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Geogrid Reinforcement of Ballasted Track

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Large-scale models comprising a single tie/ballast system were constructed over artificial subballast-subgrade supports having variable compressibility ranging from rigid to very flexible (with California bearing ratio of 1). Test configurations included a 0.45-m depth of crushed limestone ballast conforming to an American Railway Engineering Association (AREA) Grading No. 4. A 920-mm-long by 250-mm-wide by 150-mm-deep steel footing was used to model the bearing area of a typical tie. Each rail seat was subjected to a program of repeated loading equivalent to a cumulative axle tonnage of 2 to 20 million tonnes in track. The performance of test sections reinforced with a single layer of geogrid at variable depths below the footing (tie) was compared against unreinforced test configurations. The results showed that geogrid reinforcement in ballast over compressible ballast support can be effective in reducing the rate of permanent deformation associated with lateral ballast spreading. The optimum reinforcement depth-to-tie-width ratio was determined to be from 0.2 to 0.4 for the single-tie tests with compressible artificial supports. No performance benefit was observed for reinforced ballast sections over a rigid support. By far the greatest influence on the performance of test sections was the compressibility of the artificial supports used. Permanent deformations at a given tonnage increased dramatically with increased support compressibility both for reinforced and unreinforced tests. A preliminary attempt was made to relate the performance of reinforced model tests to the performance of comparable configurations in track.

Under repeated tie loading, railway ballast undergoes nonrecoverable vertical deformations, mostly due to ballast densification, aggregate degradation, and the lateral spread of ballast beneath the ties. A joint Queen's University and Royal Military College research program has been underway for several years to investigate the influence of track parameters on the performance of large-scale model tie/ballast systems and to investigate strategies to improve the performance of these systems. A companion paper *(1)* dealing with unreinforced single tie/ballast systems was presented by the authors at the Transportation Research Board 1987 annual meeting.

Earlier work has shown that the inclusion of open-grid polymer-based reinforcement (geogrid) in ballast may be a cost-effective method to reduce track settlements associated with lateral ballast spreading *(2)*. The current study reports recent additional work related to geogrid reinforcement of ballasted track.

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Large-scale models comprising a single tie/ballast system over artificial subballast-subgrade supports of variable compressibility, hereafter referred to as artificial support, were built and subjected to a program of repeated loading. The principal objectives of this investigation were to

1. Compare the performance of geogrid-reinforced and unreinforced ballast sections with respect to the rate at which permanent deformations are generated during repeated loading;
2. Examine the effect of ballast support compressibility on permanent deformation and elastic rebound for reinforced and unreinforced ballast test sections;
3. Establish a practical optimum depth of geogrid reinforcement below a tie; and
4. Relate laboratory test results to field applications.

The general test arrangement is shown in Figure 1. A 450-mm depth of ballast was confined within a rigid test box 3 m long by 1.5 m wide. Tests were performed with and without geogrid inclusions. For reinforced configurations, a single layer of geogrid was placed at a variable depth below the footing (tie) base.

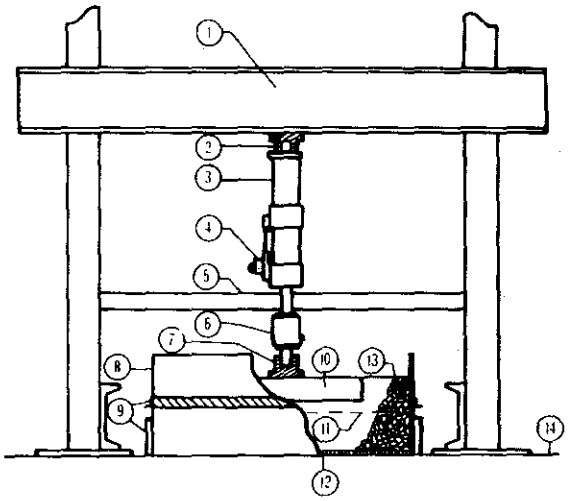
A range of ballast support stiffnesses was incorporated into test sections. A perfectly rigid subgrade condition was simulated by placing ballast material directly over the concrete floor. For compressible ballast support models, rubber mats of variable stiffness were placed over the concrete floor.

A 920-mm-long (L = 920 mm) by 250-mm-wide (B = 250 mm) by 150-mm-deep steel footing was used to model the bearing area of a typical tie below the rail seat (i.e., one rail). The footing was placed within the 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 peak load of 85 kN at selected frequencies from 0.5 to 3 Hz.

TEST DETAILS

Ballast

Crushed limestone aggregate was used for all test configurations. The aggregate was screened close to an American Railway Engineering Association (AREA) No. 4 grading with a size distribution between about 10 mm (3/8 in.) and 50 mm (2 in.) *(3)*. AREA No. 4 gradation limits and mean particle size distribution for the test ballast are given on Figure 2. The ballast had a Los Angeles abrasion (LAA) value of 27 and 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 GM1 GEOGRID
12 ARTIFICIAL SUPPORT
13 AREA #4 BALLAST
14 CONCRETE FLOOR

FIGURE 1 General test arrangement.

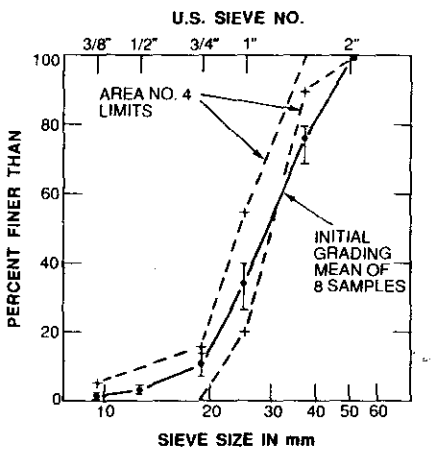


FIGURE 2 Ballast size distribution.

mill abrasion (*MA*) value of 8.5. The ballast depth below the footing was 300 mm, which corresponds to the minimum recommended depth for new construction according to the AREA *(3)*. The ballast was placed in 150-mm lifts and compacted by a vibrating plate tamper with a mass per unit area of 105 kg/m^2.

Geogrid Reinforcement

A high-density polyethylene polymer mesh was used for all reinforced tests (Tensar GM1 geogrid). The GM1 mesh consists of square openings with an aperture width of 46 mm and has identical mechanical properties in longitudinal and transverse directions.

A fresh sheet of geogrid was used for each test and was trimmed to fit without warping within the area of the ballast box. The geogrid was placed at depths D_r of 50, 100, 150, and 200 mm below the base of the footing.

Footing

Footing dimensions were selected to model one-half 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 (3)*. When the AREA approach is used, the footing length L of 920 mm also corresponds to about the tamper influence distance along the tie on either side of each rail. The footing was constructed from a 3.15-mm-thick rectangular hollow steel section and was closed at the end to prevent aggregate infilling.

Ballast Support

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

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

A flexible ballast support condition was modeled by using a closed-cell gum rubber mat. A subgrade modulus of 129 MN/m^3 was calculated for this material with a plate 762 mm in diameter and a maximum load of 85 kN. A California bearing ratio (*CBR*) value of 39 was determined for the same material by 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.

Very flexible ballast support conditions were modeled by using double layers of rubber mat materials. For example, a layer of gum rubber plus a layer of open-sheet neoprene rubber gave a subgrade modulus of 18 MN/m^3 and a *CBR* value of 1. A double layer of gum rubber increased the subgrade modulus to 62 MN/m^3 and gave a *CBR* value of 10. These low values indicate extreme compressibility that would tend to be avoided for the subballast-subgrade formation in a field situation. However, these weak artificial supports were used to clearly establish trends in ballast load-deformation behavior related to ballast support compressibility.

LOADING SYSTEM AND DATA ACQUISITION

Tie loadings were applied through an MTS closed-loop electrohydraulic actuator controlled by a DEC PDP11/34 computer.

The majority of tests reported in the current study were carried out in a load-controlled mode using a peak load of 85 kN and loading frequencies from 0.5 to 3 Hz. An 85-kN load (tie bearing pressure = 370 kPa) represents a typical magnitude of dynamic load felt by ballast directly beneath the tie for a track modulus between 14 and 85 MN/m per meter of rail *(4)*. The magnitude of permanent deformations generated in track is insensitive to the magnitude of loading frequency when low rates of loading are used *(5)*. 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 *(6)*.

A load cell and linear variable displacement transducer (LVDT) located above the actuator base were used to monitor footing loads and vertical footing displacements at all test stages. At programmed intervals, the load-deformation response of the footing during a loading cycle was taken, and at regular intervals the permanent deformation of the footing was recorded and stored by the computer.

TEST PROGRAM

Results from 15 tests have been used in the current study to provide data with which to compare the relative performance of reinforced and unreinforced tie, ballast, and support configurations. These test configurations are presented in Table 1. Tests were subjected to a maximum number of load repetitions that was equivalent to 2 to 20 million cumulative axle-tonnes in track. The equivalent axle-tonnage was calculated by summing the number of load repetitions and multiplying by twice the applied load. 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 tonnes *(7–9)*. In 1980, annual traffic of 10 to 60 million gross tonnes (MGT) was recorded for typical heavy branch-line and main-line track sections in Canada.

TABLE 1 SUMMARY OF TESTS

Test No.	Load Level (kN)	Support Condition (CBR)	Reinforcement Depth D_r (mm)
1	85	Rigid	Unreinforced
1A	85	Rigid	Unreinforced (repeat)
2	85	Rigid	50
3	85	Rigid	100
4	85	Rigid	150
5	85	39	Unreinforced
6	85	39	50
7	85	39	100
8	85	39	100 (repeat)
9	85	39	150
9A	85	39	200
10	85	1	Unreinforced
11	85	1	100
12	85	1	200
13	85	10	Unreinforced

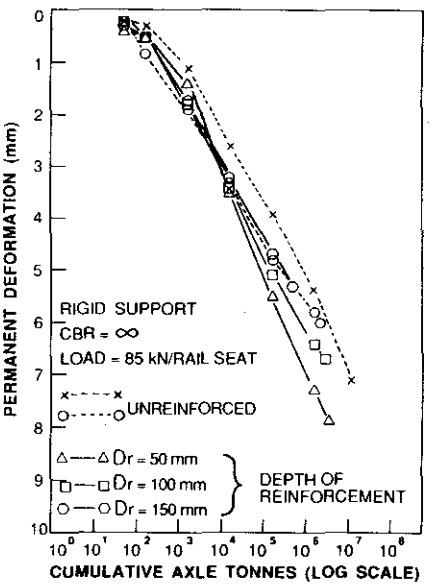


FIGURE 3 Accumulated permanent deformation (rigid support).

TEST RESULTS

Effect of Reinforcement on Permanent Deformations

A fundamental objective of this study was to determine the conditions under which geogrid reinforcement of railway ballast was effective in reducing the rate of development of permanent settlements below railway ties. Figures 3–5 show accumulated permanent deformations recorded for all tests as a function of equivalent cumulative axle tonnage. Permanent deformations shown on the figures are those measured at the base of the footing. A number of important observations can be made from these figures.

Figure 3 shows that the permanent settlements recorded after 1 to 10 MGT are small regardless of test configuration when the ballast is placed over a rigid support. The differences in accumulated settlements are probably caused by minor variations in ballast placement rather than the presence or absence of the reinforcement. Consequently, despite a small increase in recorded settlements for the reinforced configurations with respect to the control configurations at the end of the test of less than 2 mm, the performance difference is considered negligible.

In contrast, Figures 4 and 5 show a clear performance benefit due to the inclusion of geogrid at certain elevations within the ballast layer for tests constructed over a compressible ballast support. For comparative tests with a *CBR* = 39 support, permanent deformations were reduced for reinforcement depths D_r = 50, 100, and 150 mm below the tie. At D_r = 200 mm, the reinforced test showed greater settlement and larger settlement rates than the control test. However, the performance difference is probably within the range of test repeatability, and for practical purposes the D_r = 200 mm test over a *CBR* = 39 artificial support represents the limiting depth at which reinforcement is effective in these laboratory tests. The trend in

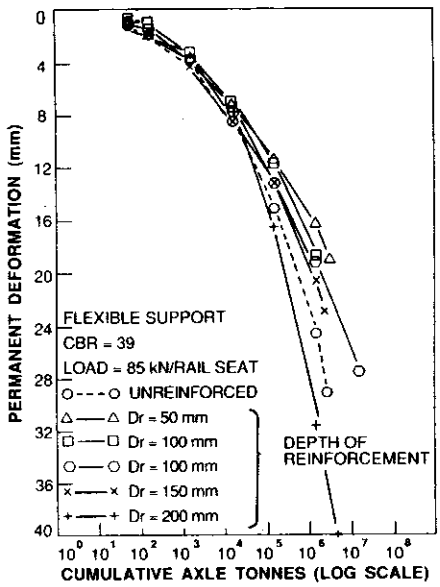


FIGURE 4 Accumulated permanent deformation (flexible support).

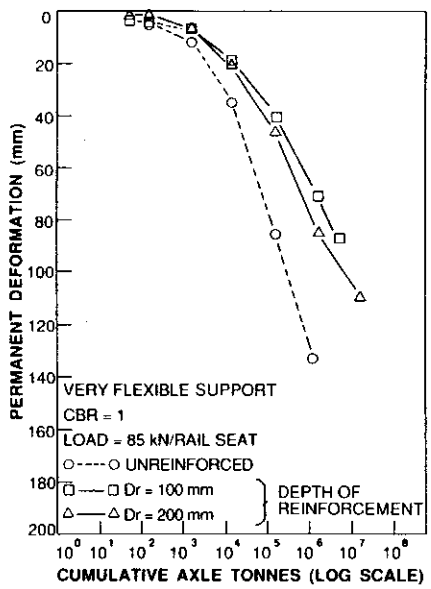


FIGURE 5 Accumulated permanent deformation (very flexible support).

reinforcement effect shown on the figure is similar to comparable small-scale tests built with compressible artificial subgrades *(10)*. For $D_r \cong 1$, there were marginally greater plastic settlements for the reinforced cases.

The *CBR* = 1 tests with reinforcement at D_r = 100 and 200 mm reduced permanent deformations more dramatically than the *CBR* = 39 tests. For example, at 2 million tonnes and D_r = 100 mm, the permanent deformations were reduced by about 20 percent for a *CBR* = 39 support condition. The same reinforcement depth and *CBR* = 1 support gave a 50 percent reduction. Taken together, the data shown on Figures 3–5 suggest that the ability of reinforced sections to reduce permanent deformations under repeated loading improves with increasing subballast-subgrade formation compressibility.

Effect of Ballast Support Compressibility on Permanent Deformations

The influence of ballast support compressibility on the permanent deformation response of control tests and tests with reinforcement at D_r = 100 mm is shown in Figure 6. The data show that as ballast support *CBR* → ∞, the relationship between the magnitude of permanent deformation and the log number of cumulative tonnage becomes more linear. Linear semilogarithmic settlement trends have been observed in full-scale single-tie tests in which unreinforced ballast was placed over a firm subballast-subgrade formation *(11)* and by the European railways who have monitored conventional main-line track constructed over very competent subgrades *(7–9)*. In contrast, the deformation histories of the unreinforced and reinforced tests with very flexible artificial supports (*CBR* = 1 and 10) are distinctly nonlinear on a semilogarithmic plot. These data indicate that once some threshold tonnage is achieved for each support condition, the rate of track settlement per log cycle of cumulative tonnage increases. Similar nonlinear deformation-tonnage curves have been reported by the European railways for main-line track in need of ballast maintenance *(7–9)*.

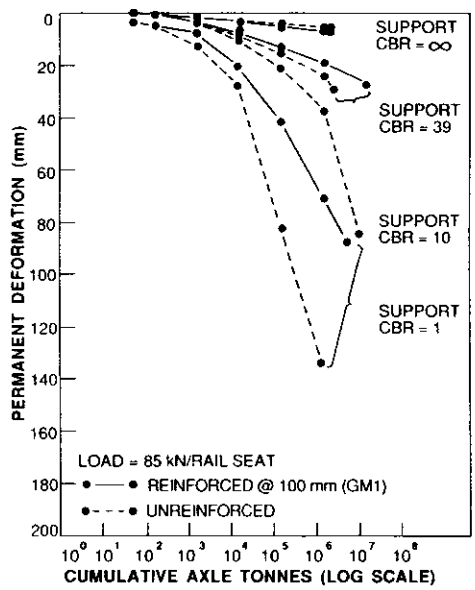


FIGURE 6 Influence of support compressibility on permanent deformations.

Elastic Rebound

Elastic rebound (unloading) is the difference between recoverable and nonrecoverable deformations associated with each load repetition and can be used to evaluate the resilience (elasticity) of track subjected to repeated loading. Figure 7 shows the range of elastic rebound recorded in the ballast-subgrade formation for 85-kN tests after 1,000 load applications. The data reveal that the magnitude of elastic rebound is sensitive to ballast support compressibility but relatively insensitive to the presence and depth of geogrid reinforcement.

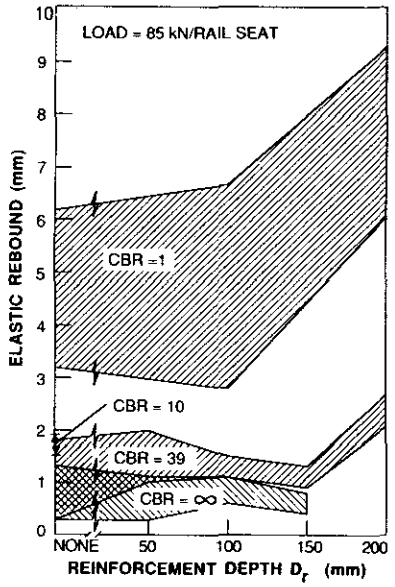


FIGURE 7 Elastic rebound.

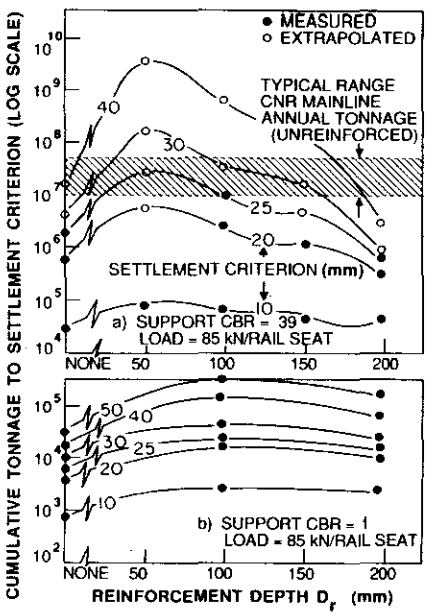


FIGURE 8 Optimum depth of reinforcement from single tie-ballast model tests.

Additional Observations

During excavation of reinforced-ballast sections, it was observed that numerous aggregate particles were tightly wedged into the grid apertures and could not be removed by hand. This observation is consistent with the concept of ballast-geogrid interlock as an important mechanism in resisting the lateral deformation of ballast under repeated loading. In addition, the geogrid was observed to form a well-pronounced depression bowl in nonrigid artificial support tests, consistent with the widely held belief that to mobilize the tensile and interlocking capacities of this material, large deformations in the surrounding aggregate are required. In the field, where ballast may be placed over low-CBR subballast-subgrade formations, the mobilization of the geogrid reinforcement may be even greater due to plastic deformation of the ballast support. Consequently, the relative improvements reported for reinforced configurations in this paper may actually be conservative.

Optimum Depth of Reinforcement

Figure 8 shows the equivalent tonnage required to achieve a given settlement criterion for all 85-kN tests with compressible-ballast support. Where necessary, settlements at large tonnages have been estimated by linearly extrapolating load-deformation results after 2 million tonnes. The mean settlement criterion adopted by a given railway to initiate mechanized maintenance 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 *(7–9)*.

The plots indicate that an optimum depth of reinforcement is in the range of 50 to 100 mm below the tie (i.e., D_r/B = 0.20 to 0.40). These results are consistent with the results of earlier small-scale model tests that examined the effect of reinforcement in sand layers over compressible artificial subgrades subjected to repeated loading *(10)*. In the small-scale tests the optimum ratio D_r/B was about 0.33, and the benefit due to the reinforcement was seen to decrease for D_r/B greater than this value.

Figure 9 shows the settlement rate expressed in millimeters per log cycle of accumulated tonnage after 2 million equivalent-axle-tonnes for 85-kN tests. The data show that the optimum depth for *CBR* = 39 tests is in the range of 50 to 100 mm but may be somewhat deeper for configurations with a subgrade *CBR* of 1. The figure also indicates that subballast-subgrade formation compressibility has a greater influence on the settlement rate than does the location of the reinforcement.

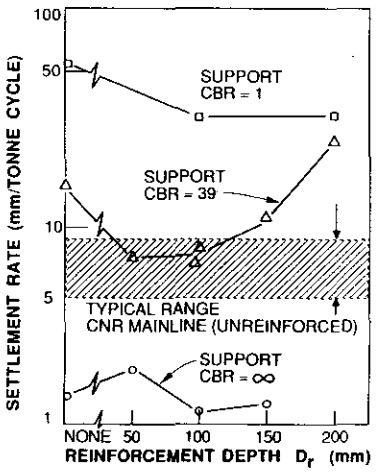


FIGURE 9 Railseat settlement rates after 2 MGT.

Implications for Track Design

Superimposed on Figure 8 is a range of typical Canadian National Railways (CNR) annual heavy branch-line and main-line tonnage *(12)*. This range shows that test configurations with $CBR = 39$ artificial support achieve settlement values after accumulated tonnages that are representative of annual traffic densities in CNR track. In contrast, the percentage reduction in permanent deformation for $CBR = 1$ tests is more dramatic, but the improvement is not meaningful because unacceptably high deformations would occur after only weeks of heavy branch-line or main-line traffic.

Superimposed on Figure 9 is the measured track settlement rate for a section of CNR conventional track after 2 million tonnes of main-line traffic *(12)*. Similar rates have been reported by the European railways for conventional track considered to be optimized *(7–9)*. Nevertheless, settlement rates in track constructed over poor subgrades or curved track have led to measured settlement rates as high as 26 mm per log cycle of accumulated tonnage *(7–9)*. On the basis of available field data, the $CBR = 30$ tests appear to give settlement rates that are reasonable for main-line track.

From practical considerations, a reinforcement depth between 50 and 100 mm is unsatisfactory because the tines for tamping equipment typically extend to between 100 and 150 mm below the base of the tie. However, a safer 200-mm depth of reinforcement may be effective in reducing settlements in actual track because the single-tie and rail seat model used in the current study may underestimate the optimum reinforcement depth. In the field, rolling loads are delivered over several ties; in addition, ballast spreading in the longitudinal track direction is more constrained. Qualitatively, these effects lead to an equivalent width B that is greater than the width of a single tie. If it is assumed that the experimentally determined optimum ratio $D_r/B = 0.2$ to 0.4 is valid, it is possible that a 200-mm depth of reinforcement in actual track will be as effective in reducing the rate of permanent deformation for ballasted track as indicated by the model tests with D_r/B 0.2 to 0.4. In addition, the use of a purely elastic artificial support may penalize the performance benefit that would otherwise occur for the comparable configuration in a field condition. Actual subballast-subgrade formations with low CBR values will generate additional plastic deformations that can assist to mobilize the inherent capacity of geogrids to resist lateral spreading of ballast. On the basis of the previous comments, much work remains to be done to calibrate the laboratory test results with the performance of actual reinforced-track structures in the field.

Nevertheless, if it is assumed that the model tests are conservative, the potential for increased maintenance cycle times can be appreciated from Figure 10, which shows that if reinforcement is placed at an effective depth in ballast over a $CBR = 39$ support, the tonnage saved after 20 to 30 mm of accumulated settlement is equivalent to 1 year of heavy CNR branch-line or main-line traffic. Alternatively, the potential benefit of reinforcement under the same conditions can be expressed as a 25 to 50 percent reduction in the rate of settlement after 2 million cumulative tonnes, as shown in Figure 9. For conditions under which permanent settlements greater than 30 mm are permitted, the semilogarithmic settlement trend in the test data can be

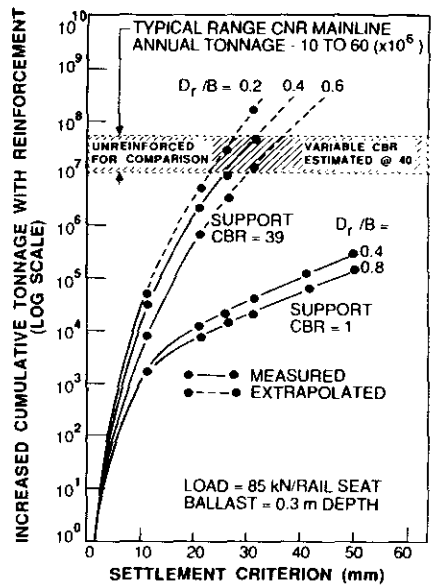


FIGURE 10 Cumulative tonnage saved from single tie-ballast tests.

extrapolated to predict even greater savings in terms of years between mechanized maintenance duties *(2)*.

The results of the current study indicate that there is a combination of criteria that must be met before ballast reinforcement can be considered a cost-effective method to improve track performance. If the track subballast-subgrade formation is too stiff, the performance difference between reinforced and unreinforced systems is negligible. Conversely, if the ballast support is too compressible, the reinforcing benefit is pronounced, but the maintenance cycle times remain uneconomically short (i.e., curves fall below the 10-MGT line in Figure 10). Figure 9 shows that even though reinforcement is a viable option to increase maintenance cycle times, a modest improvement in the quality of the subballast-subgrade formation may be equally effective. For new construction, the latter is likely more cost-effective, whereas on rehabilitation work restricted to the track ballast the former is probably the preferred approach.

CONCLUSIONS

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

1. Test results showed that geogrid reinforcement in ballast can reduce the rate at which permanent (nonrecoverable) deformations are generated within ballast for track structure over compressible subballast-subgrade formations. Conversely, no performance benefit was observed for reinforced ballast sections constructed over a rigid subgrade.
2. By far the greatest influence on the generation of permanent deformations beneath the tie was the compressibility of the artificial support below the ballast. Increases in permanent deformation were proportional to increases in subgrade compressibility for both reinforced and unreinforced test sections.

3. As subballast-subgrade formation compressibility increases, the benefit derived from the geogrid reinforcement becomes more pronounced. Model tests showed that for reinforced ballast over a very flexible support the permanent deformation recorded after about 2 million tonnes was only 50 percent of that recorded for the same configuration without reinforcement.

4. The test results show that the experimentally determined optimum reinforcement depth-to-tie breadth ratio D_r/B is in the range 0.2 to 0.4 for ballast over a compressible ballast support. Tests with a $CBR = 39$ support and reinforcement at $D_r/B = 0.2$ to 0.6 resulted in tonnage savings equivalent to 1 year of heavy CNR branch-line or main-line track.

5. In actual track, the depth of reinforcement would be restricted to about 200 mm to avoid damage by the ballasting tines of reballasting equipment. Although this depth results in no performance benefit according to tests with a ballast support of $CBR = 39$, the model tests are considered conservative because the artificial supports used in the laboratory could not deform plastically. Consequently, geogrid at 200-mm depth in actual track would probably assist in reducing the rate of permanent deformation.

6. The inclusion of geogrid ballast reinforcement did not appear to alter the elastic rebound values in the large-scale test program. The most important factor affecting the magnitude of elastic rebound was ballast support compressibility. Increases in artificial subgrade compressibility resulted in a proportional increase in rebound deflection.

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