, over the range of load level and tonnage applied, deformation-log tonnage response is reasonably represented by a straight line the gradient of which increases with load level.

In contrast, the results of compressible ballast support tests (Figures 6 and 7) show that the deformation-log tonnage curves can be classified (as a first simple approximation) into one of two performance categories: Below some critical rail seat load (defined later), the curves are linear on the semilogarithmic plots; above the critical value, the test results show distinct curvatures that indicate progressive deterioration of tie support.

Below the critical load level the rate of settlement-log tonnage on any constant support is approximately proportional to the cycled peak load level. Thus the total settlement recorded after the same tonnage was approximately proportional to the cycled peak load.

Figure 8 is a plot of the equivalent tonnage required to achieve a settlement criterion for all tests with a compressible artificial support. Where necessary, settlements at large tonnages have been estimated by linearly extrapolating load-deformation results after 2 MGT. The mean settlement criterion adopted by a given railway may vary, but 40 or 50 mm may be considered a typical upper limit. Clearly, uniform settlement is not detrimental to track performance. However, track quality (expressed as the frequency of cross-level, twist, and alignment defects) will deteriorate in direct proportion to mean settlement recorded at rail seat locations. The figure shows that model tests with compressible artificial support

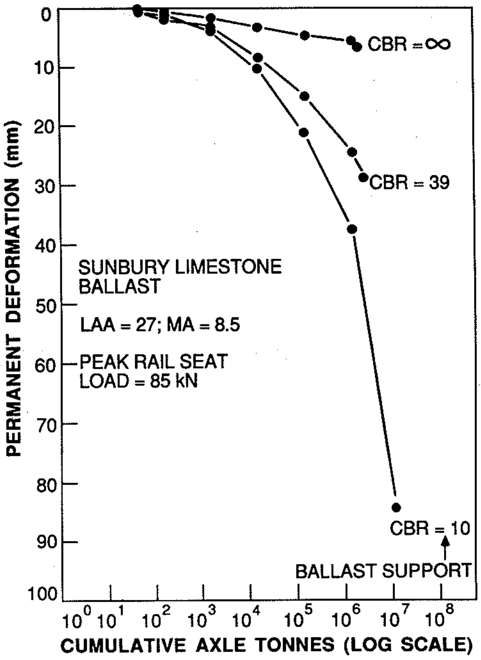


FIGURE 4 Influence of ballast support compressibility on ballast deformation.

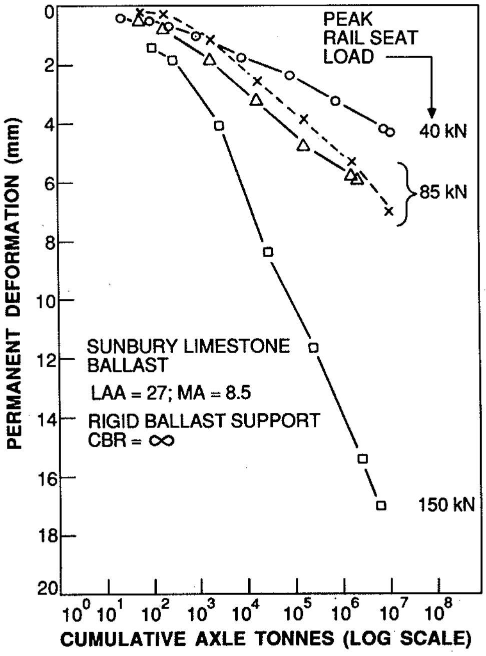


FIGURE 5 Accumulated permanent deformation (rigid ballast support).

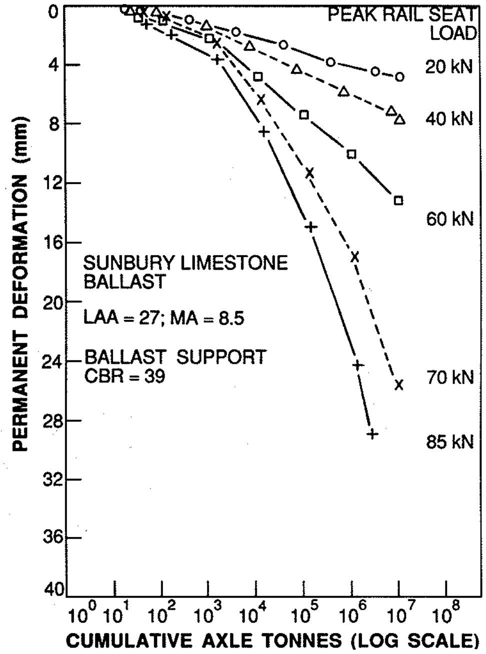


FIGURE 6 Accumulated permanent deformation (flexible ballast support).

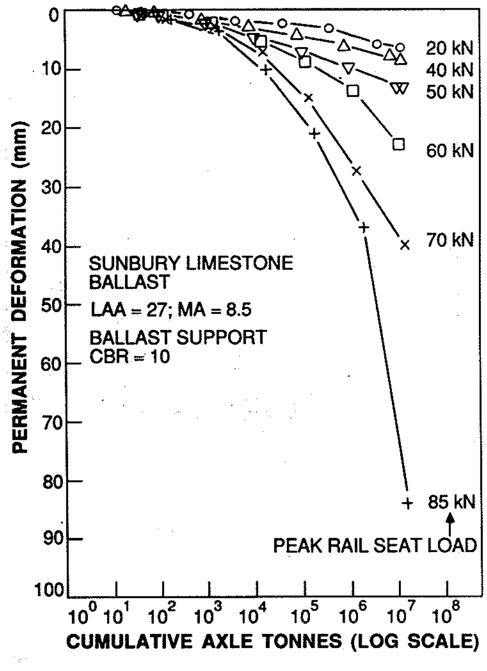


FIGURE 7 Accumulated permanent deformation (very flexible ballast support).

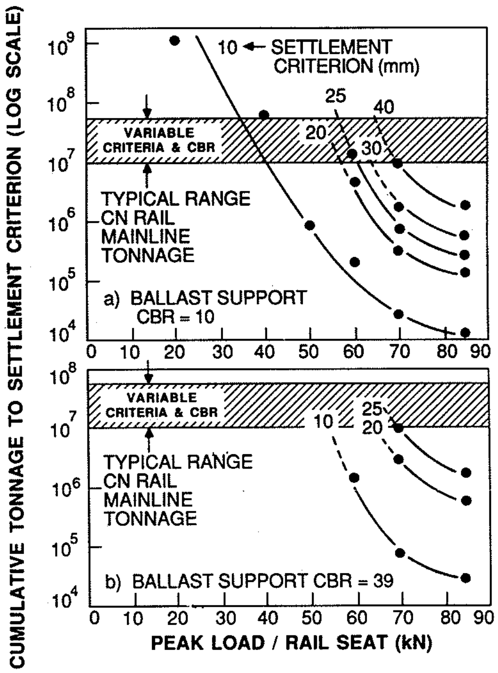


FIGURE 8 Equivalent tonnage to achieve settlement criterion.

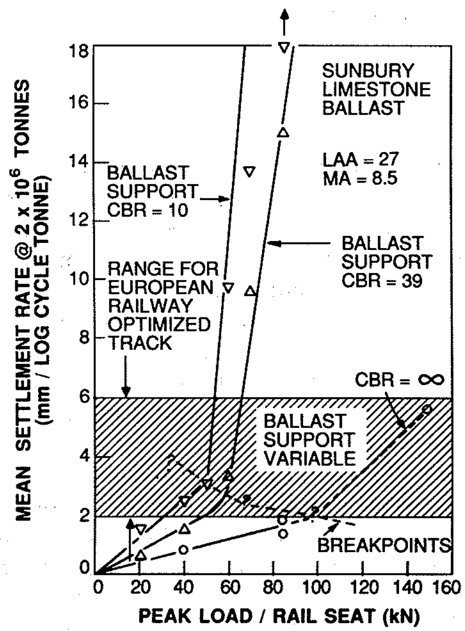


FIGURE 9 Influence of load level on settlement rates.

achieved (or would have achieved) an accumulated tonnage that is typical of annual CN Rail heavy branch-line and main-line track (*13*) while recording levels of mean settlement that are probably acceptable in track. Figure 8 also shows that, for the same cumulative tonnage, a heavier wheel load produces greater settlement (and hence more track damage) than the same cumulative tonnage delivered through a lighter axle. This observation is not surprising to many railways that have moved to heavier axle loads in recent years. In many instances they have observed a rapid deterioration of track that had previously performed in a stable manner for many years.

The relative sensitivity of test performance to load level and ballast support stiffness is shown in Figure 9. For each set of tests with a given artificial support compressibility there is a critical peak rail seat load above which there is a rapid increase in the settlement rate per log cycle of cumulative tonnage after 2 MGT. The figure shows that the critical load level is about 50 kN for the CBR = 10 support tests and somewhat higher at about 60 kN for the CBR = 39 support configurations. For the rigid support tests the breakpoint is at a value greater than 85 kN.

It is interesting to note that the breakpoints from the model tests fall within the measured range of settlement rates recorded by the European railways for optimized conventional main-line track (*7*). Above the critical load level the settlement rates increase dramatically and extend to values that would be deemed excessive for both European and North American railways (e.g., greater than 10 mm/log cycle tonne after 2 MGT).

It should be noted that the results of the model tests will be conservative compared with a comparable configuration in the field. In particular, settlement rates are probably higher because the ballast in the single tie-ballast model is less constrained. Nevertheless, the qualitative trends extracted from the model tests are considered by the authors to be valid. An important implication of the current test results is that settlement rates associated with excessive load levels (i.e., greater than critical values) are quite sensitive to the magnitude of wheel loads. For existing track, a modest increase in any wheel loads that are already at about the critical limit will lead to a dramatic increase in settlement rate. For new heavy-haul track, the subballast-subgrade formation should be constructed so that anticipated dynamic wheel loadings are within the critical limits of the ballast support.

Ballast Degradation

Under repeated loading, ballast aggregate in track can be expected to degrade. To examine this phenomenon, bulk samples of aggregate were taken at the completion of selected tests from ballast located between the tie bottom and the underlying artificial support. Mechanical grain-size analyses were carried out on these samples in an attempt to correlate single tie-ballast model performance with aggregate degradation. Initially, the full grain-size curves corresponding to samples before and after repeated loading were plotted together and compared. The results of this exercise showed a great amount of scatter. For example, full grain-size curves taken from aggregate used in lightly loaded tests often plotted within the scatter band of the initial unloaded samples for particle sizes greater than 10 mm. A more successful approach was adopted wherein only the material passing the No. 4 sieve was examined. In this approach, only fines generated during loading are compared.

It should be noted that a portion of the fines generated in any test must be due to abrasion at the steel footing-ballast interface. A model tie constructed from timber would be expected to generate less fines. Nevertheless, the tie material was kept constant in all tests and hence qualitative comparisons of results are valid.

The particle size distributions for the fines are shown in Figures 10 and 11 for tests having equivalent ballast support. The plotted points represent the average of four samples. A number of observations can be made about these figures: The volume of fines passing the No. 4 sieve is greater for the CBR = 10 tests than for the CBR = 39 tests at a given load level and the same cumulative tonnage. This result is expected because the magnitude of repetitive aggregate movements would be expected to increase with decreasing artificial support elastic stiffness. In addition, the amount of fines passing the No. 4 sieve increases markedly after approximately the critical load level identified for each ballast support condition in the previous section. This observation confirms that ballast degradation is a mechanism that is accelerated in overstressed track support. In actual track, the generation of fines contributes to ballast fouling, which in turn inhibits drainage and over time reduces the load-carrying ability of the track support.

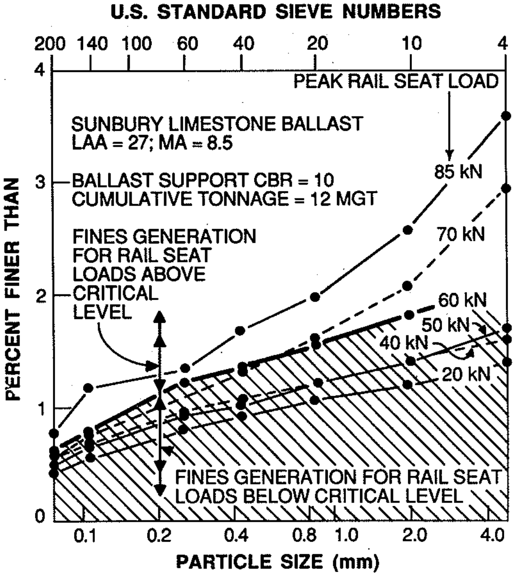


FIGURE 10 Particle size distribution for fines (ballast support CBR = 10).

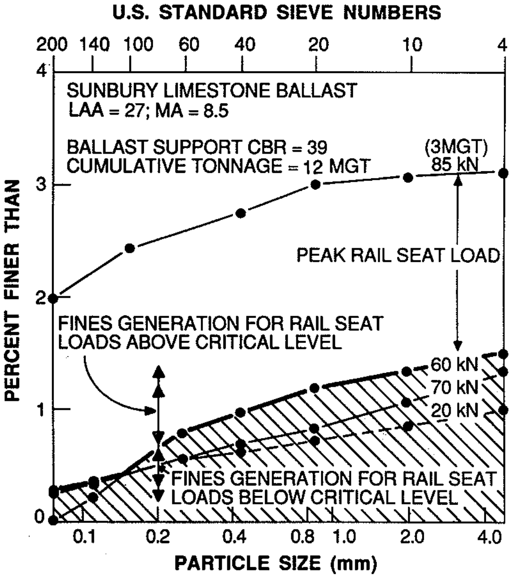


FIGURE 11 Particle size distribution for fines (ballast support CBR = 39).

Influence of Flooding on Test Results

In actual track, precipitation contributes to the deterioration of ballast aggregate. To examine the influence of a wet environment on the performance of single tie-ballast models, a test was carried out in which the ballast was fully saturated to a depth corresponding to the base of the tie for the full duration of loading. The results of this wet test are plotted with those of similar (standard) dry tests in Figure 12. The tests shown were constructed with rigid ballast support. The figure illustrates that, over the range of tonnage applied, both wet and dry tests exhibited a linear semilogarithmic settlement trend but that the rate of settlement for the wet test was almost twice that of the comparable dry tests. The implication of these results for actual track support is that ballast life in the field is reduced when poor drainage exists.

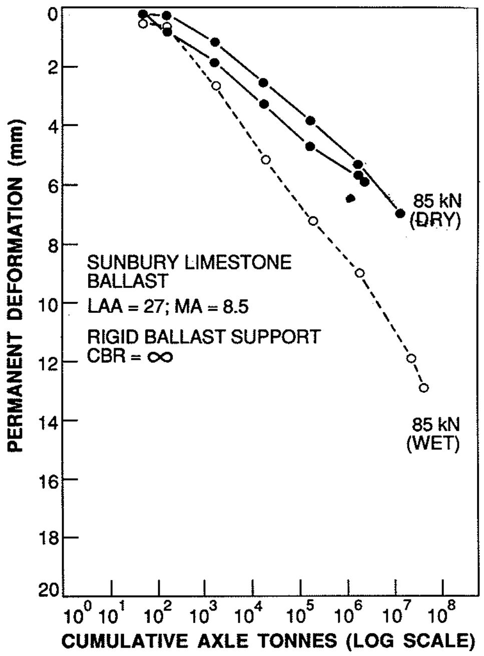


FIGURE 12 Influence of flooding on settlement rates.

SUMMARY OF CONCLUSIONS AND IMPLICATIONS

The major conclusions that can be drawn from the current study and the implications for track can be summarized as follows:

1. The magnitude and rate of permanent deformation accumulation are sensitive to ballast support compressibility. Competent ballast support results in a permanent deformation-log tonnage response that is essentially linear. Progressively weaker ballast supports are characterized by increasing semilogarithmic rates of settlement with tonnage. For any given competent support, the total settlement after a given tonnage was approximately proportional to the cycled peak load.
2. Test results show that, for a given ballast support compressibility and cumulative tonnage, heavier axle loads will do more damage to ballast than lighter axle loads.
3. The current study illustrates that for a given ballast support there is a critical load level that, if exceeded, will cause a dramatic increase in ballast settlement rates after 2 MGT. In contrast, below the critical value, settlement rates are less sensitive to the magnitude of wheel loads.
4. The critical load level for the single tie-ballast models after 2 MGT was observed to increase with increases in ballast support stiffness.
5. The generation of fines in the ballast below the tie after about 10 MGT was observed to increase markedly when the critical wheel load level was exceeded in the model tests.
6. The generation of fines at a given load level and cumulative tonnage was observed to increase with increasing ballast support compressibility.
7. Flooding of the ballast layer in the single tie-ballast model tests increased the rate of settlement to almost twice that recorded for dry configurations.

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