FRA/ORD-84/18

BALLAST TESTING AT FAST: 1976-82

FAST Facility for Accelerated Service Testing

TRANSPORTATION TEST CENTER
PUEBLO, COLORADO 81001

FEBRUARY 1985

This document is available to the public through
The National Technical Information Service,
Springfield, Virginia 22161

PREPARED FOR
THE FAST PROGRAM

AN INTERNATIONAL GOVERNMENT - INDUSTRY RESEARCH PROGRAM

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL RAILROAD ADMINISTRATION
Washington, D.C. 20590

ASSOCIATION OF AMERICAN RAILROADS
1920 L Street, N.W.
Washington, D.C. 20036

RAILWAY PROGRESS INSTITUTE
801 North Fairfax Street
Alexandria, Virginia 22314

RPI

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use.

NOTICE

The United States does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FRA/ORD-84/18		

4. Title and Subtitle	5. Report Date
Ballast Testing at FAST: 1976-82	August 1984
	6. Performing Organization Code
7. Author(s) J. Heiss	8. Performing Organization Report No. TTC-012(FAST-FR84)
9. Performing Organization Name and Address The Association of American Railroads P.O. Box 11130 Pueblo, Colorado 81001	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFR 53-82-C-00282
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Railroad Administration Office of Research and Development Washington, D.C. 20590	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract The railroads, for whom ballast has long been a subject of serious study, have sought to develop criteria for choosing, maintaining, and predicting ballast performance in revenue track. During 1976-1982, two studies (Ballast I & II) were conducted on sections of the FAST loop at the Transportation Test Center (TTC), Pueblo, Colorado.

Ballast I research on Depth, Shoulder Width, Material Type, and substructure deformations confirmed many characteristics seen in revenue track, and provided valuable experience in the conduct, per se, of such testing. Findings implied that excess depth can be detrimental to geometry stability (that increasing shoulder width improved profile stability but had little or no effect on horizontal track stiffness) and confirmed the need to distinguish between specific geologic sources for like ballast types with common "generic" names. The AREA/Talbot method for finding subgrade stress was found adequate for design purposes under the conditions investigated.

Ballast II extended the 'type' studies and focused on ballast deformation, stress and strain, gradation and particle shape and (to a limited extent) geotextile performance. Ballast with larger, elongated particles, broader gradation, and low flakiness evidenced better performance. Geotextile results showed a need for heavier weight fabrics. The Los Angeles Abrasion test proved questionable for predicting in-track degradation. A Bibliography of ballast-related studies is appended.

17. Key Words	18. Distribution Statement
Ballast Ballast Depth Ballast Shoulder Width Geotextiles Gradation Shape Factors Stress and Strain	Document Available through National Technical Information Service 5285 Port Royal Road Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	86	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

PREFACE

The author wishes to acknowledge the contribution of Mr. Bruce Bosserman, Manager of FAST Ballast Experiments until November of 1981.

Special thanks are extended to those firms which donated test material to the Ballast testing programs conducted at FAST:

Vulcan Material Company, Inc.
Burlington Northern
Missouri Pacific
Chicago Northwestern
Union Pacific
New York Trap Rock Co.
CF&I Steel Corp.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

AASHO	American Association of State Highway (and Transportation) Officials (now AASHTO)
AREA	American Railway Engineering Association
ASTM	American Society for Testing and Materials
BS	British Standards Institute
C/E	U. S. Army Corps of Engineers
CIGGT	Canadian Institute of Guided Ground Transport (also refers to CIGGT's ballast and shape factor index)
FAST	Facility for Accelerated Service Testing, Transportation Test Center, Pueblo, Colorado
LAA	Los Angeles Abrasion Test
MGT	Million Gross Tons
NECIP	Northeast Corridor Improvement Project
TTC	Transportation Test Center, Pueblo, Colorado
UC	Uniformity Coefficient
F	British Standard 812 Flakiness Index
E	British Standard 812 Flakiness Index

METRIC EQUIVALENTS

Term	Definition	Equivalent
o	degree	
',ft	foot	0.3048 meter
",in	inch	25.4 millimeter
lb(s)	pound(s)	453.59 grams
MGT	million gross tons	0.907 MGMg
mi	mile(s)	1.6094 kilometers
oz	ounce(s)	28.35 grams
ton		0.907 megagrams
yd	yard	0.914 meter

EXECUTIVE SUMMARY

General

This report is a summary of the first two ballast experiments conducted at the Transportation Test Center (TTC), Pueblo, Colorado, between 1976 and 1982. These experiments were executed at the TTC's Facility for Accelerated Service Testing (FAST). The attempt has been made to present the significant results of FAST ballast testing, placing emphasis on those results which have practical application in the railroad industry.

Previously published materials from this testing will be cited and new material from the second experiment will be presented. Major topics covered in the report are: ballast material types, variations in the ballast section dimension, gradations and shape factors, stress and strain, and geotextiles.

Ballast I

This experiment was in place upon the inauguration of the FAST Program in 1976 and was continued through September of 1979 (425 MGT). Three major tests were included within the first experiment: Ballast Shoulder Width Test, Ballast Depth and Ballast Material Type; in addition, studies were conducted involving settlement and stress and strain on the subgrade and in the ballast section.

Ballast Shoulder Width Test - Two segments of FAST Section 15 were designated for testing of 6" and 18" shoulder widths (uniform depth and ballast type). Studies indicated that increasing the shoulder width decreased the amount of geometry-related maintenance required and reduced the rate of geometric degradation, especially in the vertical profile.

Ballast Depth Test - Studies were conducted on test segments with ballast depths of 6", 12" and 18". These studies indicated that increasing the ballast depth beyond what is required for proper distribution of loads to the subgrade might have negative effects on track geometry retention characteristics.

Ballast Type Test - Five ballast types were installed for the purpose of determining performance difference between material types. The five types were a granite of AREA Gradation 5, a limestone of AREA Gradation 4, a traprock of AREA Gradation 34, a dolomite of AREA Gradation 4, and a steel mill slag of AREA Gradation 4. A wide range of performance differences were found between the types.

Stress and Strain - Results of these tests indicate that Talbot's method of calculating subgrade stress (AREA Proceedings, Vol. 21, 1920, pp. 765-814) is conservative but suitable for design purposes.

Other results indicated that dynamic loadings were almost completely elastic--that there was minimal unloading between axles adjacent to the coupler. Under the car centers unloading was complete, and in cases, an extensional strain was seen in the ballast. Static measurements indicated that approximately half of the long term ballast settlement occurred in the first 2 MGT's of traffic, and 90% of the permanent strain was reached between 10 and 20 MGT.

Ballast II

After 425 MGT's of traffic had been accumulated on the FAST Test Track, Sections 3, 17, and 22 were rebuilt for the second ballast experiment. This test commenced in September of 1979 and continued into 1982. The main thrust of the second experiment was to find relationships between the measurable indices of the ballast and its in-track performance. Other tests included in Ballast II were a service life test of geotextiles and direct comparison of performance under track of wood and concrete tie construction.

Ballast Indices vs Performance - The purpose of this test was to find how the various measureable indices of ballast related to the performance in the field. The indices investigated included Los Angeles Abrasion, gradation, and shape factors. It was found that the Los Angeles Abrasion test is not a good predictor of ballast durability. It was also found that gradation and shape factors have measureable influences on performance. The presence of elongated particles as well as relatively large particle sizes and broad gradation curves have positive effects on track strength while the presence of flat particles has negative effects.

Geotextiles - This was a limited test, only investigating the service life of geotextiles installed in railroad tracks at the subgrade/ballast interface. It was found that the lightweight fabrics (8 oz/sq yd and less) tested have a limited life. Manufacturers of geotextiles now recommend heavier weights of fabric for this this type of installation.

Wood vs Concrete Tie Performance - This test did not confirm the widely held position that concrete ties contribute to degradation of certain types of softer ballasts. In granite and granite-like ballast materials, no significant difference was found in the degradation of particles under the two types of construction in most cases.

Concrete tie track consistently displayed higher values of track modulus, confirming results of earlier tests elsewhere. Concrete tie track also exhibited higher lateral strength than its timber counterpart.

1.0 INTRODUCTION

The importance of ballast performance to the overall economics of railway operation is often underestimated. Since the beginning of scientific investigation into the structural behavior of the track, ballast has been recognized as a major contributor to the stability and longevity of serviceable track.

The problem faced by railway engineers is to find an economical ballast material that will provide satisfactory in-track performance. Present knowledge of the relationships between material properties relative to an objective specification and the performance of material in the track is inadequate to ensure a given level of safe and economic railway operation. Practical limits on the sources available and the variability within and between sources complicate the engineer's task. In today's environment of heavier axle loads, increased traffic, rising maintenance costs and, in some cases, increased speeds, a serious gap has developed between the performance required of a ballast material and the methods available to specify a suitable material, design the ballast section, and predict the performance.

Research on ballast performance and materials spans a 90+ year history. The experimental and analytical work of Zimmerman (1888), Talbot (1913-1942), and Clark (1957) resulted in development of several empirical design methods based on average values of roadbed support. More recent work has been presented by Salem (1966), Lundgren (1970), Shenton (1973), Prause (1974), Robnett (1975), and Selig (1981). Though by no means exhaustive, this list of examples represents a body of work which has had a major impact on the experiments conducted at the Facility for Accelerated Service Testing (FAST) at the Transportation Test Center, Pueblo, Colorado.

Aside from the research work conducted on railway ballast, a large portion of the standards applied to ballast today has resulted from work conducted by highway interests. During the 1930's, extensive studies were conducted on road and concrete aggregates, and tests were developed for their evaluation. Although railroad ballasts were not included in the studies, many of the methods developed during this period were applied to the evaluation of ballast. Much of the current AREA specifications date from this period, including the AASHO coarse aggregate gradation curves adopted in 1944.

At the inception of the FAST program, investigations into railroad ballasts were obviously justified. Since 1976, two ballast experiments with wide-ranging objectives have been conducted on the FAST test track. The first experiment was in place at the beginning of FAST operation and remained in place, at least in part, for a duration of 616 MGT, although major portions of this test were concluded at 425 MGT. The second experiment was installed during the fall of 1979, with operation commencing at the 425 MGT level and continuing until 650 MGT.

The primary purpose of the first experiment was to evaluate the effects on track performance of variations in the ballast section such as depth, material type and shoulder width. Also included in the first experiment was a study of stress and strain in the ballast and subgrade. The second experiment extended the material type studies of the first experiment and also included studies on the effects of gradation and particle shapes on track performance. A limited study of geotextile performance was also conducted during the second ballast experiment.

This report presents the significant results of FAST ballast testing through the conclusion of the second ballast experiment in 1982.

2.0 FIRST BALLAST EXPERIMENT

The first experiment was installed in the FAST track at the inception of the FAST program in September of 1976. This initial phase of experimentation continued until the 425 MGT level in September of 1979. Some portions remained in the track until 616 MGT in November of 1981.

Included within the experiment were three major tests which investigated variations in basic geometry of the ballast section plus other tests investigating ballast material types and investigations into the stress and strain behavior of railroad ballast. A map depicting the layout of the tests in this experiment is included in Appendix A.

The first to be discussed is the Ballast Shoulder Width test. Its purpose was to determine how lateral track stability was affected when the ballast shoulder width varied. FAST Section 15 was designated for this test and shoulder widths of 6 inches and 18 inches were installed. Although shortcomings were experienced in the technique for measuring the lateral strength of the track, useful results were produced by the test. This test is discussed in detail in the following section.

The second test was the Ballast Depth Test. It is theorized (and early laboratory tests conducted by Talbot indicate) that, as the ballast depth increases, the stress on the subgrade decreases and the distribution of stresses becomes more uniform over the surface of the subgrade. The purpose of this test was to investigate the effects on overall track performance when ballast depth was increased to reduce the imposed stresses on the subgrade. Details of the test are discussed in the second following section.

Other tests were conducted during the course of the first ballast experiment. Included were the ballast material type test and investigations on the stress, strain and settlement. These tests are discussed in the third following section.

2.1 <u>SHOULDER WIDTH TEST</u>

The Ballast Shoulder Width test was conducted in Section 15, a tangent section, of the FAST test track. Section 15 was divided into two segments, one with a 6 inch shoulder width and the other with an 18 inch shoulder width. Each of these test segments were 550 feet long. A blast furnace slag from a local source meeting the gradation requirements of AREA #4 was installed at uniform depth through the test section. Track construction was timber ties placed on 19-1/2 inch centers. Grade was essentially level over the entire test section. The objective of the test was to measure the effects of variation in the shoulder width on overall track performance.

For the purpose of this test, the ballast shoulder width was defined as the horizontal distance from the end of the tie to the point where the ballast breaks into an obvious slope. Measurement of this parameter proved to be less than precise, especially where rounding of the shoulder occurred.

For the 400 MGT duration of the test, the mean and standard deviations of the shoulder widths were as follows:

		NOMINAL SHOULDER WIDTH 6 inch	18 inch
Actual Width	Mean	9.4	16.9
	Std. Dev.	3.3	5.0

Using the Student's T test, the differences in the shoulder width geometry were significant at the 99% level but from the wide variation in the measurement as expressed by the standard deviations, the exact magnitude of the shoulder width differences cannot be precisely evaluated.

The track parameter believed to be most affected by shoulder width is lateral track stiffness. Several inconsistencies were identified with the method used to measure the horizontal track stiffness at FAST at the time of this experiment, but the method did produce data suitable for comparison of strength within this test. This data should be used, however, for comparisons to future tests or other tests. This data gives the values of horizontal pull required to achieve a given lateral displacement of the track:

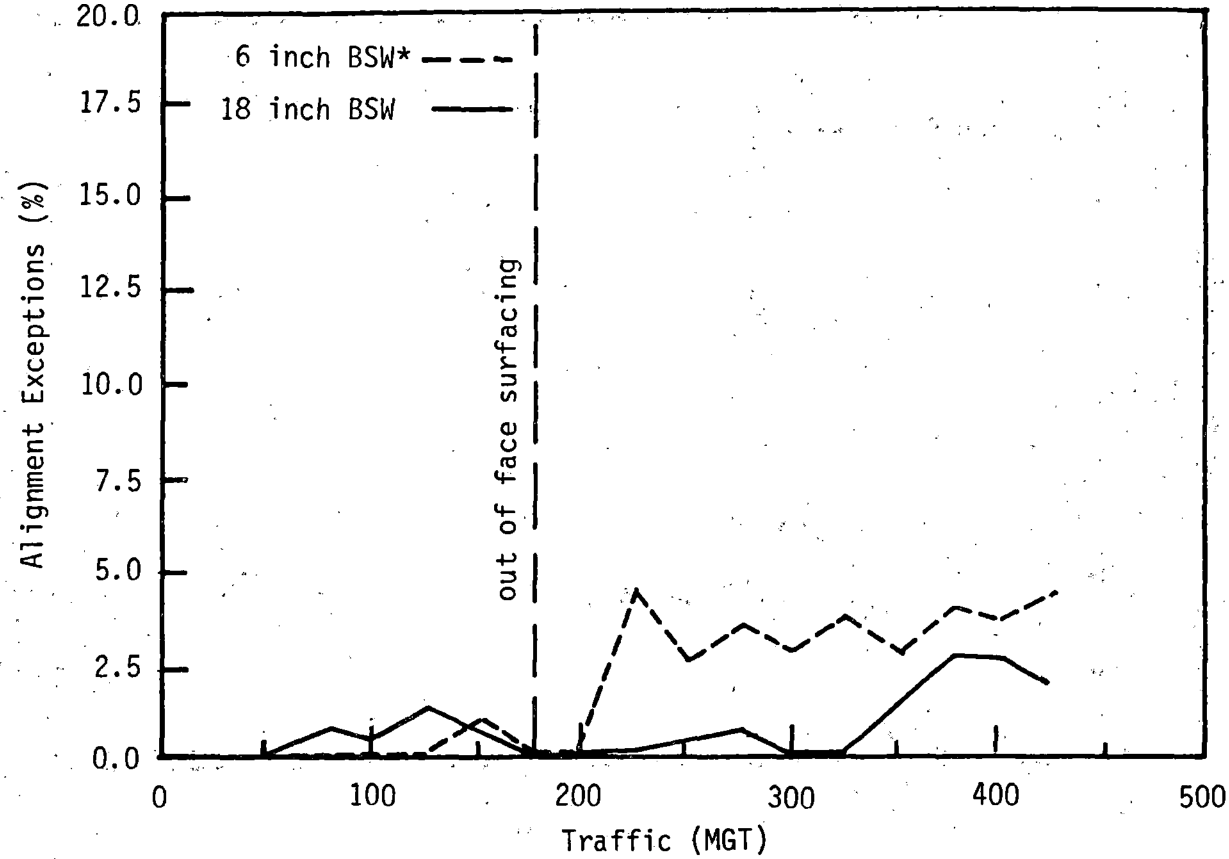
	NOMINAL SHOULDER WIDTH 6 inch	18 inch
0.05 inch displacement	6,300 lb	6,000 lb
0.20 inch displacement	13,200 lb	14,000 lb

The indication from this data is that the shoulder width has little or no effect on the lateral stiffness of the track. This conclusion is in line with Talbot's results in his experiments in the laboratory.

Track settlement was measured for the duration of this test using a top-of-rail survey technique in the unloaded condition. No significant difference was found in the average settlement of the two test segments.

Another major performance parameter for this test was track geometry (i.e., profile and alignment). Measurement of track geometry began at 50 MGT. To measure these parameters, a Plasser EM-80 Track Geometry Car was used. The basis for analysis of track geometry was the percentage of the test zone length which failed to meet the geometric requirements of FAST Track Class A. The FAST track geometry standards are very similar in format to the track classes defined by the FRA rules. FAST Class A has an exception level for line and profile of 1/4 inch from uniform in a 62 foot chord. This classification is approximately twice as stringent as FRA Class 6. Because of the tight exception specification, exceptions in the geometric standards of the track appear early in the deterioration of the track.

Figure 1 shows the exception levels for alignment during the 425 MGT's for this test. A significant increase in the alignment exceptions appeared at 225 MGT in the 6 inch shoulder width section but remained at a relatively constant level for the remainder of the test. The cause of the increase in



*Ballast Shoulder Width

FIGURE 1. SECTION 15 ALIGNMENT EXCEPTIONS VS MGT.

exceptions remain unexplained, but it is seen that a steady, long-term degeneration of alignment did not occur in either the 6 inch or 18 inch shoulder width test segments.

The profile performance of the test segments was approximately equal for the period up to 175 MGT. After that time, the segment with the 6 inch shoulder width experienced significant increases in the profile exceptions. The differences seen in the profile were much greater than those for alignment. The profile data is presented in Figure 2.

For the duration of this test, data was kept for the maintenance man-hours required to maintain the track in a serviceable condition. Figure 3 depicts the maintenance man-hours expended on the two test segments. It is seen that the zone with the 6 inch ballast shoulder width required approximately 40% more effort by the end of the test.

From the data collected and analyzed for this test, it is concluded that increasing the shoulder width can reduce the track geometry deterioration of the track and produce savings in the maintenance required.

This test did not attempt to determine the ideal shoulder width, and, from the data, no conclusion as to the optimum width can be made. Significantly, it was seen in this test that the improvement in vertical geometry was more evident than that for horizontal geometry. This fact might possibly be

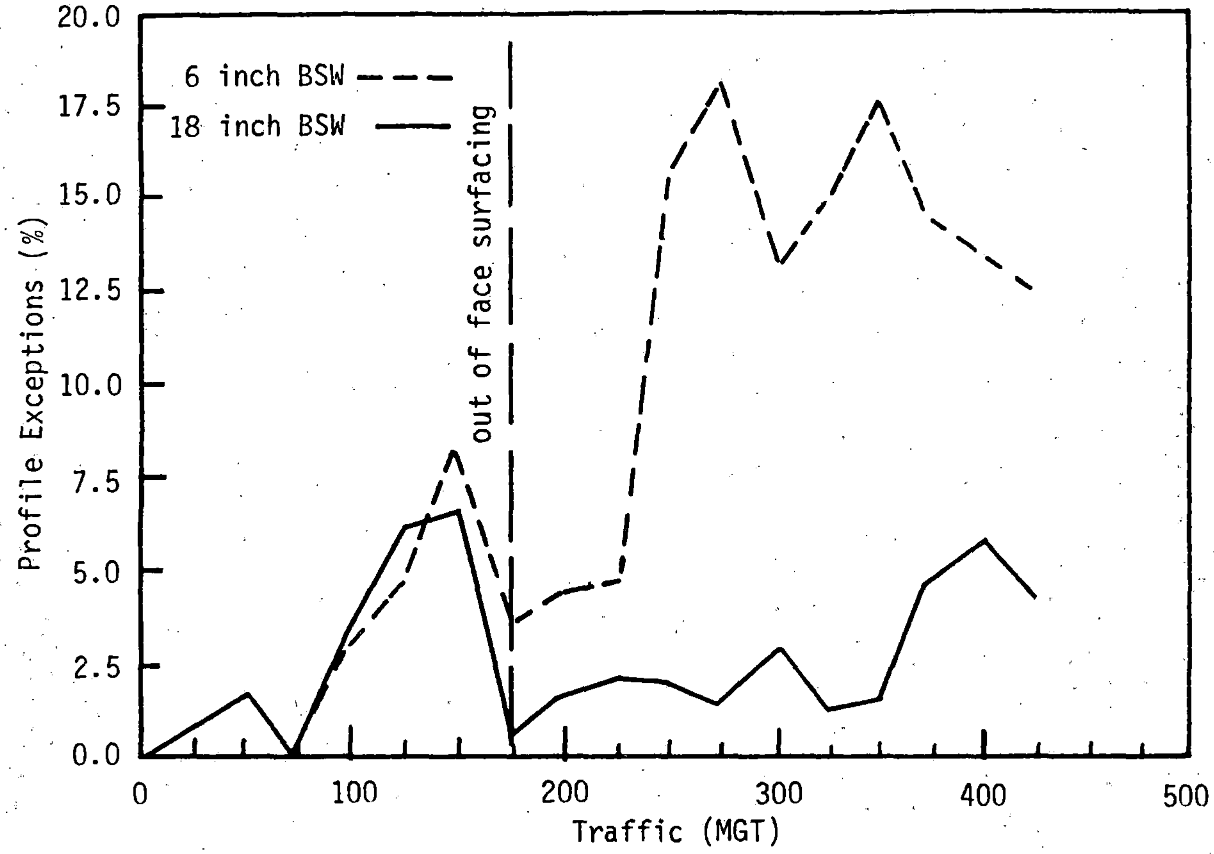


FIGURE 2. SECTION 15 PROFILE EXCEPTIONS VS MGT.

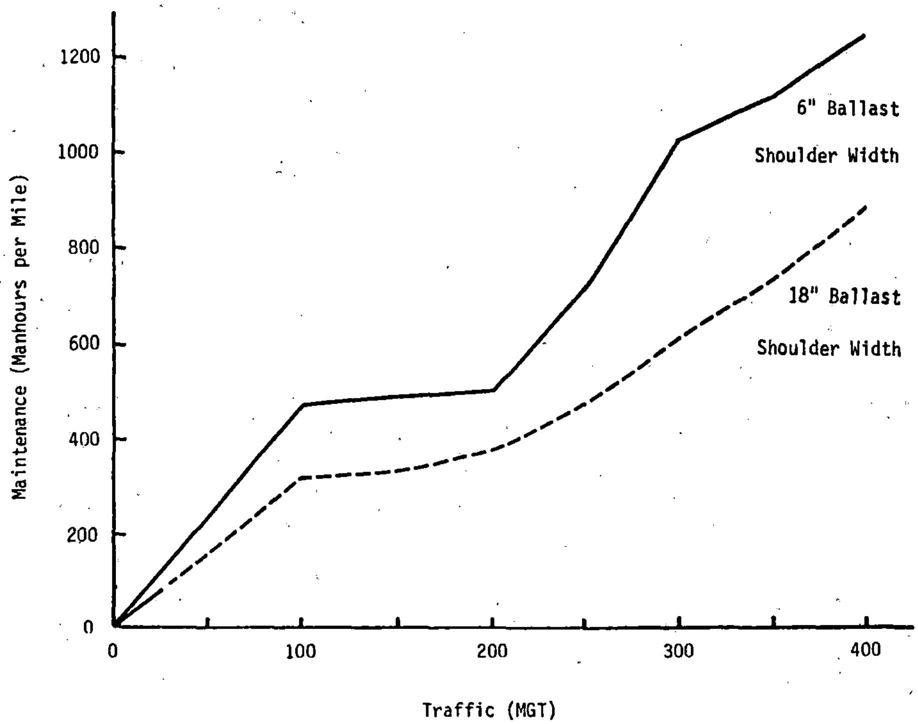


FIGURE 3. CUMULATIVE TRACK GEOMETRY-RELATED MAINTENANCE.

explained in the horizontal residual stresses which build in the ballast section under traffic.

Further details of this test are contained in Reference [1]*.

2.2 BALLAST DEPTH TEST

One of the prime functions of ballast is to distribute the load from the tie to the subgrade. Talbot demonstrated conclusively in the laboratory that the pressures on the subgrade were reduced as the ballast depth increased and that the loading became more uniform over the surface of the subgrade. The purpose of this test was to determine the effects on other properties of track performance as the ballast depth was increased.

The test layout consisted of 12 inch and 18 inch depths of granite ballast in Section 18 of the FAST track and a segment with a 6 inch depth of granite ballast in Section 20 of the test loop. The granite ballast met the AREA #5 gradation and a 12 inch shoulder width was maintained through the three test segments.

Track geometry data for the three test segments was analyzed for the period of 0 to 425 MGT (Figures 4 and 5). For the analysis of both profile and alignment, the least track geometry exceptions occurred in the segment with the 12 inch ballast depth.

These results should not be interpreted as indicating that 12 inches is the optimum ballast depth. The actual determination of the best ballast depth is dependent on the load spreading characteristics of the ballast and the bearing capacity of the subgrade, as well as the maximum wheel load. It should be noted that the subgrade at the FAST test track is very well drained in general and with the lack of precipitation, the bearing strength of the subgrade is high. It can be said that ballast depths greater than required to distribute the load to the subgrade at an acceptable level could be detrimental to the geometric stability of the track.

Instrumentation was installed in Section 18 to measure the stress applied to the subgrade under actual train loading. It was found that under the most severe instrumentation location, the average applied stress under an axle was 8.8 psi and the highest peak loading was 17.5 psi. At the instrumented sites there was 21 inches of ballast between the bottom of the tie and the surface of the subgrade.

In the analysis of this subgrade stress data, the Talbot/AREA formula for calculating subgrade stresses was applied to investigate the accuracy of this traditional method. The formula is as follows:

$$P_s = \frac{(16.6 \cdot P \cdot 0 \cdot DF \cdot FS)}{0.5 \cdot L \cdot B.h^{1.25}}$$

----

*References follow text on page 34. See Appendix C for details on obtaining FAST reports.

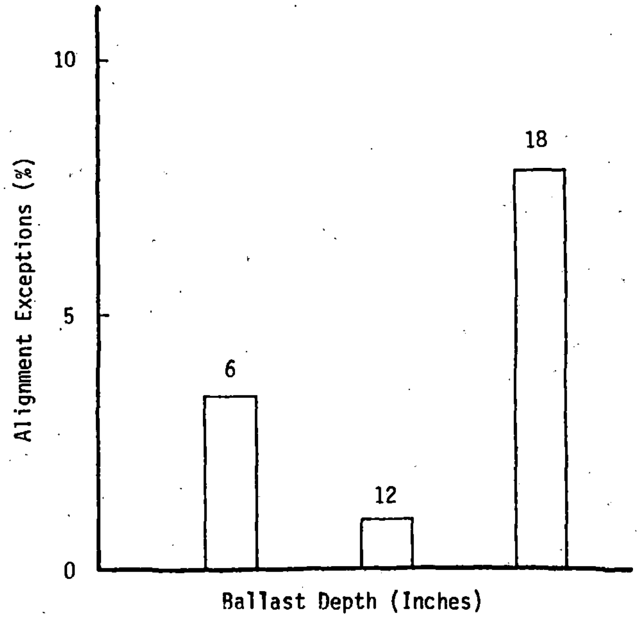


FIGURE 4. BALLAST DEPTH TEST, TRACK GEOMETRY - ALIGNMENT (MEAN 0-425 MGT).

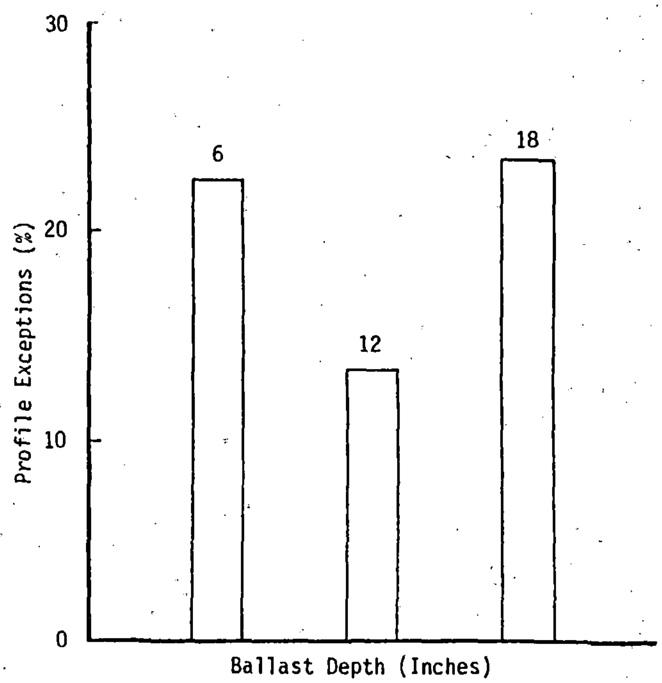


FIGURE 5. BALLAST DEPTH TEST, TRACK GEOMETRY - PROFILE (MEAN 0-425 MGT).

where:

P_s = Contact stress at the subgrade (psi)
P = Design wheel load (lb)
0 = Impact factor (AREA recommends a value of 1.5 for all conditions)
DF = Distribution factor (for timber ties on 19-1/2 inch spacing, AREA recommends a value of 0.4)
FS = Factor of Safety (AREA recommends a value of 2.0)
B = Breadth of tie (inches)
L = Length of tie (inches)
h = Depth of ballast and subballast (inches)

for our example:

P = 32,875 lb
B = 9 inches
L = 102 inches
h = 21 inches

resulting:

P_s = 32.1 psi

The calculated value of 32 psi for P_s is approximately twice the peak value of 17.5 psi but does include the Factor of Safety (FS) value of 2.0. The measurements made at FAST were made on a newly constructed track that was well maintained. Under these conditions, setting the value of FS at 1.0, the resulting P_s becomes 16 psi, more closely approximating the 17.5 psi peak value measured. Taking this process one step further and removing the impact factor from the equation (since rail and wheel surface conditions were excellent at the time of this test) the value for P_s becomes 10.7 psi, which is only slightly higher than the average values measured.

Although conservative, the semi-empirical Talbot/AREA method of calculating subgrade stress fits well with the actual data taken from the track. Unless subgrade conditions are encountered that might require special attention such as organic or expansive soils, the Talbot/AREA method appears adequate for design purposes.

Details of ballast and subgrade instrumentation methods and results are contained in Reference [2].

2.3 <u>OTHER TESTS</u>

During the course of the first ballast experiment, several other tests were performed in the track. These tests included the Ballast Type Test and Stress and Strain investigations.

2.3.1 <u>Ballast Type</u>

The Ballast Type test was conducted in Sections 18 and 20 of the FAST test track. Five types of ballasts were installed in these sections. Two of the materials were sedimentary, (limestone and dolomite) two were igneous, (granite and traprock), and the fifth material was a blast furnace slag.

Analyses were made on the track geometry data and the maintenance man-hour demand for the period of the test up to 425 MGT. This data is given in Table 1. It is seen from the table that the limestone ballast had the greatest number of geometry exceptions for both alignment and profile. None of the other materials performed exceptionally in both categories although the dolomite did do better than average when considering both alignment and profile.

In the maintenance demand category, the limestone section required the most maintenance and the slag ballast the least.

In conjunction with the Ballast Type test, extensive ballast physical state measurements were made at 134 MGT in the limestone and traprock materials only. These tests were performed by the Department of Civil Engineering at the State University of New York at Buffalo [3], and in their report the following observations were reported:

1. Compared to the initial measurements after construction, ballast densities in both material types increased substantially with traffic.

2. The density distributions (See Table 2) along the tie after traffic were very similar to the initial tests, i.e., higher densities under the rail seat than under the center of the tie and uniform density through the crib. However, the magnitude of the differences varied substantially with ballast type. In the limestone section, the differences were very small.

3. In the limestone ballast, tamping caused almost no change in the under-tie rail seat density but in the traprock section, tamping significantly lowered the ballast density in the same area (7.5 pcf).

4. Both crib density and tie center density showed a slight decrease after tamping but were still significantly higher than the after construction densities for both ballast types.

5. Tamping resulted in a significant decrease in the crib density around the rail seat where the tamper feet were inserted for both ballast types.

6. In the traprock ballast, tamping caused a large scatter in densities from one tie to another.

7. After 0.1 MGT of traffic after tamping, the rail seat densities in the limestone apparently decreased while the crib density returned to nearly the pre-tamping levels. In the traprock ballast, little effect was seen in the rail seat density after 0.1 MGT of traffic and the effect on the crib densities was erratic.

8. Differences in degradation of both ballast types was insignificant after the 134 MGT of traffic. However, in the limestone ballast it was observed that the fines remained intermingled with the large ballast particles while in the traprock ballast, the fines migrated downward.

TABLE 1. TRACK GEOMETRY DEVIATIONS.

	Granite	Traprock	Dolomite	Limestone	Slag
0-425 MGT					
Profile	20%	23%	14%	32.5%	17%
Alignment	2.6%	3.3%	4.3%	18.3%	5.4%
Maintenance Man-hours					
$\frac{\text{Mh}}{\text{MGT-Mile}}$	3.75	2.87	3.56	4.88	2.81

* Percent deviation indicates the portion by length of the test zone that fails to meet the geometric standards of FAST Class A. In general, a deviation of 1/4" in a 62 foot chord for both profile and alignment constitutes an exception for FAST Class A.

TABLE 2. IN-SITU BALLAST DENSITIES

Limestone	Under-Tie			Crib		
	Inside Rail	Center	Outside Rail	Inside Rail	Center	Outside Rail
New Constr, Tamped	112.5	98.0	112.9	106.3	104.9	101.8
134.6 MGT	114.8	109.7	114.0	112.6	111.2	113.1
After Tamped	113.7	107.6	114.4	94.3	110.6	98.9
134.7 MGT	112.4	106.4	112.1	108.5	112.3	112.5

Traprock	Under-Tie			Crib		
	Inside Rail	Center	Outside Rail	Inside Rail	Center	Outside Rail
New Constr, Tamped	117.9	104.0	118.7	109.2	107.6	111.2
134.6 MGT	127.7	117.1	126.6	119.2	118.2	117.3
After Tamped	113.7	114.6	125.7	112.5	117.9	119.1
134.7 MGT	114.5	115.3	124.7	107.7	120.1	118.5

Table 3 gives the various indices of the limestone and traprock ballasts. It is seen from the table that the gradations of the two ballasts are significantly different in the larger particle sizes while the content of particles in the smaller sizes is similar. It was not clear at this time whether the relative track stability is influenced by the differences in the gradation between the two materials.

TABLE 3. INDICES OF TRAPROCK & LIMESTONE BALLAST

	Traprock	Limestone
L.A. Abrasion	13.2%	26.3%
British Crushing Value	13.1%	22.2%
D(50)	0.98 in	0.91 in
Uniformity (D80/D20)	1.71	1.47
D(80)	1.33 in	1.15 in
D(20)	0.78 in	0.78 in

2.3.2 Stress and Strain

To measure deformations in the track structure under train loadings, extensive instrumentation was installed in Sections 17, 18 and 20. In addition to subgrade stress cells, inductive strain gages were installed in both the ballast and the subballast to measure vertical strains. These strains were measured both dynamically under the train and statically to determine the permanent deformations. Vertical extensometers were also installed to determine the dynamic and static deformations in the subgrade surface. The extensometers were anchored at a point 10 feet below the subgrade surface. The instrumented section contained both concrete and timber ties. Ballast and subballast depths varied between 15 and 21 inches and included three types of material: granite, limestone and traprock.

The limestone and traprock ballasts were graded in accordance with the AREA grade 4 classification, whereas the granite material was graded at the AREA grade 5 specification. The subballast was a well graded gravelly sand. The subgrade was native material, a silty-to-very silty, fine-to-medium sand, varying in some areas to a silty sand.

Dynamic measurements were obtained in the timber tie segments after 3 MGT of traffic using an abbreviated work train consist. After 75 MGT, dynamic measurements were taken in all instrumented sections using the normal FAST consist. Cumulative deformations were measured from the beginning of the test until 175 MGT.

As a result of the dynamic testing, several consistent trends were observed: [2]

1. The behavior under dynamic load was almost completely elastic (i.e., all stresses and strains were completely recoverable within the measurement sensitivity available). Permanent deformations were only observed in the static testing in the long term.

2. Unloading, either between axles on a truck or between trucks adjacent to couplers, was small.

3. Subgrade stresses and deflections returned to nearly zero under the center of each car.

4. A small degree of tensile strain was observed in the ballast and the subballast under the center of the car.

For the long term static measurements, the following trends were observed:

1. Accumulation of vertical deformation in the ballast continued from the beginning of the test until tamping operations occurred, but at a decreasing rate as MGT increased. In general, 50% of the deformations had occurred by 2 MGT and 90% before 20 MGT of traffic during the test duration of 175 MGT.

2. Tamping operations caused an extensional strain in the ballast under the ties. The resumption of traffic caused a recompression of the ballast rate similar to that described above.

3. The subballast accumulated deformations similar to the ballast but was unaffected by the tamping operation.

4. Subgrade deformations also accumulated at a decreasing rate with MGT but over a much longer time frame than that for the ballast. Generally, 50% of the 175 MGT deformation had occurred by 20 MGT. Tamping operations did not affect the subgrade.

A summary of the deflection data is given in Tables 4 and 5.

For the reader interested in the detailed results of the stress and strain test, a complete report is offered in Reference [2].

TABLE 4. TOTAL DEFLECTION BY BALLAST TYPE

	Limestone	Traprock	Granite
3 MGT	0.057"	0.113"	0.091"
75 MGT	0.127"	0.092"	0.112"

TABLE 5. TOTAL DEFLECTION BY BALLAST DEPTH

	15" Depth	21" Depth
3 MGT	0.091"	0.143"
75 MGT	0.112"	0.166"

2.4 IMPORTANT RESULTS OF THE FIRST BALLAST EXPERIMENT

The major findings of the First Ballast Experiment, as detailed above, are useful assumptions for discussion of the Second Experiment. In summary, they are:

1. Increased ballast shoulder width has little effect on the lateral strength of the track but does increase geometric stability, especially in the vertical profile.

2. Increasing ballast depth beyond that required to distribute the imposed loads to the subgrade may be detrimental to geometric stability.

3. The Talbot/AREA formula for estimating subgrade stresses is satisfactory for track design under ordinary soil conditions.

3.0 SECOND BALLAST EXPERIMENT

The second ballast experiment was initiated in December of 1979. At that time, the FAST test track had accumulated 425 MGT of traffic. In this section, all MGT values will assume 425 MGT as the 0 MGT point. A map depicting the layout of the second ballast experiment is included in Appendix B.

The second experiment was to extend the work started in the first experiment on ballast types with the difference being that different sources of granite and granite-like materials were to be used rather than investigating materials of completely different compositions. In this group of test materials, an investigation of aggregate parameters was to be compared to performance rather than comparing different material types.

The decision to initiate a second ballast experiment was taken as an opportunity to replace the ballast under the concrete ties in Section 17, which had experienced a large degree of geometric instability. As Section 22 was also to be rebuilt at this time (as a direct wood/concrete tie comparison test) this section was also designated as a ballast test zone. Section 3 construction was timber ties at this time. Both the Section 3 and 17 test sections were 5 degree curves and the Section 22 test was tangent track.

Seven materials were included in the second test. The measured properties of these materials are tabulated in Appendix B. Although the materials were all granite-like, a large degree of variance existed in the particle indices (i.e., gradation and shape).

Great effort was made during this rebuild to assure uniform subgrade reaction in the test segments. The consulting firm of Haley and Aldrich, Inc., of Cambridge, Massachusetts was retained to perform testing and design necessary to achieve this goal. For the most part, uniform subgrade conditions were achieved in the test segments but late in the testing, an area of excessive subgrade settlement was located in the center portion of the 5 degree curve in Section 3.

As operations over the newly constructed sections commenced, it became apparent that improvements in the performance of the concrete ties in Section 17 was only partially achieved. Originally, this section contained only one ballast type, a granite material of AREA 5 gradation. During the rebuild, four more materials were installed in this section along with a control segment of the original material. As expected, this original material continued to display geometric instability but one of the new materials exhibited instability as bad if not worse. This new material had a grading coarser than the original but did contain a very large number of flat particles. This event in the testing reinforced the desire to investigate effects of particle shape on ballast performance. The other three materials greatly improve the lateral stability of the concrete ties.

In soil mechanics, shearing resistance of a cohesional soil is defined by Coulomb's equation:

$$S = \sigma \tan \phi$$

where: S = shear strength
σ = normal stress (lb/in^2)
ϕ = angle of internal friction

The source of S is the friction between the individual cohesionless particles, known as interlocking. Recent work at the University of Massachusetts[4] has shown that after cyclic loading similar to rail operations, the ballast assumes residual compressive stresses in the horizontal direction. The residual compressive stress is accompanied by an apparent increase in angle of internal friction, resulting in an increase in shear strength per Coulomb's formula.

This work confirms the value of placing a slow order over a recently surfaced portion of track. However, as the angle of internal friction is soon raised to levels higher than achievable by densification alone, a new question arises: "What additional factors in the ballast govern the level of residual stress?" The experience in the concrete ties in Section 17 suggests that particle shape is a strong influence.

Also included in the second experiment was a limited investigation of geotextile durability in Section 17 and a test in Section 22 of differences in identical ballast under both wood and concrete tie construction.

3.1 BALLAST INDICES VS PERFORMANCE

The correlation of ballast material properties which can be measured by laboratory tests and the in track performance of those materials is of significant interest to engineers selecting ballast for use in their railroads. The second ballast experiment afforded the opportunity to gather performance data on seven ballast materials and determine the relationhship of that performance with the laboratory indices of the ballast.

The current AREA specifications require that the following tests be performed in the laboratory for acceptance of a ballast material:

1. Content of soft and friable pieces by ASTM C235-68

2. Content of material finer than #200 sieve by ASTM C117

3. Content of clay lumps by ASTM C142

4. Los Angeles Abrasion by ASTM C131 or C535

5. Sodium Sulfate Soundness by ASTM C88

6. Density (for slag materials) by ASTM C29

7. Content of flat and elongated particles with an aspect ratio greater than 5:1 (No designated test procedure)

8. Gradation by ASTM C136

The performance parameters used in this analysis were loss of mean particle size (as a measure of ballast particle durability) and track maintenance. Geometry and modulus were used as measures of track stability. The laboratory indices used for comparison were Los Angeles Abrasion, gradation, and measures of flat and elongated particle content.

The first index investigated was a Los Angeles Abrasion test. This test, along with a gradation analysis, was performed on all test ballasts prior to their installation in the track. These ballasts remained in the track for a period of 225 MGT. At the conclusion of the testing, samples were retrieved from directly under the tie at the rail seat, and a gradation analysis was once again performed. Two methods were used to compare the degradation of the ballast particles to the Los Angeles Abrasion test results. The two parameters chosen to represent the degradation were the percent reduction of the D(50) size and the percent increase in particles passing the 3/8" sieve. In both cases, no correlation was found between the in-track degradation and the Los Angeles Abrasion test predictions. The results of the change in D(50) vs the Los Angeles Abrasion test are shown in Figure 6. As can be seen from this graph, no relationship exists between the performance and the prediction. The test using the particles passing the 3/8" sieve did not show any relationship either. To further check that this result was accurate, the D(80) and D(20) sizes were also checked against the Los Angeles Abrasion results. No relationship was found using these parameters. It is concluded that the Los Angeles Abrasion test is not a good predictor of in-track ballast degradation.

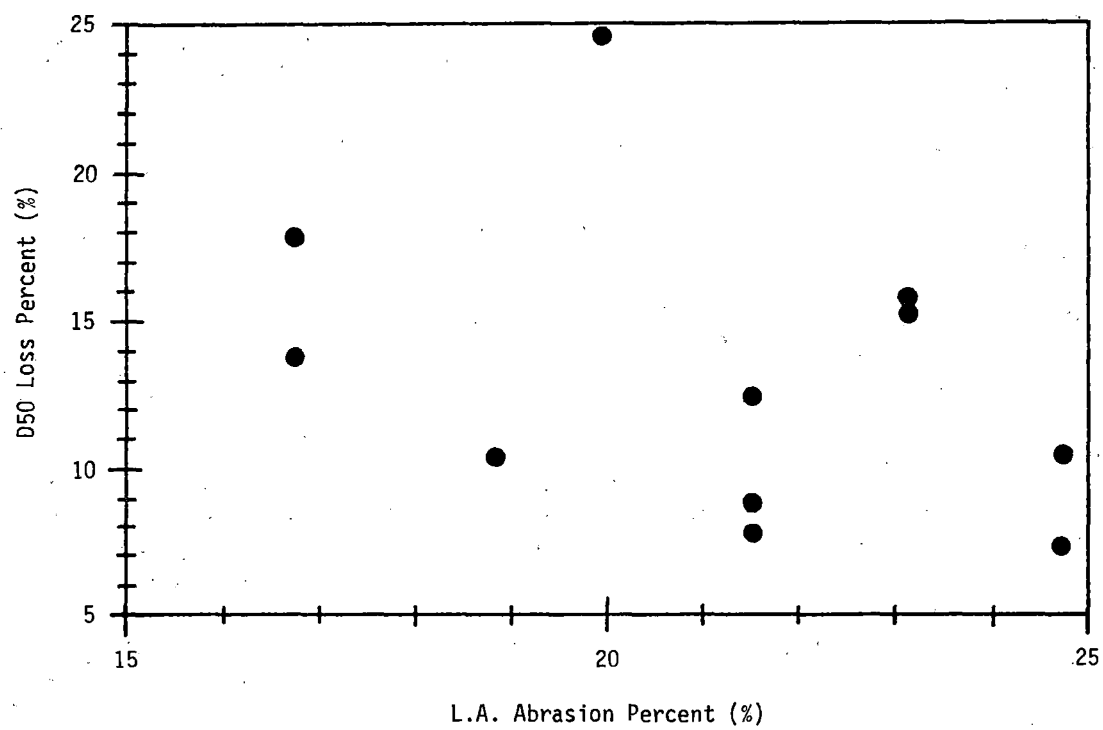


FIGURE 6. L.A. ABRASION VS MEDIAN PARTICLE SIZE.

The analysis of ballast degradation also indicated that the broadness of the ballast gradation increased as the mean particle size was reduced. This is shown in Figure 7 and is significant to the 99% statistical level.

Further in this testing, various properties of the test ballasts were compared with the performance parameters measured during the traffic accumulation portion of the test. The ballast properties chosen for examination were:

1. D(50): the mean particle size

2. UC: a uniformity coefficient based on the D(80) size divided by the D(20) size.*

3. F: the flakiness index based on the British Standard 812 test modified to English system sieve sizes.**

4. E: the elongated index based on the British Standard 812 test modified to English system sieve system.

5. CIGGT: a shape factor index described by the Canadian Institute for Guided Ground Transport.[5] (The ballast specifications in Appendix B employ the CIGGT shape factor index.)

The performance parameters used in this analysis are:

1. Maintenance Manhours for geometry and ballast section maintenance. The data is normalized to manhours per MGT per mile.

2. Track Geometry Degradation Rate: data used for this parameter were growth rate of the standard deviation of crosslevel (for the vertical plane) and alignment (for the horizontal plane).

3. Track Modulus

Problems were expected during this analysis due to the wide scatter of the data for most of the parameters. The measurements used have inherently wide error bands. In spite of these initial reservations, significant results were obtained for some of the parameters from the available data.

----

* D(80)/D(20) was chosen to represent uniformity rather than the traditional D(60)/D(10) used in soil mechanics, since the latter tends to ignore the distribution of the larger particles. This choice was arbitrary.

** The BS 812 Flakiness and Elongation Index tests are described in detail in Appendix B.

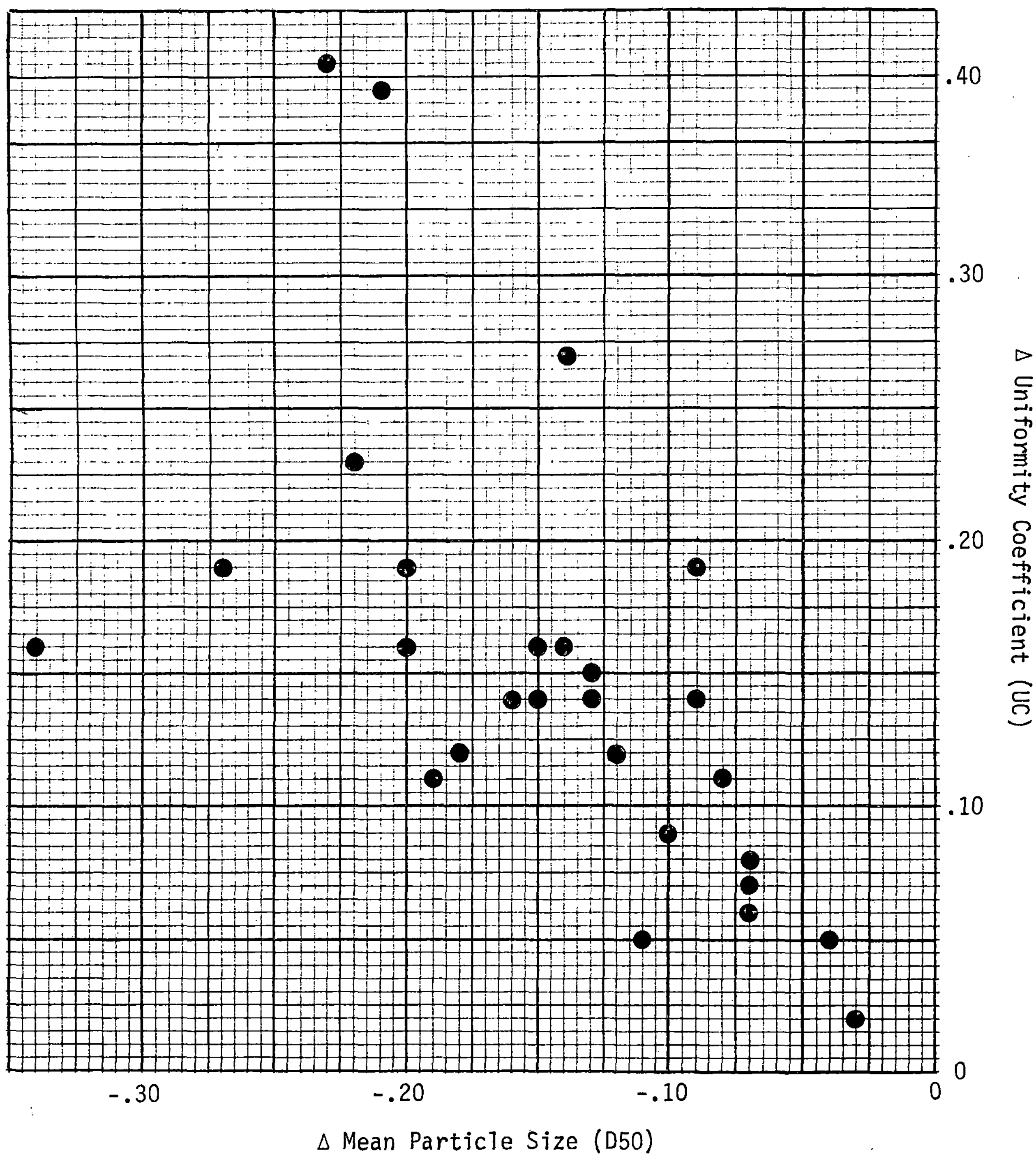


FIGURE 7. CHANGE IN MEAN PARTICLE SIZE VS CHANGE IN UNIFORMITY.

The first set of equations derived involved the performance of the wood tie test sections. Four equations were statistically significant when comparing the Track Modulus with the ballast properties of Elongation (E), Mean Particle Size (D(50)), Flakiness (F) and Uniformity (UC).

$$\text{Modulus (lb/in/in)} = 55.0(E) + 1945.4 \tag{1}$$

$$\text{Modulus (lb/in/in)} = 66.7(E) + 1092.1(D(50)) + 201.2 \tag{2}$$

$$\text{Modulus (lb/in/in)} = 57.9(E) + 944.1\,(D(50)) - 16.2\,(F) + 983.8 \tag{3}$$

$$\text{Modulus (lb/in/in)} = 53.1(E) + 1083.9\,(D(50)) - 14.7\,(F) + 433.1(UC)\ 198.3 \tag{4}$$

Equations (1) and (2) are significant at the 99% level and equations (3) and (4) at the 95% level. In analyzing these equations. The quantitative aspects should be de-emphasized due to the limited sample size of the experiment, but the qualitative implications of the models indicate the relative importance of the ballast properties to the in-track performance. It also should be kept in mind that these are statistical models which do not attempt to explain the mechanisms involved. Subgrade effects were not considered in these equations as the subgrade conditions were assumed to be uniform in the test segments.

In all four equations, the presence of elongated particles (per BS 812) has strong positive effects on the track modulus. Other equations that were derived in this analysis but did not meet the 95% confidence criteria for reporting also showed similar positive effects from the presence of the elongated particles. The range of BS 812 Elongation Index values for the samples tested was from 9% to 40%. The benefit from elongated particles might be explained from a mechanical standpoint by their intrusion into the slip planes formed between ballast particles.

The second most important influence indicated in this model is the mean particle size, D(50). As the overall ballast particle size increases, the track modulus increases. This result has been previously reported in FAST literature and is confirmed in these results.

Of lesser significance to the modulus is the uniformity of the gradation (UC) and the presence of flaky particles (F). Statistically, the significance of these properties in the model are relatively low, but do they exert an influence. Modulus increases as the content of flaky particles decreases and the uniformity of the gradation increases. The range of flakiness index values (BS 812) of the ballasts used in this analysis was 11% to 35%.

It was noted earlier that the four equations derived applied to the performance of timber tie track. The data base for the timber ties was significantly larger than that for the concrete tie track, making the derivation of statistically significant relationships for the concrete tie track very difficult. However, similar performance properties for concrete tie track should not be discounted.

Of importance in these results is that the gradation properties of the ballast are controllable by specification, regardless of ballast source. The shape properties, though controllable to a degree by crushing methods, are mostly properties of the source formation.

A beneficial selection would be a ballast with a relatively high content of elongated particles, a low flakiness index and a large, uniform gradation. Of the current AREA ballast grading specifications, the grade 24 most closely fulfills the gradation requirements.

A second set of statistically significant equations was derived during this analysis. The performance variable in these equations is maintenance manhours required for straightening skewed concrete ties. FAST maintenance policy requires that ties be straightened when they have moved 2 inches from their original position with respect to the rail at either end. Since skewing is not allowed to progress very far, the maintenance effort required to straighten is a good measure of the occurrence of the skewing. The variable Mh is the maintenance effort normalized to manhours per mile per MGT.

Both of the following equations were significant at the 95% level:

$$Mh = 4.88(CIGGT) - 9.89 \tag{5}$$

$$Mh = 6.29(CIGGT) + 2.86(UC) - 17.7 \tag{6}$$

In both of these equations, the shape factor index, as described by the Canadian Institute for Guided Ground Transportation[5], is the most significant contributor to the maintenance demand. The ballasts in this test had CIGGT shape factor indices ranging from 2.04 to 2.44. The referenced report recommends that ballasts with a CIGGT value less than 2.21 gave generally satisfactory performance in concrete tie track except when very small particle sizes were involved such as AREA grade 5.

The second term appearing in equation (6) is the gradation uniformity coefficient (UC) in the same form as described earlier. In this case however, as the uniformity of the gradation increased, the maintenance demand of the track increased. In equation (6) it should be noted that the (UC) term did not approach the significance of the CIGGT term ($F_{(CIGGT)} = 44.4$, $F_{(UC)} = 8.41$).

These results emphasize the importance of controlling the gradation and shape of railway ballasts. Proposed ballast testing at FAST will more closely examine the effects of gradation on the track strength characteristics, and should provide more quantitative rather than qualitative guidelines.

3.2 OTHER TESTS

3.2.1 Wood vs Concrete Ties

As part of the rebuild effort for the second experiment, Section 22 of the FAST Test Track was reconstructed for the purpose of making a direct comparison of the performance of concrete ties as opposed to wood ties. As part of this test, Section 22 was designated as a ballast test zone. The construction in Section 22 consisted of two zones of 300 ties each. The first zone was constructed with concrete ties meeting AMTRAK's Northeast Corridor specification with elastic rail clips. The second zone was constructed using hardwood ties and cut spikes. Under both of the zones, a traprock ballast of the type used on the Northeast Corridor was used.

Within this test, several factors relating to ballast performance were measured.

The results of the Track Settlement measurements are shown in Figure 8. The settlement rates were very similar for both types of construction. The high settlement values for 50 MGT were traced to an error in the survey benchmark. Like other measurements of Track Settlement made at various times in the FAST program, approximately half of the total settlement during the 93 MGT period of measurement occurred during the first 2 MGT of traffic.

Track Modulus measurements were made through 58 MGT of the test. The results are shown Figure 9. The extreme modulus readings between 2 and 5 MGT were due to a frozen ballast condition and should be disregarded. Of significance is that the concrete tie track showed consistently higher modulus values (7800 lb/in/in average) than its wood tie counterpart (3700 lb/in/in).

Lateral Strength measurements were made at the 93 MGT level of the test, before and after an out-of-face surfacing effort. A fixture was used for these measurements which allowed a single tie to be pulled horizontally free of the lateral restraint of the rail but still bearing the weight of the rail. A load/deflection plot of the results is given in Figure 10. In the undisturbed condition (before tamping), the concrete tie section shows considerably higher values for lateral strength than the wood tie section. After tamping, the difference between the two types of construction is considerably less than before the surfacing. Although the concrete ties still showed somewhat higher lateral strength, the measurement illustrates the effect of tamping on the lateral strength of both types of construction.

It should be noted that for this measure of Lateral Track Strength, a single tie was measured on each trial. When tie spacing is considered (24" for concrete ties and 19 1/2" for wood ties), the difference in the lateral strength per foot of track becomes less than the lateral strength values for a single tie, although the concrete tie segment is still somewhat stronger. The actual differences under dynamic train load are unknown.

In Section 22, during this test, and at other locations in the FAST Test Track, sieve analyses were performed on those ballasts that were located under both wood and concrete ties. Table 6 gives the results of the sieve analysis for the traprock in Section 22, and Figures 11, 12, and 13 give the results of the sieve analyses for three other types of ballast. Except for the Granite I material (Figure 11) little or no difference in the ballast particle degradation is seen between the wood and concrete tie construction when used with hard ballast material.

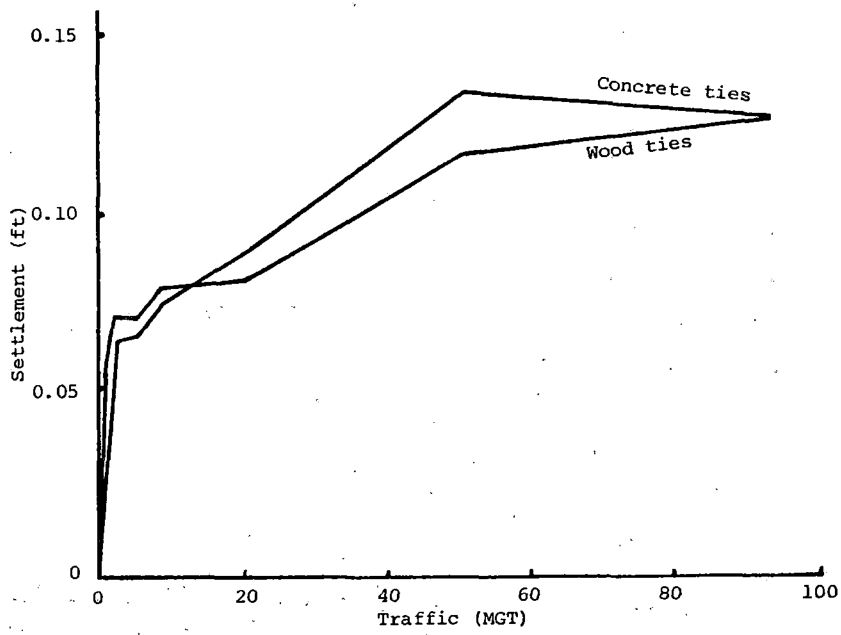


FIGURE 8. SECTION 22, TOP OF RAIL SETTLEMENT VS TRAFFIC.

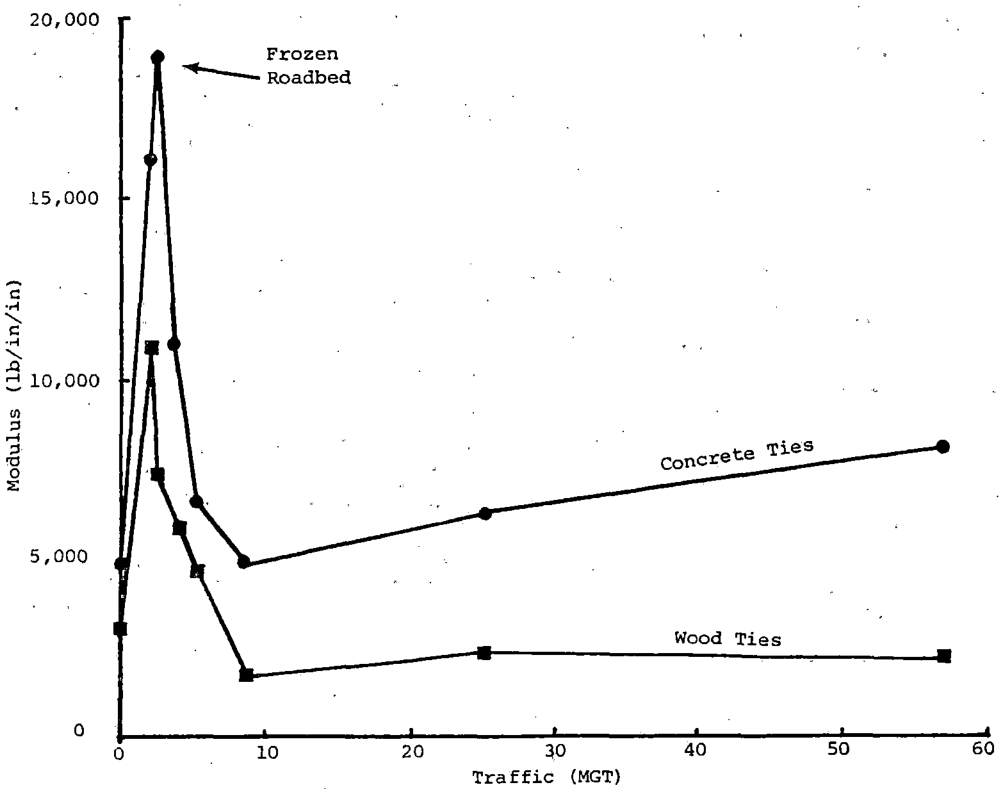


FIGURE 9. SECTION 22, VERTICAL TRACK MODULUS.

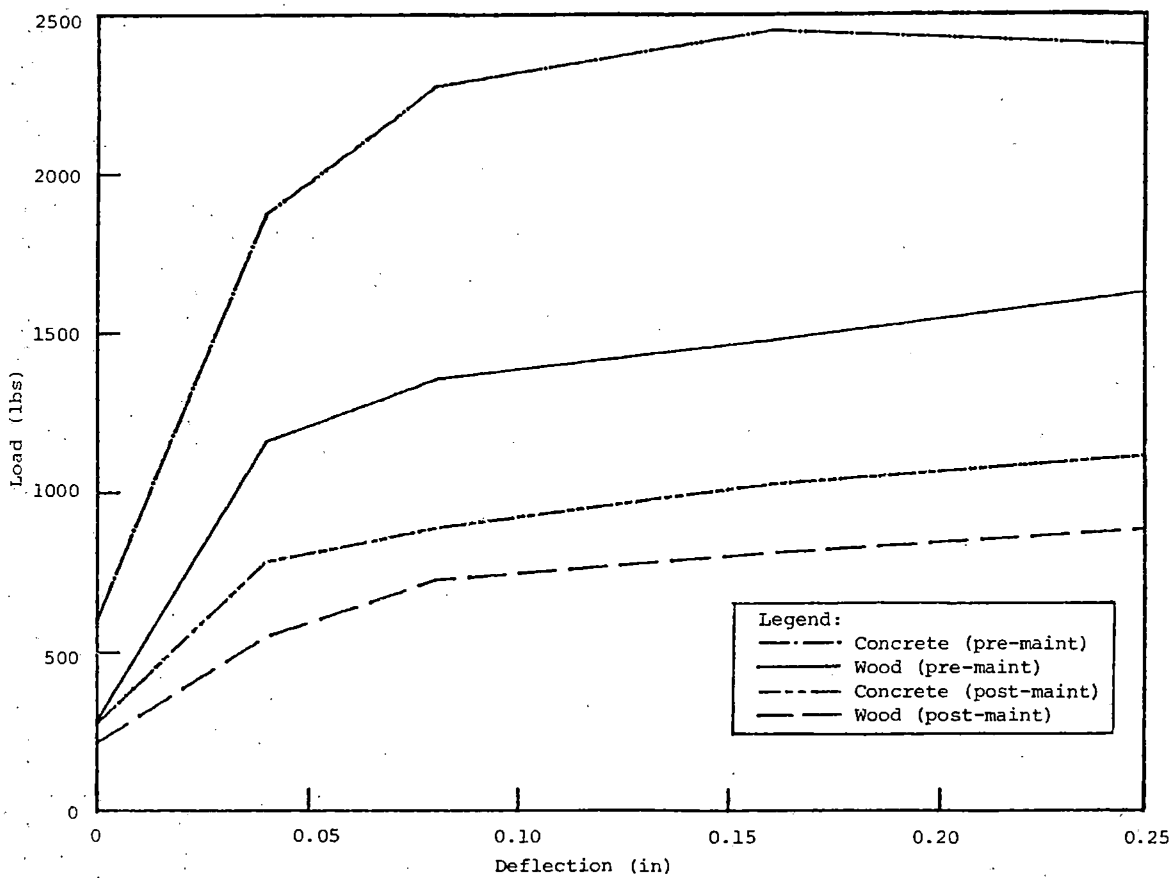


FIGURE 10. SECTION 22, LATERAL TIE RESISTANCE, (AFTER 90 MGT TRAFFIC), PRE - AND POST-MAINTENANCE.

TABLE 6. SECTION 22 BALLAST GRADATION.

Sieve Size	0 MGT	93 MGT Wood	93 MGT Concrete	225 MGT Wood	225 MGT Concrete
2½	100	100	100	100	100
2	97	98	97	99	98
1½	49	60	55	67	55
1	5	11	11	18	11
3/4	1.3	3	5	5	2
1/2	0.4	1.2	1.9	1.9	0.5
3/8	0.3	0.7	1.1	1.5	0.5

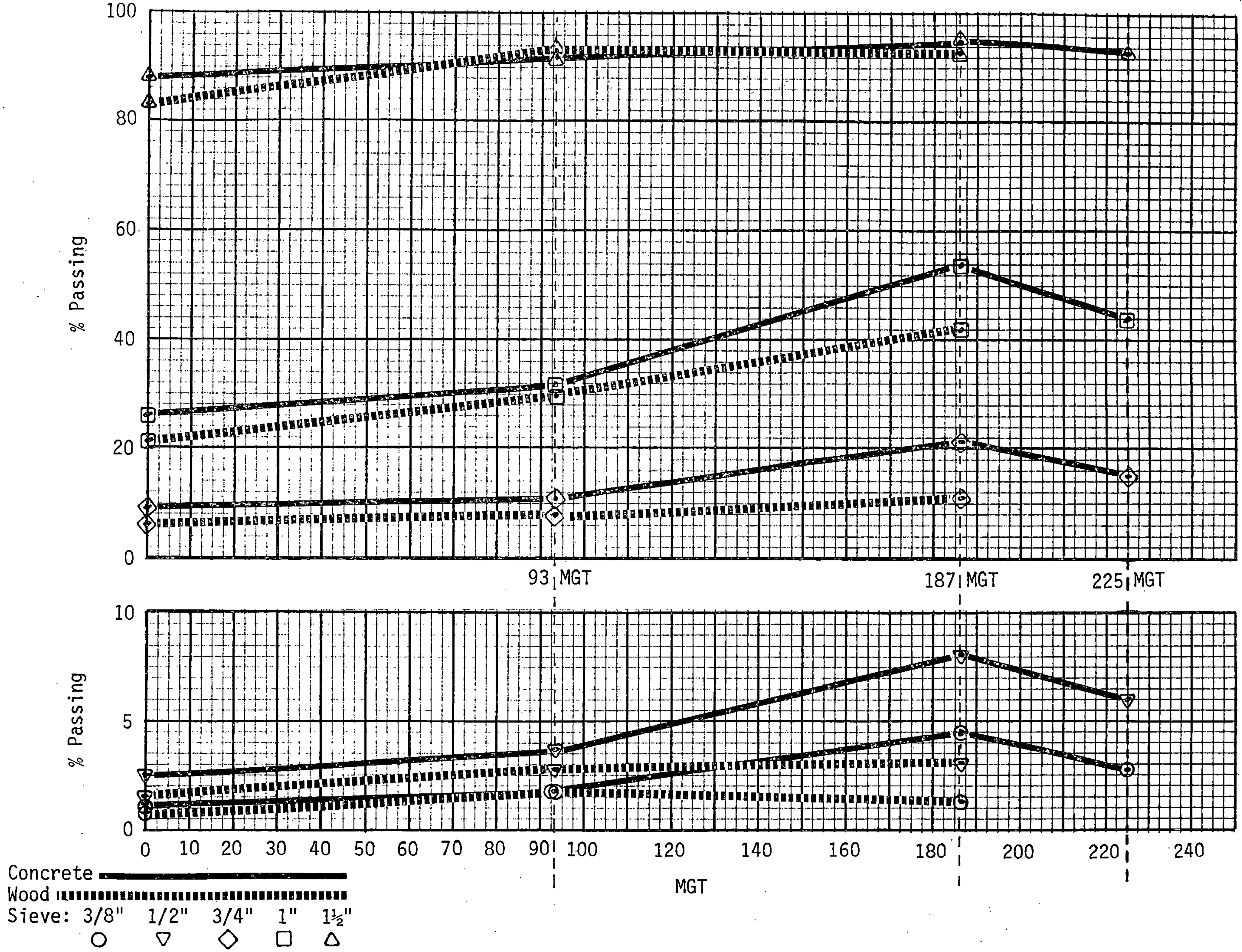


FIGURE 11. CHANGE IN GRANITE I GRADATION.

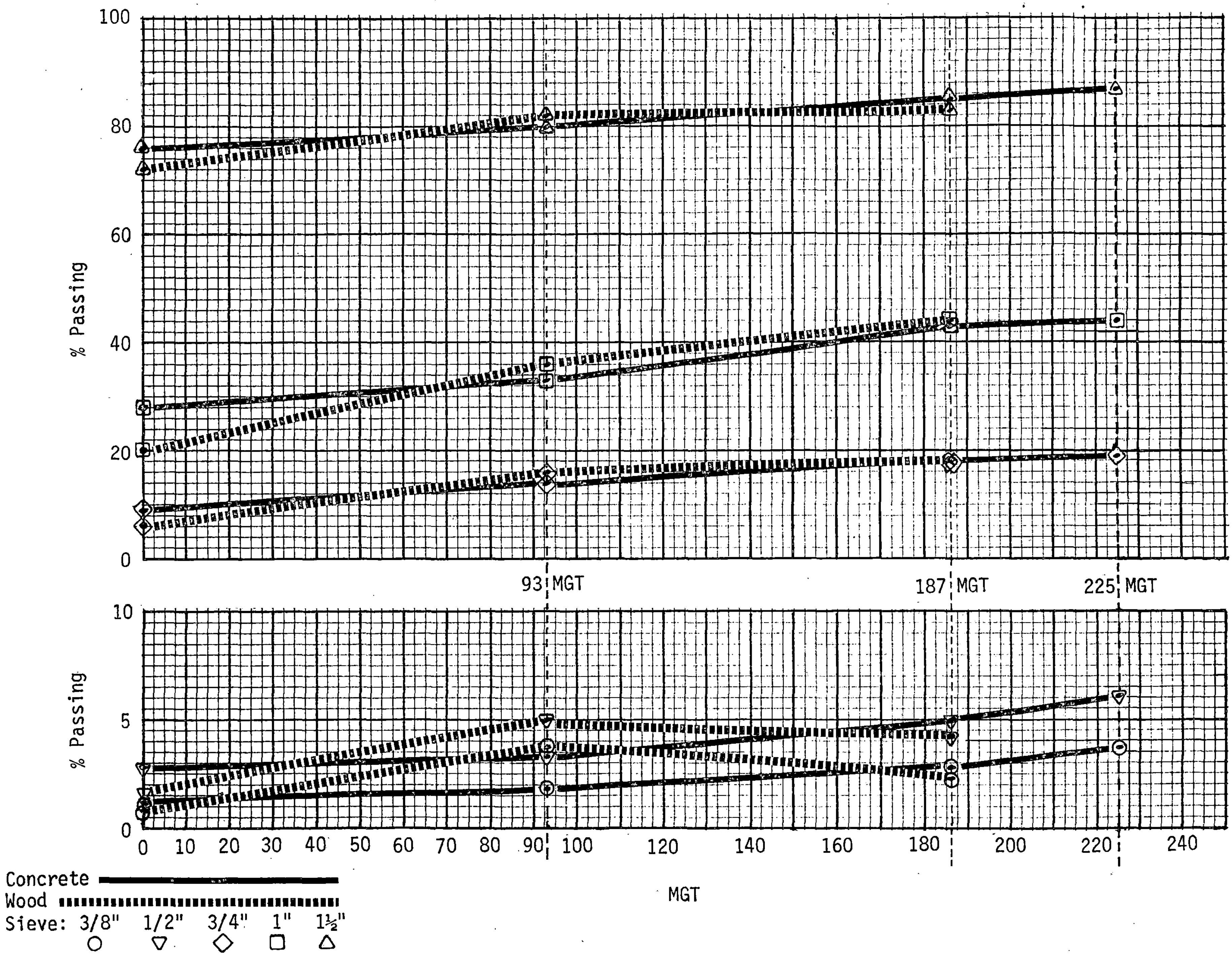


FIGURE 12. CHANGE IN GRANITE II GRADATION.

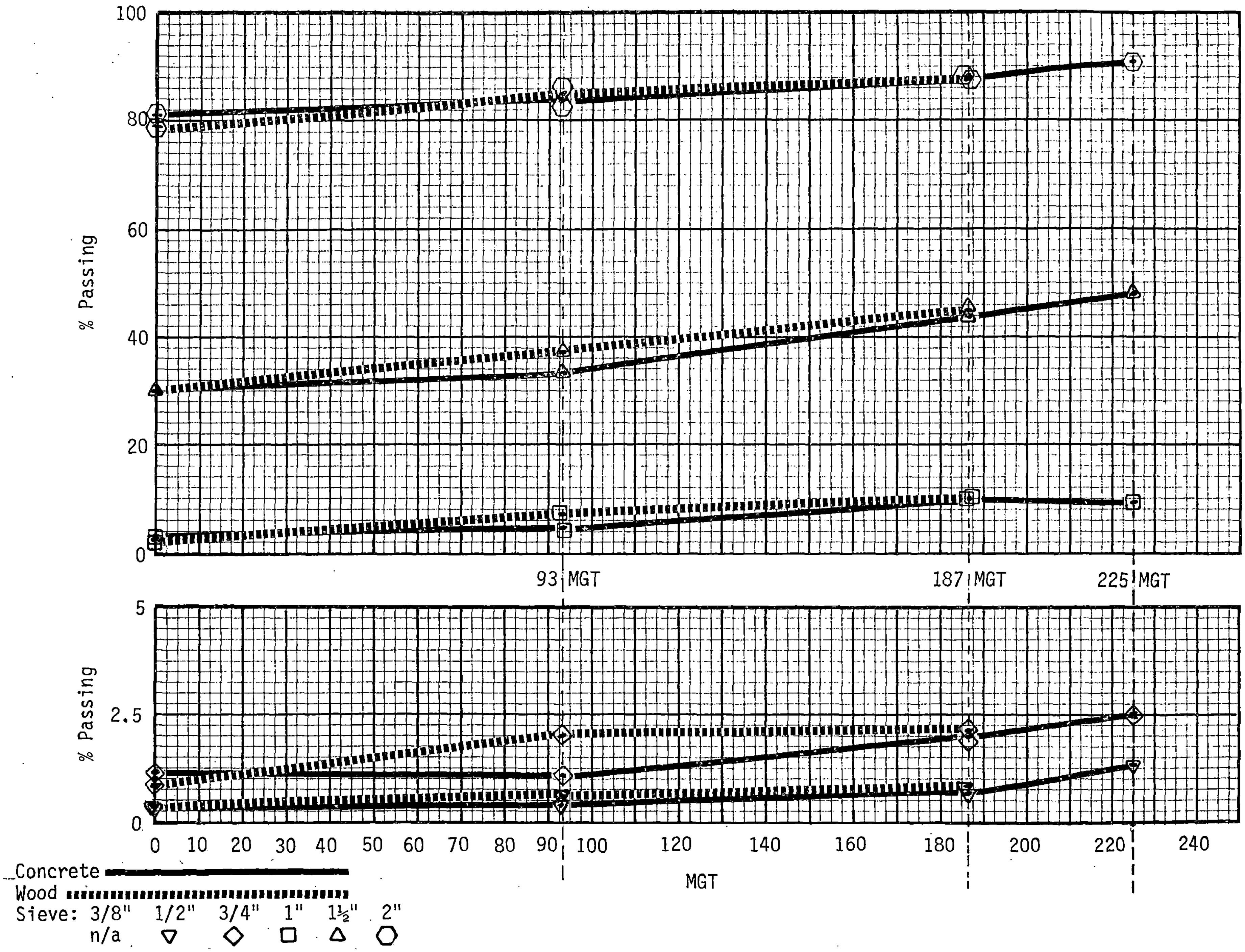


FIGURE 13. CHANGE IN GRANITE III GRADATION.

3.2.2 Geotextiles

In the 5 degree curve of Section 17, six zones of geotextiles were installed. The objective of this test was to determine the service life of the geotextiles in railroad application. Three different brands of geotextile in two weights each were installed in the test. These were:

Type I - 6 oz/sq yd, non-woven needle-punched continuous filament polyester.

Type II - same as Type 1 except 4.5 oz/sq yd

Type III - 6 oz/sq yd, non-woven continuous filament polypropylene

Type IV - same as Type III except 4 oz/sq yd

Type V - 8 oz/sq yd, non-woven needle punched staple filament polypropylene

Type VI - same as Type except 5.3 oz/sq yd

Additional properties of the geotextiles in the test are given in Table 7.

TABLE 7. PUBLISHED INDICES ON TEST GEOTEXTILES.

Type	I	II	III	IV	V	IV
Tensile Strength ASTM D-1682	160	115	135	207	265	135
Tensile Elongation ASTM D-1682	80	88	63	62	75	78
Toughness Index ASTM D-1682	12800	9700	13041	8370	19800	10000
Abrasion Resistance C/E CW02215	120	40	---	---	200	114
Puncture Resistance C/E CW02215	95	55	75	50	150	100
Tear Resistance ASTM D-2263	93	62	103	74	85	70

ASTM: American Society for Testing and Materials

C/E: U.S. Army Corps of Engineers

Two inspections were made of the 6 test zones. The first inspection was held at 86 MGT and the final inspection was made at 191 MGT. At each of these inspections, wear patterns unique to each brand of fabric were evident, varying in degree by weight of the fabric, the lighter fabrics showing greater degradation.

The Type I and II fabrics showed the greatest development of penetrations in both size and numbers. The development of the penetrations was the result of horizontal migration of the filaments in the fabric, leaving thin areas in the fabric surface. At the 86 MGT inspection, some of the holes were up to 1/2 inch in diameter and grew to approximately 1 inch in diameter by the 191 MGT inspection.

At the 86 MGT inspection, the Type III and IV geotextiles also had penetrations, although these were much smaller, being approximately 1/8 inch in diameter. These penetrations seemed to be associated with ballast particles that had been embedded in the subgrade during the previous tests. By the inspection at 191 MGT, the holes had grown in size and number.

The Type V and VI geotextiles showed the greatest resistance to penetration. No holes were found at the 86 MGT inspection. By the time of the final inspection, a few small holes had appeared.

Samples of the geotextiles were removed from the track at the 191 MGT inspection. Photographs of each of the brands of fabric are shown in Figures 14, 15 and 16.

At some time after the installation of this test, some of the manufacturers of geotextiles increased the recommended weights of fabrics for railroad installation to weights much greater than those installed in this test. The results of this test indicate that the higher weights are justified.

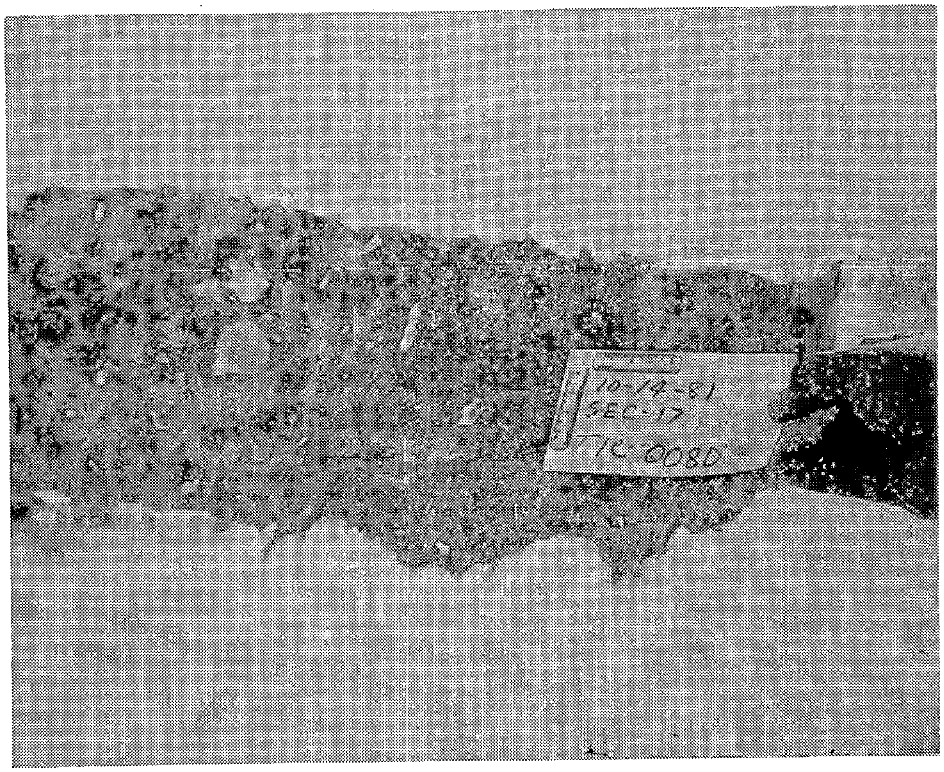


FIGURE 14. SAMPLE, TYPE I GEOTEXTILE AT 191 MGT.

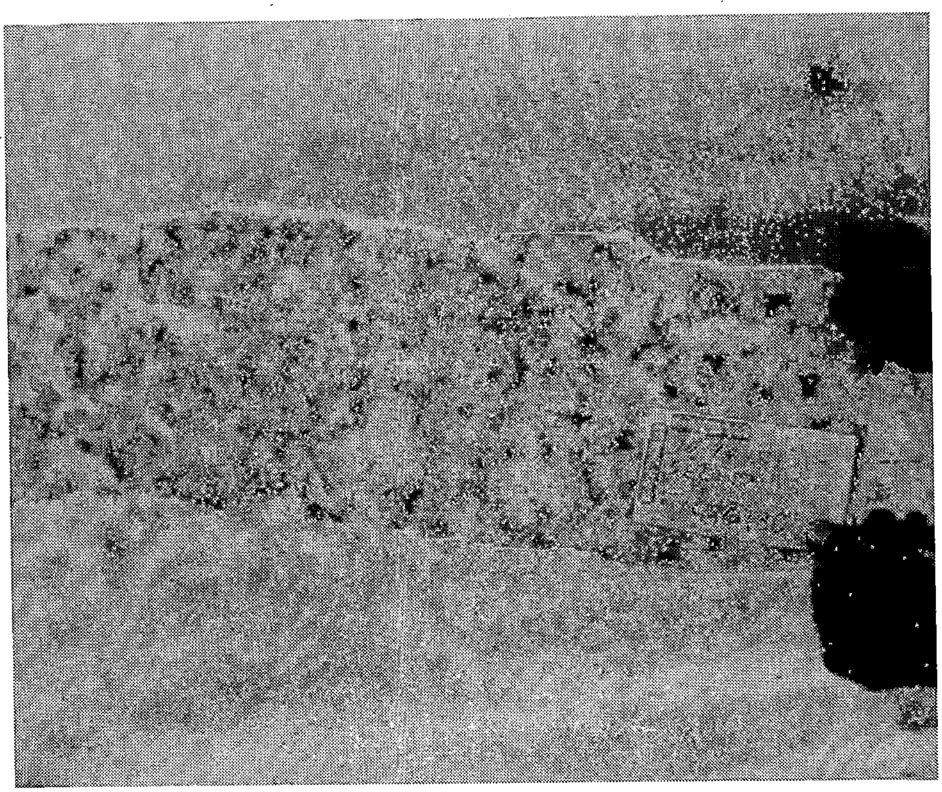


FIGURE 15. SAMPLE, TYPE III GEOTEXTILE AT 191 MGT.

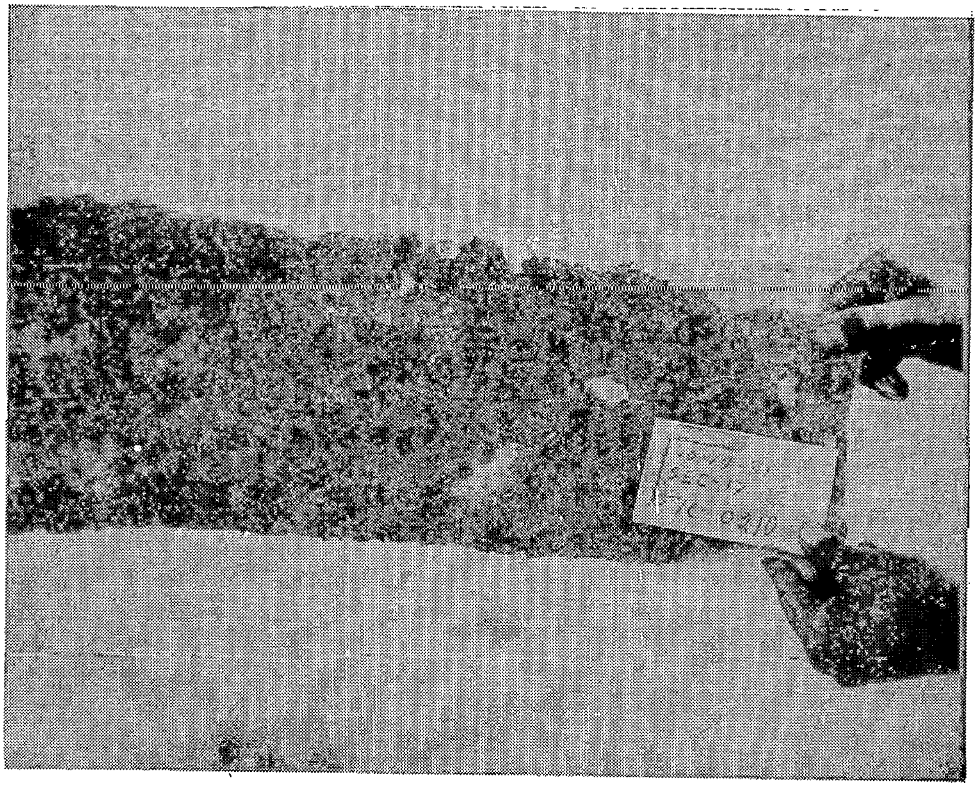


FIGURE 16. SAMPLE, TYPE VI GEOTEXTILE AT 191 MGT.

4.0 IMPORTANT RESULTS OF THE SECOND BALLAST EXPERIMENT

The three major points may be concluded from the second experiment:

1. Ballast gradation and shape factors have the following effects on track modulus (within the limits of values for the ballasts tested):

   - Elongated particles increase modulus.
   - Larger particles increase modulus.
   - Uniform gradations increase modulus.
   - Flaky particles decrease modulus.

2. No significant difference in ballast particle degradation rates for the granite and granite-like materials were found between wood and concrete tie track construction.

3. Geotextiles in weights of 8 oz/sq yd and below have limited service life in railroad track application.

REFERENCES

1. Bosserman, B., et al, Ballast Shoulder Width Experiment, FAST/TTC/TN-81-03, Transportation Test Center, Pueblo, Colorado, 1981.

2. Bosserman, B., et al, Ballast Experiments Intermediate (175 MGT) Substructure Stress and Strain Status Report. FAST/TTC/TM-81-03, Transportation Test Center, Pueblo, Colorado, 1982.

3. Johnson, J. I. and Yoo, T. S., Followup FAST In-Situ Ballast Density Measurements and Gradation Tests, State University of New York at Buffalo, February 1978.

4. Norman, G. M., Ballast Box Experiments for Evaluating Field Performance. University of Massachusetts, Department of Civil Engineering, March 1982.

5. Raymond, G. P., et al, Ballast Selection and Grading: A Summary Report, CIGGT Report 79-4, April 1979.

APPENDIX A

FIRST BALLAST EXPERIMENT

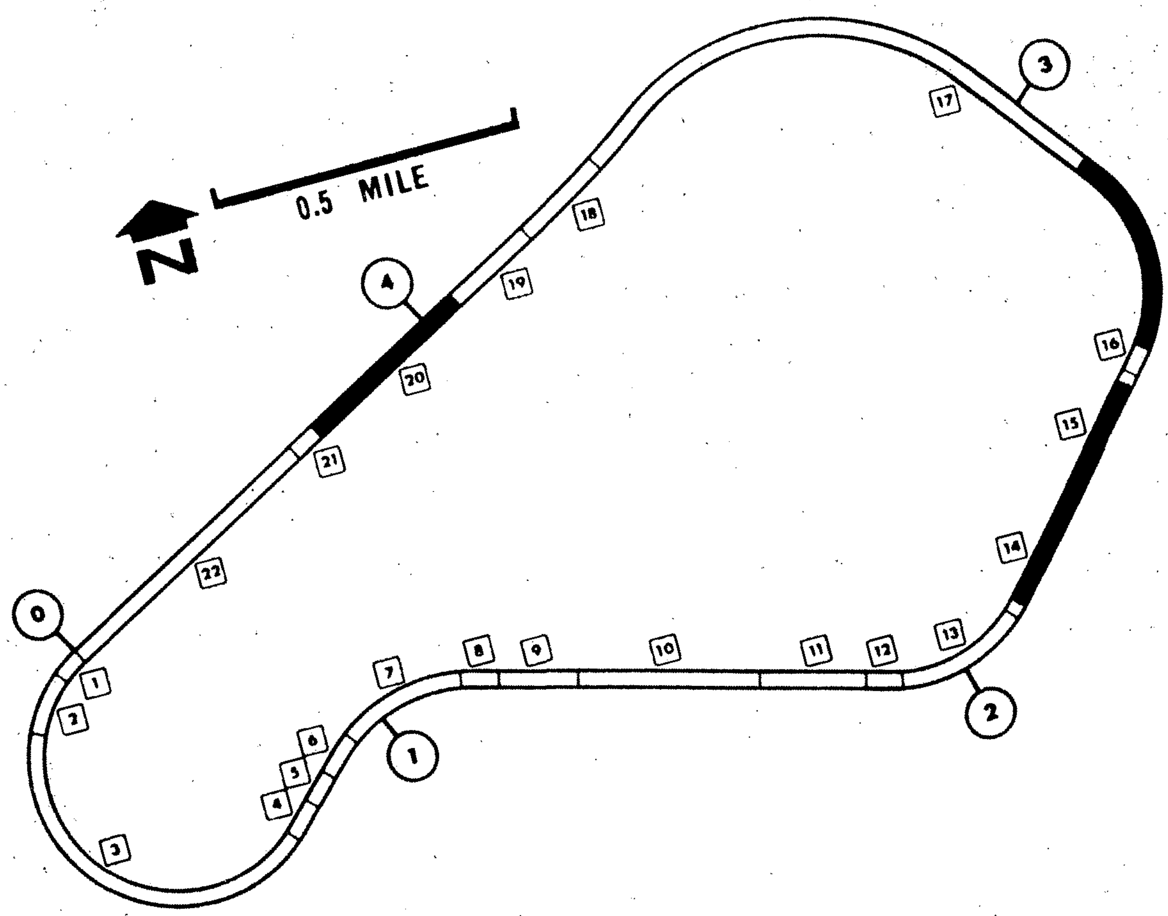
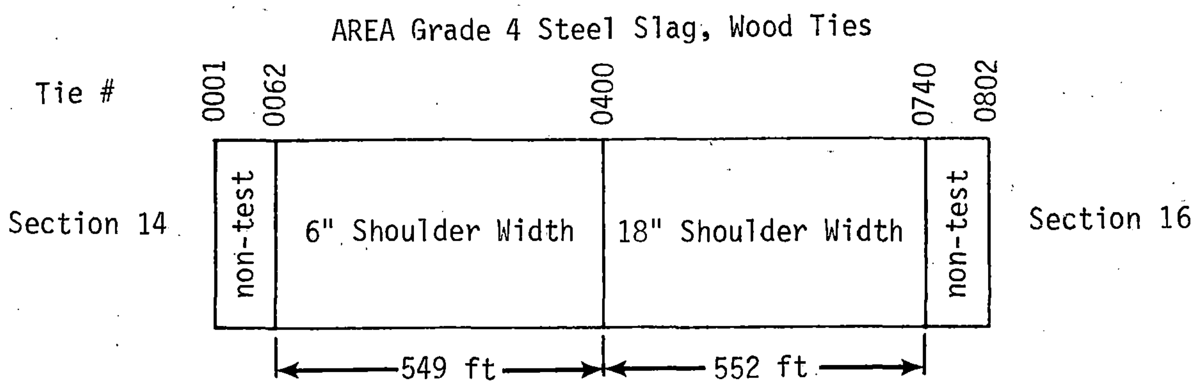


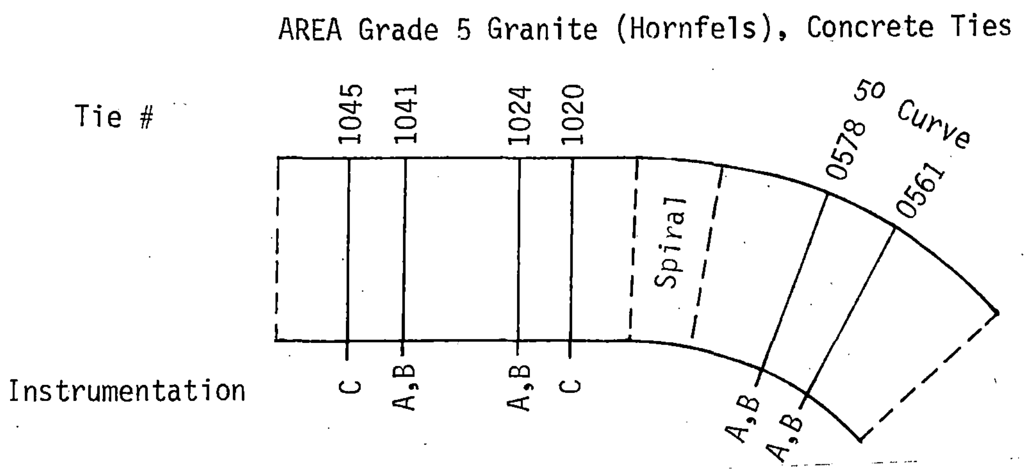
FIGURE A-1. FAST LOOP, SHOWING BALLAST I TEST SEGMENTS.

Test Configuration - First Ballast Experiment

Section 15 Ballast Shoulder Width Test



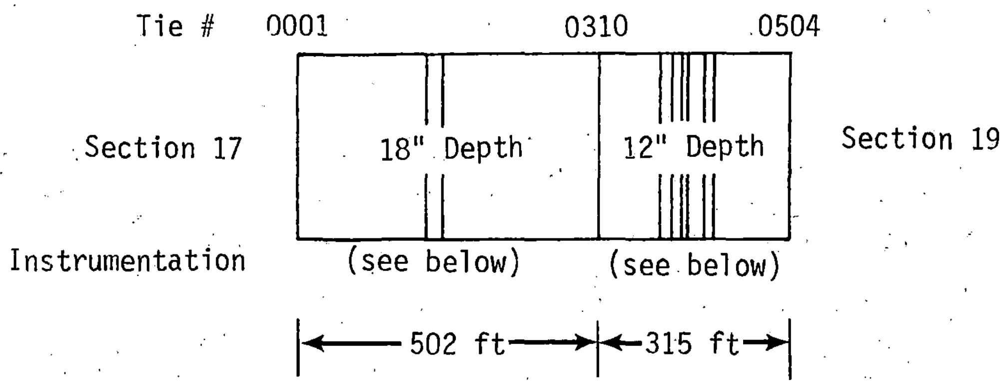
Section 17 Instrumented Section



Instrumentation A - Ballast Strain Induction Coils
B - Subgrade Deflection Extensometer
C - Subgrade Surface Stress Cells

Section 18 Ballast Type Test
Ballast Depth Test
Instrumented Section

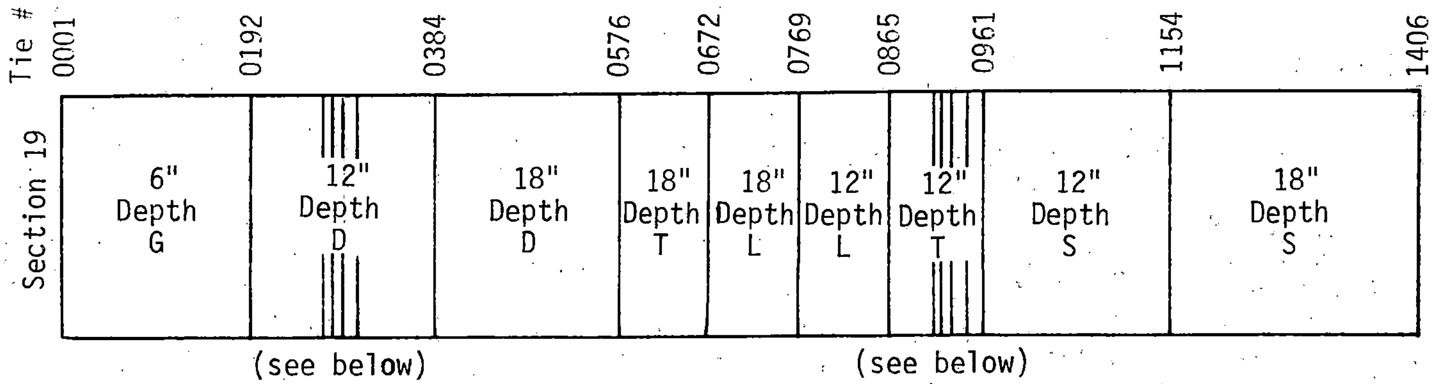
AREA Grade 5 Granite (Hornfels), Wood Ties



Instrumented Ties	Measurement
139	A,B
147	A,B
375	A
383	C
391	A,B
399	A,B
417	C
425	A

Instrumentation
A - Ballast Strain Induction Coils
B - Subgrade Deflection Extensometer
C - Subgraded Surface Stress Cells

Section 20 Ballast Type Test
Ballast Depth Test
Instrumented Section



Ballast Types

G - AREA Grade 5 Granite (Hornfels)
L - AREA Grade 4 Limestone
T - AREA Grade 3-4* Traprock
D - AREA Grade 4 Dolomite
S - AREA Grade 4 Steel Slag

* Fall between limits

Instrumented Ties	Measurement
269	A
277	A,B
285	A,B
303	A
901	A
909	A,B
917	A,B
935	A

Instrumentation

A - Ballast Strain Induction Coils
B - Subgrade Deflection Extensometer
C - Subgrade Surface Stress Cells

Test Ballasts - Geologic Description*

<u>Test Name</u>

Granite - Hornblend - Biotite Hornblend:
Nonfoliated rock composed of minerals lacking preferred orientation and containing rock quartz and feldspar set in a fine to medium grained granoblast matrix of quartz, feldspar, biotite and amphibole.

Limestone - Volomitic Limestone:
Very light gray to light gray. Powdery white crusher dust coating. Fine grained crystalline; smooth fracture; hard, dense, brittle. Sharp angular prismatic to pyramidal. Volomite, some chalcopyrite, many fragments of crinoid, stem and shell fragments, all crystal. Fresh, hard, brittle and dense except is porous with cavities lined with dolomite crystals. Some green staining, probably due to copper carbonate. Weak effervescence.

Dolomite - Dolomitic Limestone:
Light gray to light brownish-gray. Some pieces coated with fine crusher dust. Fine grained to aphanitic, smooth to irregular fractures. Sharp, angular prismatic to pyramidal. Calcite - moderate to vigorous reaction with 50% HCL. Igillite, dolomitic crystals. Traces - mold fragments. A few weathered pieces, mostly all fresh; based on effervescence - probably 10% dolomite, Calcite: 99%, heavy minerals: 1%.

Traprock - Basalt:
Olive gray to olive, finely derided clay caoling, due probably to weathering of chlorite, which gives the light gray color. Medium grained crystalline, smooth fracture. Sharp angular, cubical to prismatic - Plagioclose: 60%, mafics: 39%, quartz: 1%. Light crystal bond; a few pieces show iron stain from weathering, but most are fresh.

Slag - Blast Furnace Slag:
Brownish gray. Lime coating on several pieces. Amorphous to glassy. Sharp angular, cubical, equi-dimensional. Vesiculous, weak, effervescence in 5% HCL, lightweight.

----

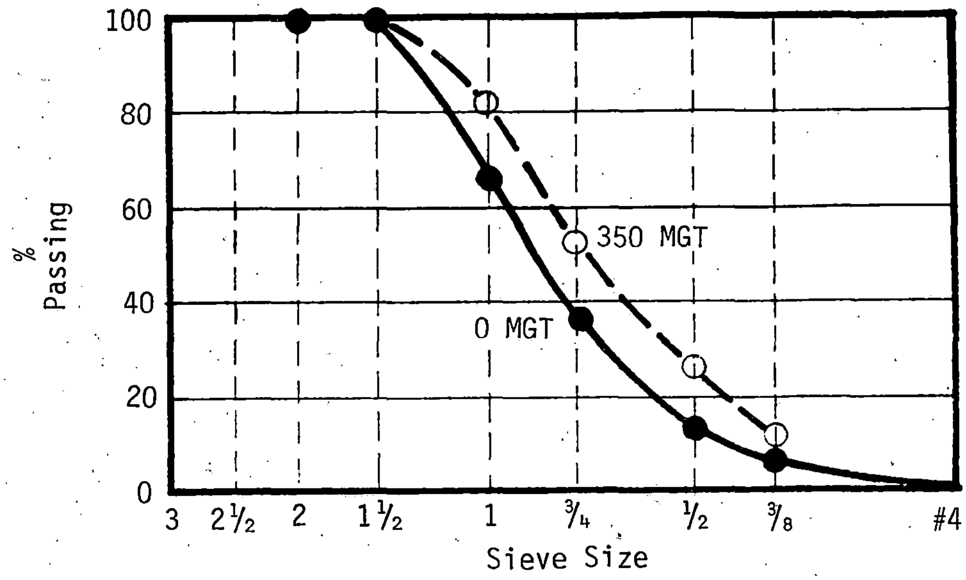
*Prepared by Department of Geologic Sciences, University of Southern Colorado, Pueblo, Colorado.

Laboratory Index Tests

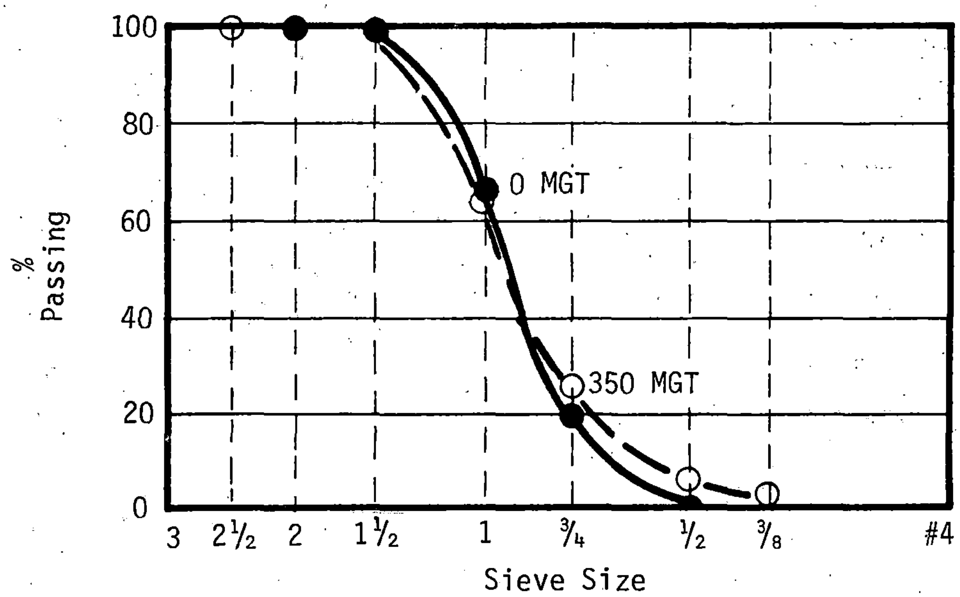
		Granite	Limestone	Dolomite	Traprock	Slag
Particle Index	ASTM D-3398	14.2	12.2	15.4	16.4	10.5
Los Angeles Abrasion	ASTM C-131	18.8%	25.7%	26.3%	13.2%	28.8%
Los Angeles Abrasion	ASTM C-535	10%	27%	28%	16%	33%
Soundness (Magnesium)	ASTM C-88	.77%	11.9%	6.3%	.55%	1.6%
Soundness (Sodium)	ASTM C-88	1.3%	8.4%	9.1%	.2%	.1%
Bulk Specific Gravity	ASTM C-127	2.67	2.65	2.71	2.94	2.54
Absorption	ASTM C-127	.4%	1.65%	1.95%	.2%	1.60%
Flakiness Index*	BS 812	20.8	9.4	10.8	22.7	5.9
British Crushing Value	BS 812	18.4	19.3	22.2	13.1	29.2

*See Appendix B

Granite



Limestone



Dolomite

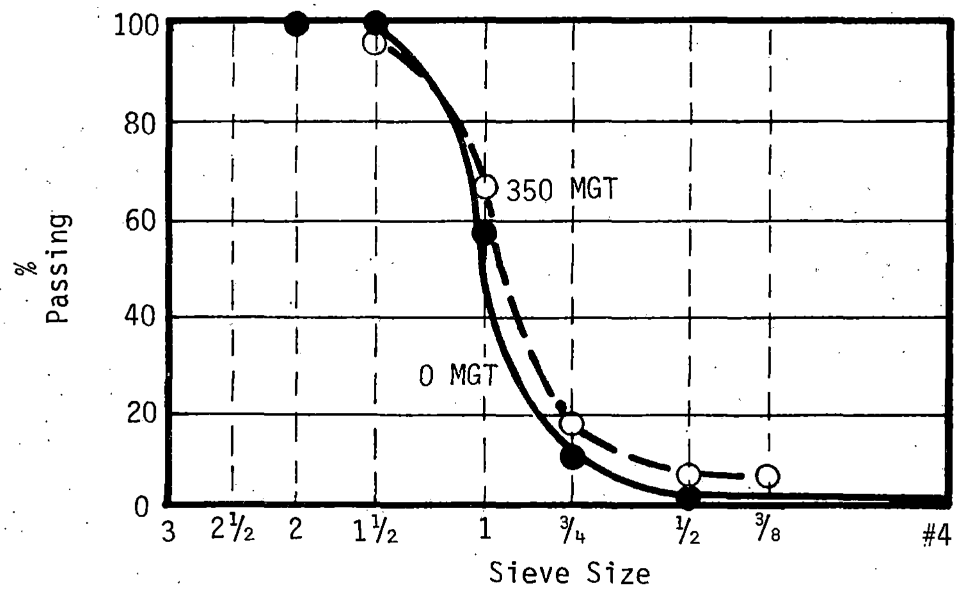
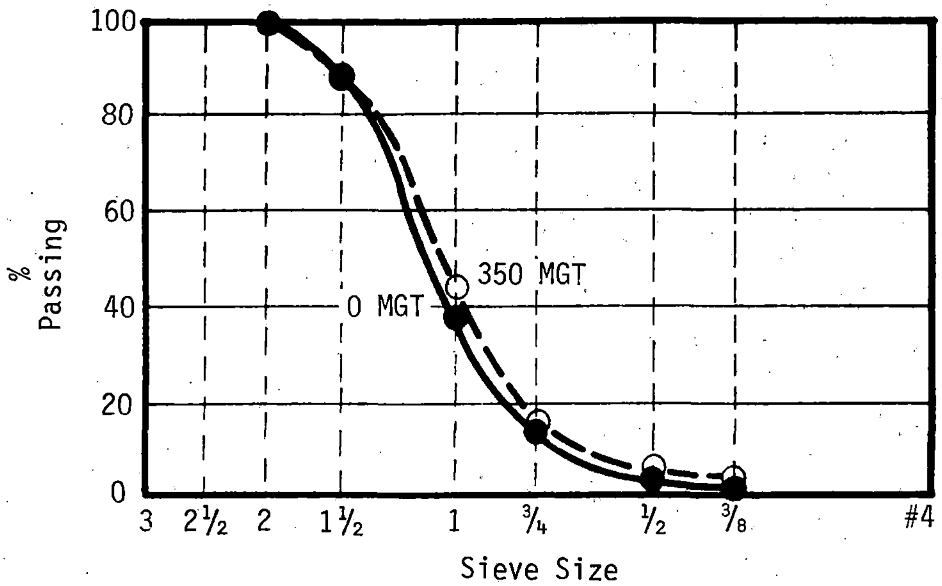


FIGURE A-2. SIEVE TEST RESULTS AT 0 and 350 MGT.

Traprock



Slag

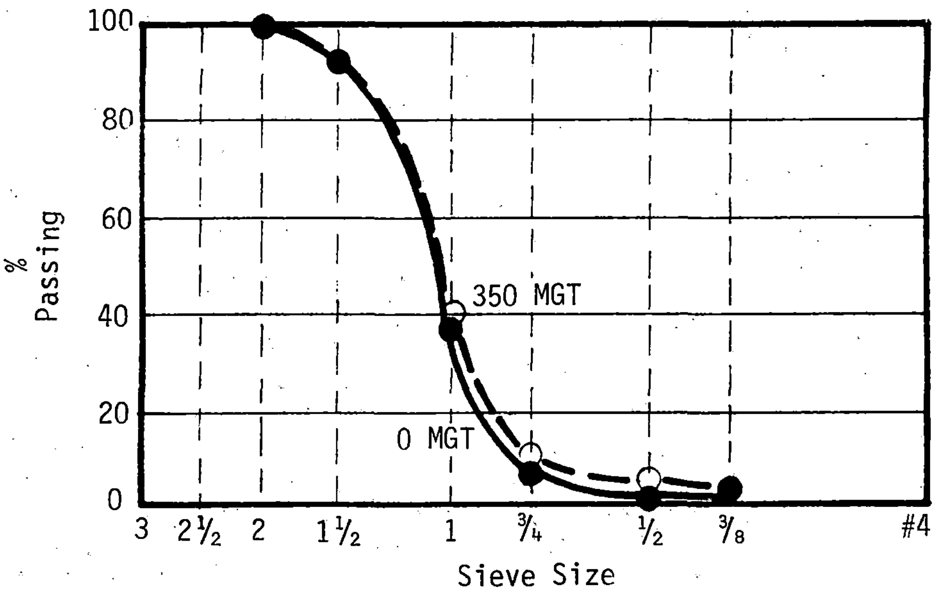


FIGURE A-2. (CONTINUED).

APPENDIX B

SECOND BALLAST EXPERIMENT

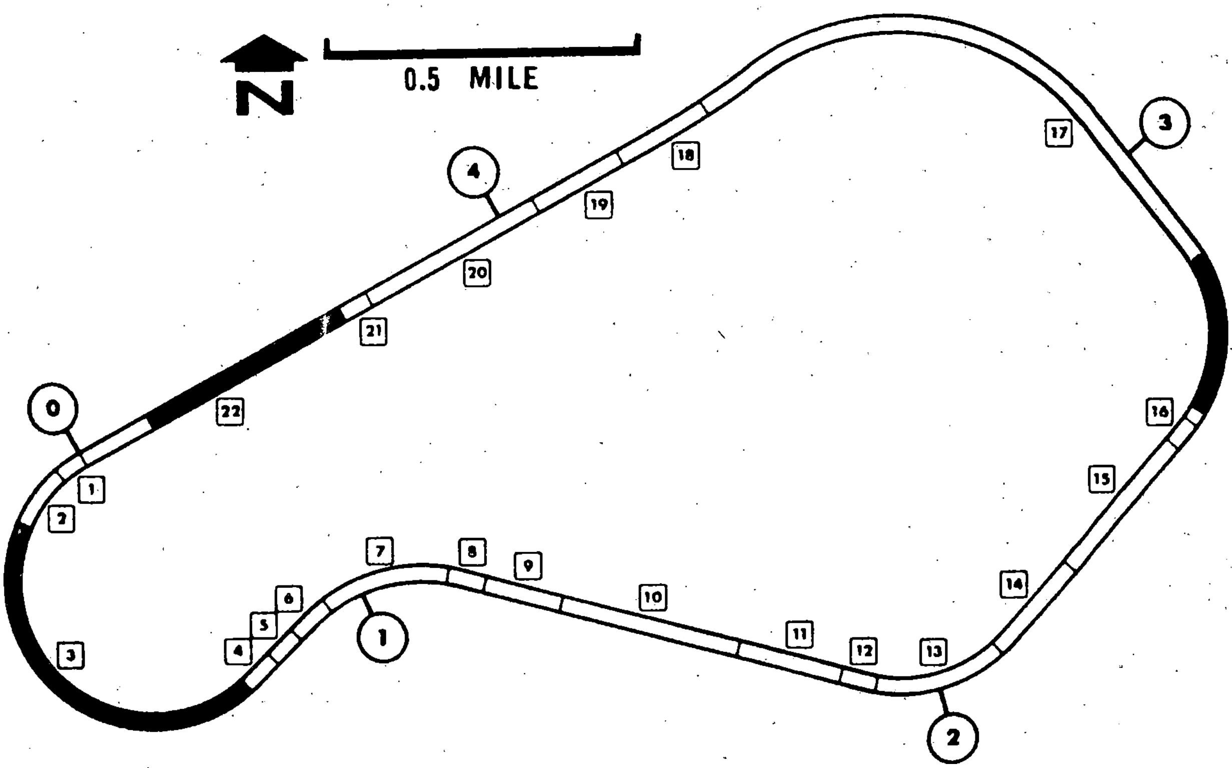
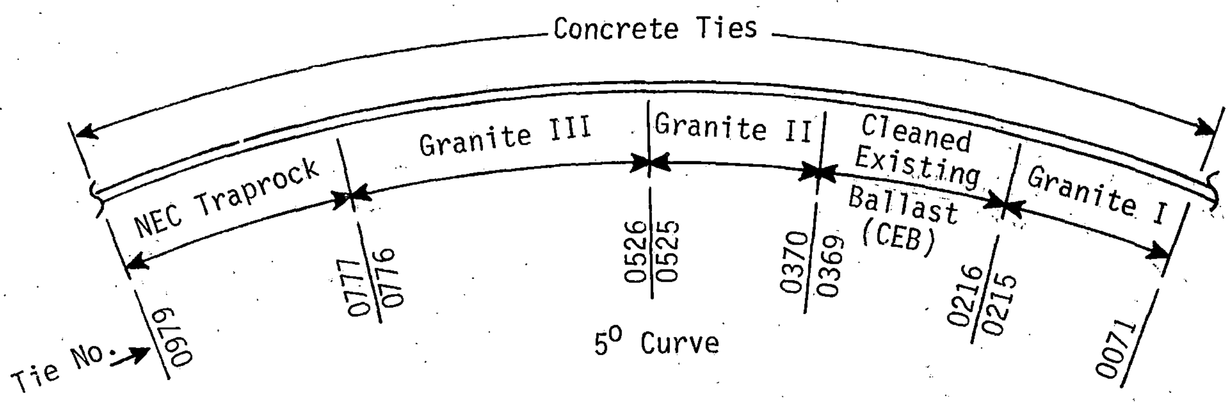
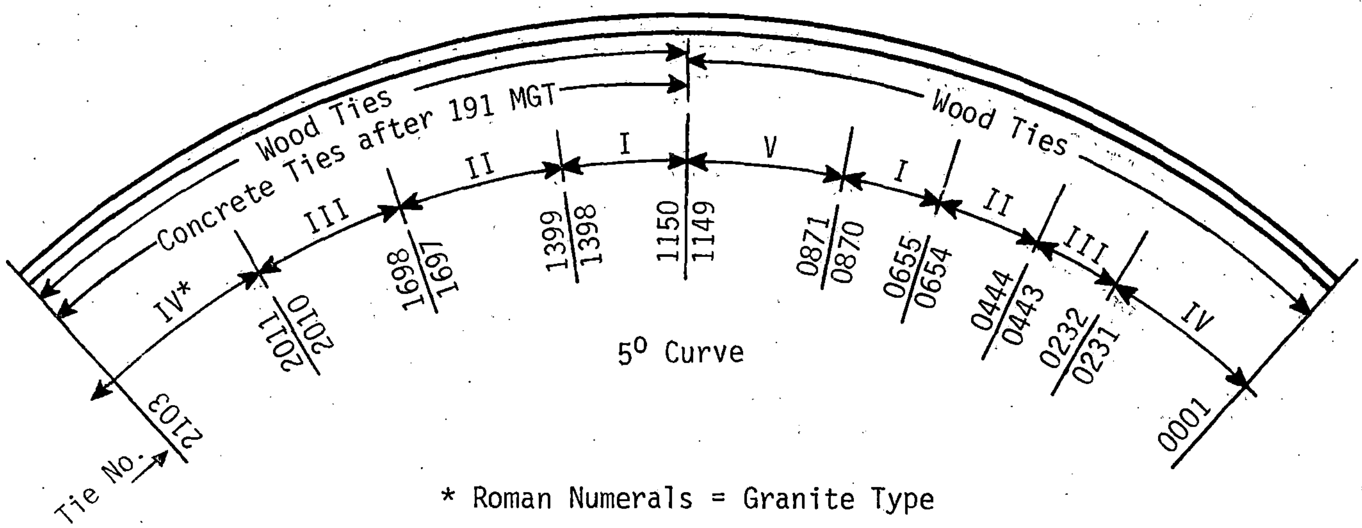


FIGURE B-1. FAST LOOP, SHOWING BALLAST II TEST SEGMENTS.



Section 17



* Roman Numerals = Granite Type

Section 03

FIGURE B-2. TEST SECTIONS 03 and 17 - CONFIGURATION

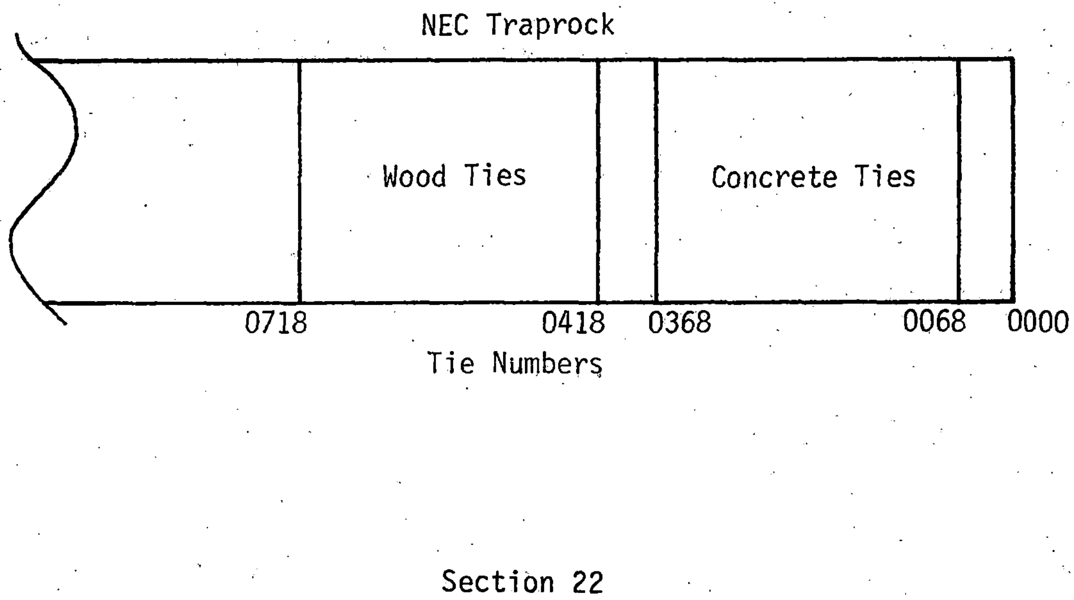


FIGURE B-3. SECTION 22 - CONFIGURATION.

BALLAST SPECIFICATIONS

Test Name: Cleaned Existing Ballast (CEB)

Geologic Description: Hornblend - Biotite Hornfels

Installation: Section 17, Concrete Ties

Index Tests:

Bulk Specific Gravity	ASTM C-127	2.67
Los Angeles Abrasion	ASTM C-131	18.8%
Absorption	ASTM C-127	0.40%
Soundness	ASTM C-88	0.77%
Flakiness Index, Initial	BS 812	20.8
Flakiness Index, Final	BS 812	12.6
Elongation Index, Initial	BS 812	----
Elongation Index, Final	BS 812	39.7
Particle Index	ASTM D3398	14.2
Crushing Value	BS 812	18.4
TSC Compactive Index		----
CIGGT Shape Factor		2.05

Petrographic Description: Not Available

BALLAST SPECIFICATIONS

Test Name: NEC Traprock

Geologic Description: Olivine Basalt Porphyry to Quartz Latite Porphyry

Installation: Section 17, Concrete Ties

Index Tests:

Bulk Specific Gravity	ASTM C-127	2.76
Los Angeles Abrasion	ASTM C-131	21.5%
Absorption	ASTM C-127	0.30%
Soundness	ASTM C-88	1.50%
Flakiness Index, Initial	BS 812	28
Flakiness Index, Final	BS 812	20.9
Elongation Index, Initial	BS 812	27
Elongation Index, Final	BS 812	40.9
Particle Index	ASTM D3398	----
Crushing Value	BS 812	----
TSC Compactive Index		1.10
CIGGT Shape Factor		2.21

Petrographic Description: A bimodal rock consisting of:

a) Olivine Basalt: holocrystalline, inequigranular, porphyritic, fine to medium grained hypidiomorphic-granular olivine basalt prophyry.

b) Quartz Latite (Rhyodacite) Porphyry: holocrystalline, inequigranular, porhyritic, fine to medium grained hypidiomorphic-granular quartz latite porphyry (rhyodacite porphyry).

BALLAST SPECIFICATIONS

Test Name: NEC Traprock

Geologic Description: Olivine Basalt Porphyry to Quartz Latite Porphyry

Installation: Section 22, Concrete Ties

Index Tests:

Bulk Specific Gravity	ASTM C-127	2.76
Los Angeles Abrasion	ASTM C-131	21.5%
Absorption	ASTM C-127	0.30%
Soundness	ASTM C-88	1.50%
Flakiness Index, Initial	BS 812	28
Flakiness Index, Final	BS 812	18.7
Elongation Index, Initial	BS 812	27
Elongation Index, Final	BS 812	38.1
Particle Index	ASTM D3398	----
Crushing Value	BS 812	----
TSC Compactive Index		1.10
CIGGT Shape Factor		2.21

Petrographic Description: A bimodal rock consisting of:

a) Olivine Basalt: holocrystalline, inequigranular, porphyritic, fine to medium grained hypidio-morphicgranular olivine basalt porphyry.

b) Quartz Latite (Rhyodacite) Porphyry: holocrystalline, inequigranular, porhyritic, fine to medium grained hypidiomorphic-granular quartz latite porphyry (rhyodacite porphyry).

BALLAST SPECIFICATIONS

Test Name: NEC Traprock

Geologic Description: Olivine Basalt Porphyry to Quartz Latite Porphyry

Installation: Section 22, Wood Ties

Index Tests:

Bulk Specific Gravity	ASTM C-127	2.76
Los Angeles Abrasion	ASTM C-131	21.5%
Absorption	ASTM C-127	0.30%
Soundness	ASTM C-88	1.50%
Flakiness Index, Initial	BS 812	28
Flakiness Index, Final	BS 812	18.9
Elongation Index, Initial	BS 812	27
Elongation Index, Final	BS 812	45.3
Particle Index	ASTM D3398	----
Crushing Value	BS 812	----
TSC Compactive Index		1.10
CIGGT Shape Factor		2.21

Petrographic Description: A bimodal rock consisting of:

a) Olivine Basalt: holocrystalline, inequigranular, porphyritic, fine to medium grained hypidiomorphic-granular olivine basalt porphyry.

b) Quartz Latite (Rhyodacite) Porphyry: holocrystalline, inequigranular, porhyritic, fine to medium grained hypidiomorphic-granular quartz latite porphyry (rhyodacite porphyry).

BALLAST SPECIFICATIONS

Test Name: Granite I

Geologic Description: Micaceous-Quartzo-Feldspathic Gneiss

Installation: Section 17, Concrete Ties

Index Tests:

Bulk Specific Gravity	ASTM C-127	2.57
Los Angeles Abrasion	ASTM C-131	23.1%
Absorption	ASTM C-127	0.30%
Soundness	ASTM C-88	0.05%
Flakiness Index, Initial	BS 812	35
Flakiness Index, Final	BS 812	17.3
Elongation Index, Initial	BS 812	29
Elongation Index, Final	BS 812	42.0
Particle Index	ASTM D3398	----
Crushing Value	BS 812	----
TSC Compactive Index		1.20
CIGGT Shape Factor		2.44

Petrographic Description: Microcrystalline to fine-grained xenoblastic micaceous-quartzo-feldspathic gneiss showing a crystalloblastic texture with fair to good foliation. The more distinct foliation is present in those thin sections showing increased percentages of mica. K-feldspar and quartz are the main constituents with the remaining mineralogy consisting of plagioclase (oligoclase), biotite, muscouite, and accessory zircon, apatite and magnetite. Alteration products include chlorite and hematite in minor amounts when present.

BALLAST SPECIFICATIONS

Test Name: Granite I

Geologic Description: Micaceous-Quartzo-Feldspathic Gneiss

Installation: Section 03, Wood Ties

Index Tests:

Bulk Specific Gravity	ASTM C-127	2.57
Los Angeles Abrasion	ASTM C-131	23.1%
Absorption	ASTM C-127	0.30%
Soundness	ASTM C-88	0.05%
Flakiness Index, Initial	BS 812	35
Flakiness Index, Final	BS 812	15.8
Elongation Index, Initial	BS 812	29
Elongation Index, Final	BS 812	36.3
Particle Index	ASTM D3398	----
Crushing Value	BS 812	----
TSC Compactive Index		1.20
CIGGT Shape Factor		2.44

Petrographic Description: Microcrystalline to fine-grained xenoblastic micaceous-quartzo-feldspathic gneiss showing a crystalloblastic texture with fair to good foliation. The more distinct foliation is present in those thin sections showing increased percentages of mica. K-feldspar and quartz are the main constituents with the remaining mineralogy consisting of plagioclase (oligoclase), biotite, muscouite, and accessory zircon, apatite and magnetite. Alteration products include chlorite and hematite in minor amounts when present.

BALLAST SPECIFICATIONS

Test Name: Granite II

Geologic Description: Granite to Quartz Monzonite

Installation: Section 17, Concrete Ties

Index Tests:

Bulk Specific Gravity	ASTM C-127	2.71
Los Angeles Abrasion	ASTM C-131	16.7%
Absorption	ASTM C-127	0.30%
Soundness	ASTM C-88	0.20%
Flakiness Index, Initial	BS 812	24
Flakiness Index, Final	BS 812	19.1
Elongation Index, Initial	BS 812	27
Elongation Index, Final	BS 812	41.3
Particle Index	ASTM D3398	----
Crushing Value	BS 812	----
TSC Compactive Index		1.10
CIGGT Shape Factor		2.12

Petrographic Description: This is a trimodal rock consisting of:

a) Granite to Quartz Syenite to Quartz Monzonite: holocrystalline, inequigranular, porphyritic fine to medium grained, hypidiomorphic-granular, porphyritic granite, porphyritic quartz syenite, porphyritic quartz monzonite.

b) Granite: holocrystalline, inequigranular, porphyritic, fine to medium grained hypidiomorphic-granular, porphyritic granite.

c) Basalt: holocrystalline, equigranular, fine-grained hypidiomorphic-granular basalt.

BALLAST SPECIFICATIONS

Test Name: Granite II

Geologic Description: Granite to Quartz Monzonite

Installation: Section 03, Wood Ties

Index Tests:

Bulk Specific Gravity	ASTM C-127	2.71
Los Angeles Abrasion	ASTM C-131	16.7%
Absorption	ASTM C-127	0.30%
Soundness	ASTM C-88	0.20%
Flakiness Index, Initial	BS 812	24
Flakiness Index, Final	BS 812	16.2
Elongation Index, Initial	BS 812	27
Elongation Index, Final	BS 812	43.1
Particle Index	ASTM D3398	----
Crushing Value	BS 812	----
TSC Compactive Index		1.10
CIGGT Shape Factor		2.12

Petrographic Description: This is a trimodal rock consisting of:

a) Granite to Quartz Syenite to Quartz Monzonite: holocrystalline, inequigranular, porphyritic fine to medium grained, hypidiomorphic-granular, porphyritic granite, porphyritic quartz syenite, porphyritic quartz monzonite.

b) Granite: holocrystalline, inequigranular, porphyritic, fine to medium grained hypidiomorphic-granular, porphyritic granite.

c) Basalt: holocrystalline, equigranular, fine-grained hypidiomorphic-granular basalt.

BALLAST SPECIFICATIONS

Test Name: Granite III

Geologic Description: Alkali-Feldspar Granite to Alkali-Feldspar Syenite, Trimodal

Installation: Section 17, Concrete Ties

Index Tests:

Bulk Specific Gravity	ASTM C-127	2.72
Los Angeles Abrasion	ASTM C-131	24.7%
Absorption	ASTM C-127	0.30%
Soundness	ASTM C-88	0.13%
Flakiness Index, Initial	BS 812	17
Flakiness Index, Final	BS 812	12.2
Elongation Index, Initial	BS 812	29
Elongation Index, Final	BS 812	40.5
Particle Index	ASTM D3398	----
Crushing Value	BS 812	----
TSC Compactive Index		1.10
CIGGT Shape Factor		2.11

Petrographic Description: This is a trimodal rock consisting of:

a) Alkali-Feldspar Granite to Alkali-Feldspar Quartz Syenite to Alkali-Feldspar Syenite: holocrystalline, inequigranular, porphyritic fine to coarse grained hypidiomorphic-granular, porphyritic alkali-feldspar granite, porphyritic alkali-feldspar quartz syenite and porphyritic alkali-feldspar syenite.

b) Alkali-Feldspar Granite to Alkali-Feldspar Quartz Syenite: holocrystalline, inequigranular, porphyritic fine to medium grained hypidiomorphic-granular porphyritic alkali-feldspar granite and porphyritic alkali-feldspar quartz syenite.

c) Alkali-Feldspar Granite: holocrystalline, equigranular, fine-grained hypidiomorphic-granular alkali-feldspar granite.

BALLAST SPECIFICATIONS

Test Name: Granite III

Geologic Description: Alkali-Feldspar Granite to Alkali-Feldspar Syenite, Trimodal

Installation: Section 03, Wood Ties

Index Tests:

Bulk Specific Gravity	ASTM C-127	2.72
Los Angeles Abrasion	ASTM C-131	24.7%
Absorption	ASTM C-127	0.30%
Soundness	ASTM C-88	0.13%
Flakiness Index, Initial	BS 812	17
Flakiness Index, Final	BS 812	10.9
Elongation Index, Initial	BS 812	29
Elongation Index, Final	BS 812	33.3
Particle Index	ASTM D3398	----
Crushing Value	BS 812	----
TSC Compactive Index		1.10
CIGGT Shape Factor		2.11

Petrographic Description: This is a trimodal rock consisting of:

a) Alkali-Feldspar Granite to Alkali-Feldspar Quartz Syenite to Alkali-Feldspar Syenite: holocrystalline, inequigranular, porphyritic fine to coarse grained hypidiomorphic-granular, porphyritic alkali-feldspar granite, porphyritic alkali-feldspar quartz syenite and porphyritic alkali-feldspar syenite.

b) Alkali-Feldspar Granite to Alkali-Feldspar Quartz Syenite: holocrystalline, inequigranular, porphyritic fine to medium grained hypidiomorphic-granular porphyritic alkali-feldspar granite and porphyritic alkali-feldspar quartz syenite.

c) Alkali-Feldspar Granite: holocrystalline, equigranular, fine-grained hypidiomorphic-granular alkali-feldspar granite.

BALLAST SPECIFICATIONS

Test Name: Granite IV

Geologic Description: Hornblende-Biotite Syenite

Installation: Section 03, Wood Ties

Index Tests:

Bulk Specific Gravity	ASTM C-127	2.65
Los Angeles Abrasion	ASTM C-131	21.5%
Absorption	ASTM C-127	0.20%
Soundness	ASTM C-88	----
Flakiness Index, Initial	BS 812	24
Flakiness Index, Final	BS 812	11.5
Elongation Index, Initial	BS 812	17
Elongation Index, Final	BS 812	33.4
Particle Index	ASTM D3398	----
Crushing Value	BS 812	----
TSC Compactive Index		1.20
CIGGT Shape Factor		2.06

Petrographic Description: Holocrystalline, inequigranular, porphyritic fine to medium grained hypidiomorphic-granular, porphyrite hornblende-biotite syenite.

BALLAST SPECIFICATIONS

Test Name: Granite V

Geologic Description: Quartzite

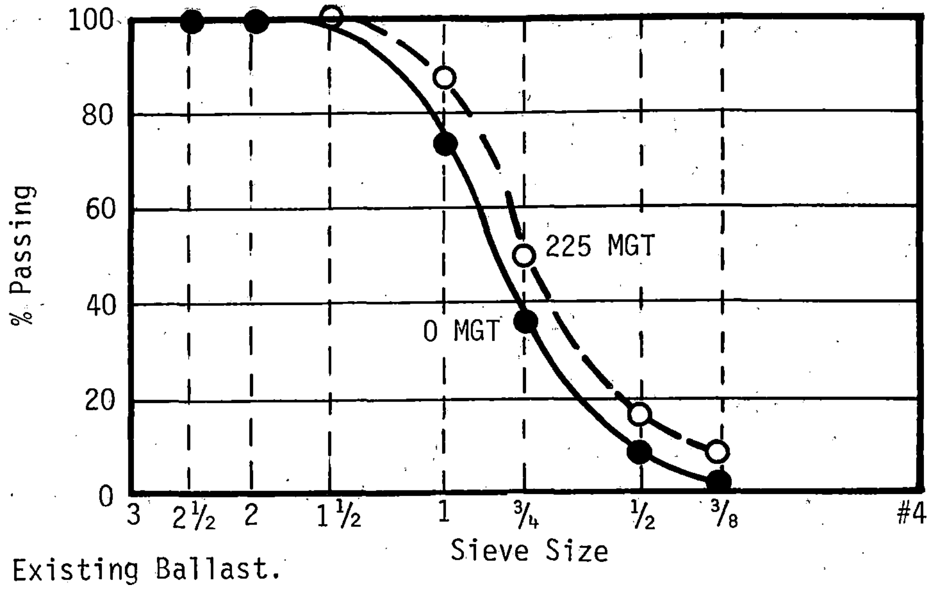
Installation: Section 03, Wood Ties

Index Tests:

Bulk Specific Gravity	ASTM C-127	2.52
Los Angeles Abrasion	ASTM C-131	19.9%
Absorption	ASTM C-127	0.10%
Soundness	ASTM C-88	0.10%
Flakiness Index, Initial	BS 812	24
Flakiness Index, Final	BS 812	17.1
Elongation Index, Initial	BS 812	28
Elongation Index, Final	BS 812	45.1
Particle Index	ASTM D3398	----
Crushing Value	BS 812	----
TSC Compactive Index		1.30
CIGGT Shape Factor		2.09

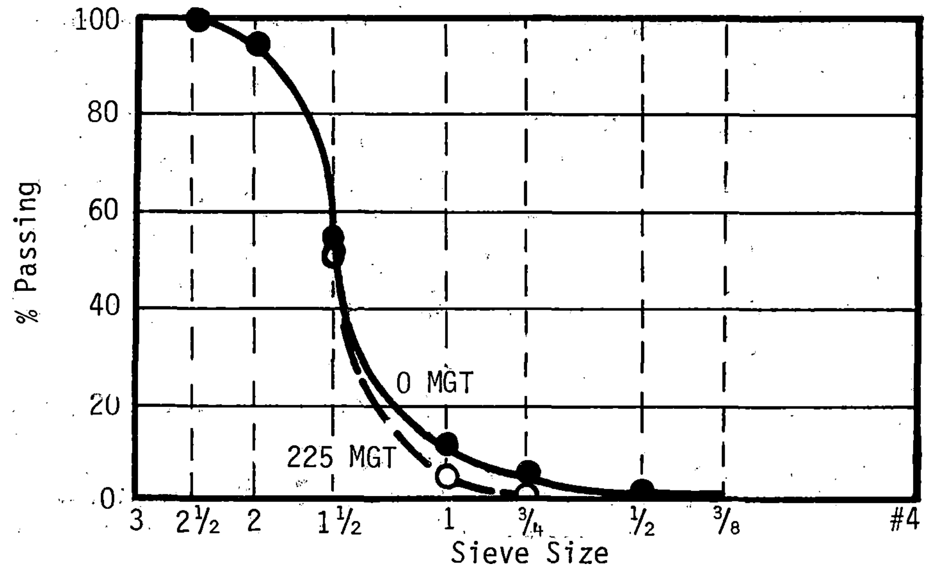
Petrographic Description: Fine to coarse grained quartzite exhibiting typical hornfels texture of interlocking sutured grains of quartz with interstitial muscouite and chlorite. Accessory minerals include rutile, zircon, and opaques (pyrite and hematite).

CEB*, Section 17,
Concrete Ties



* Cleaned, Existing Ballast.

NEC Traprock,
Section 22,
Concrete Ties



NEC Traprock,
Section 17,
Concrete Ties

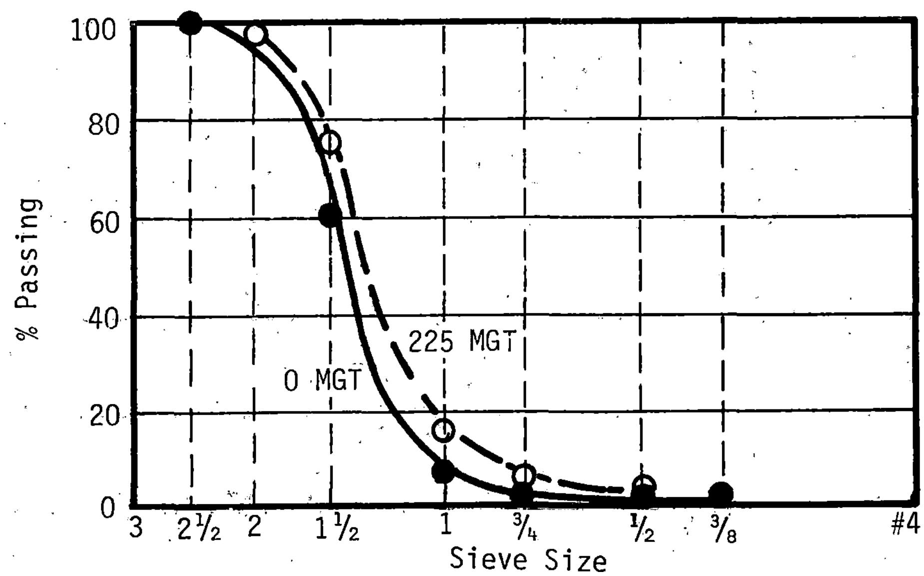
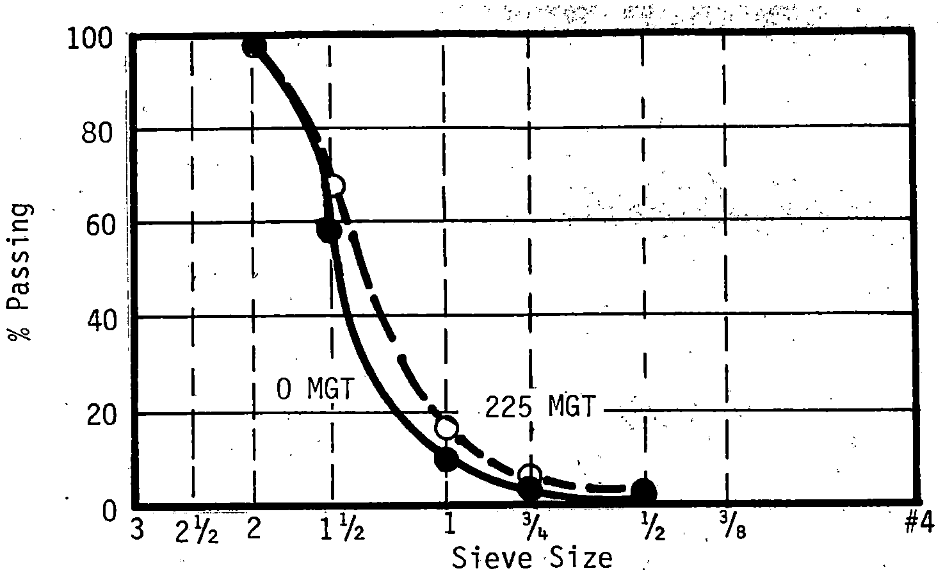
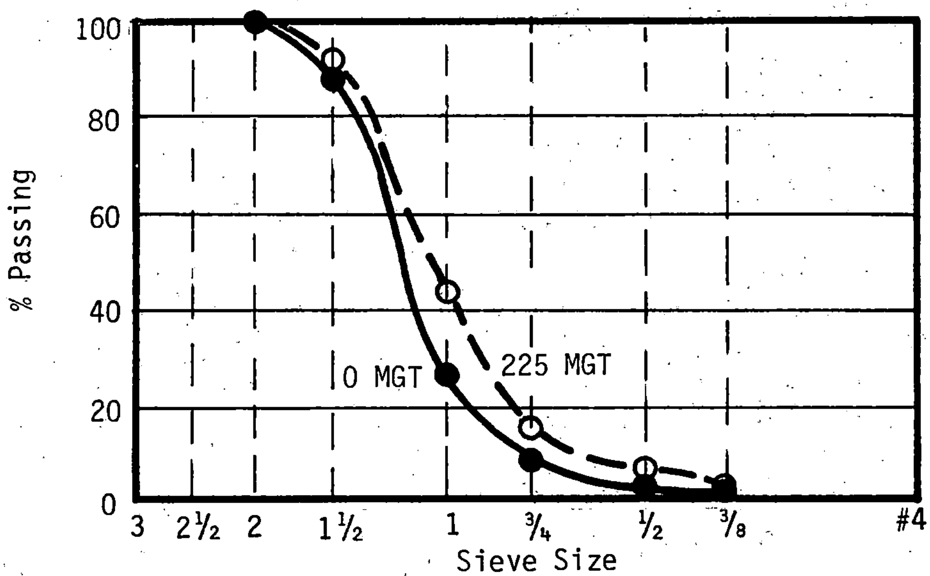


FIGURE B-4. SIEVE TEST RESULTS AT 0 and 225 MGT.

NEC Traprock,
Section 22,
Wood Ties



Granite I,
Section 17,
Concrete Ties



Granite I,
Section 03,
Wood Ties

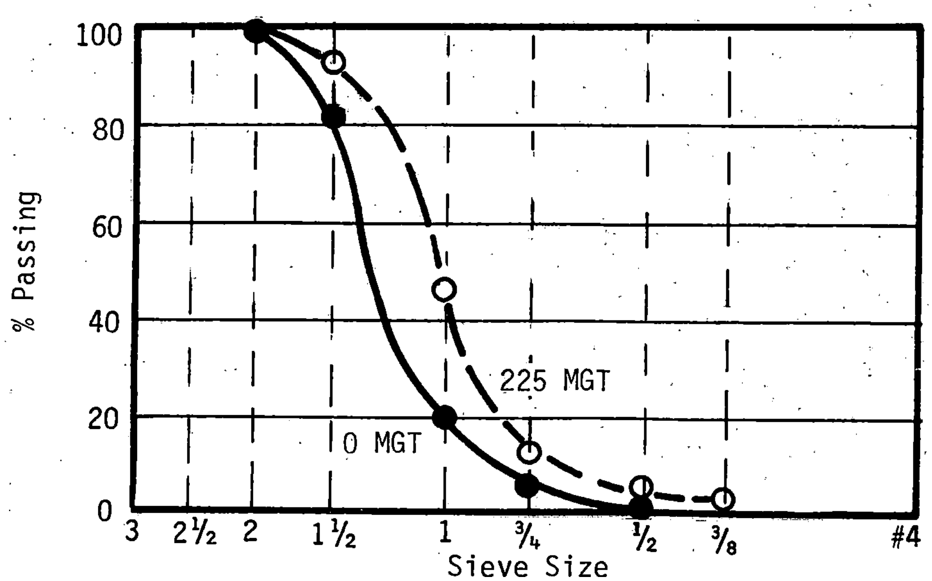
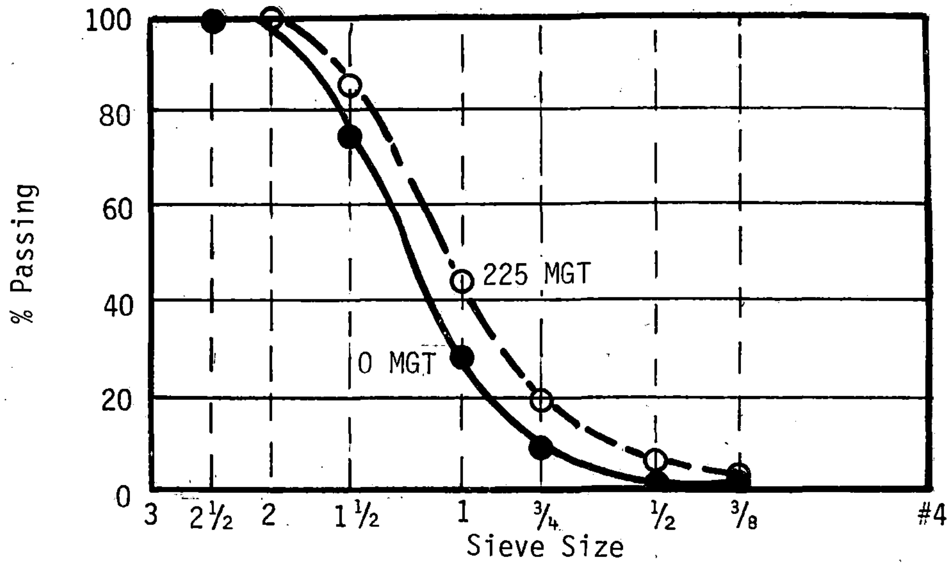
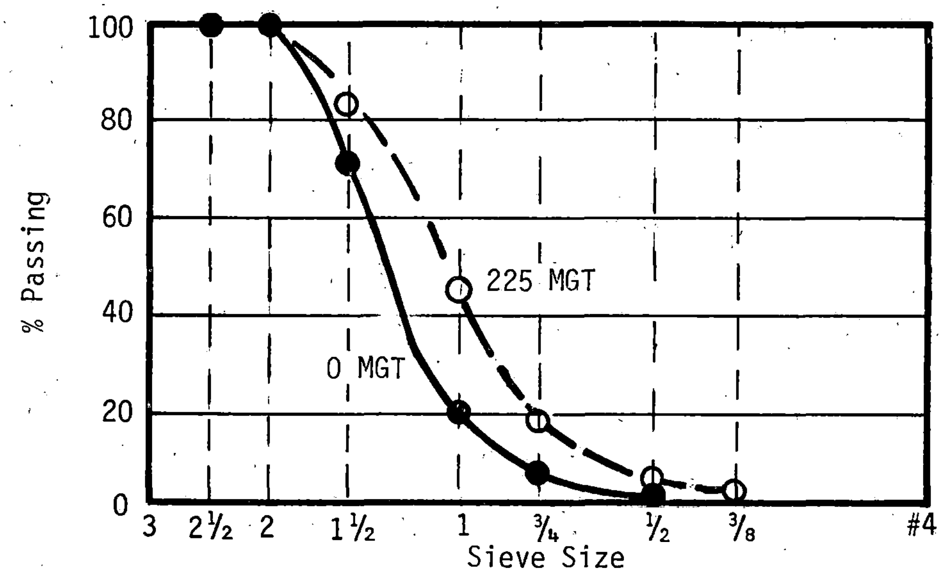


FIGURE B-4. (CONTINUED).

Granite II,
Section 17,
Concrete Ties



Granite II,
Section 03,
Wood Ties



Granite III,
Section 17,
Concrete Ties

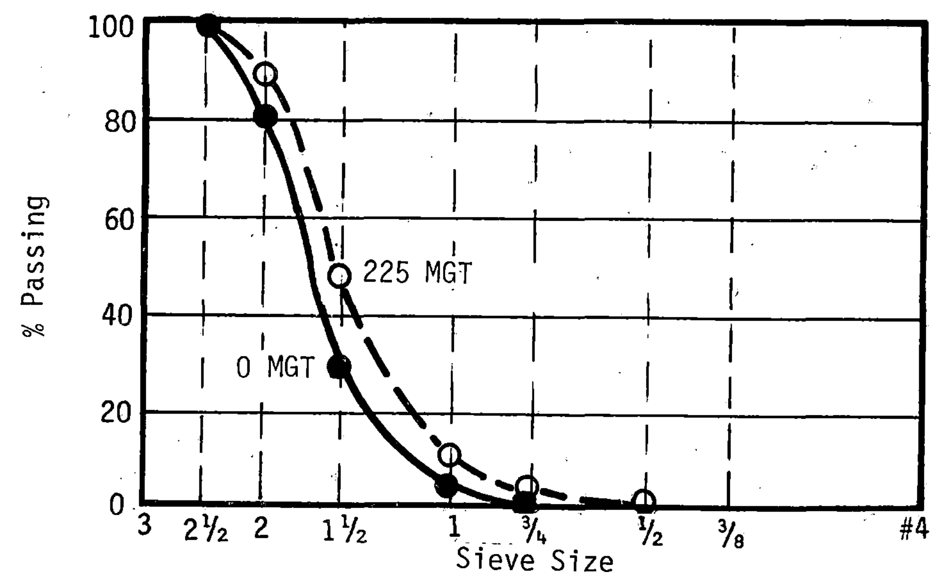
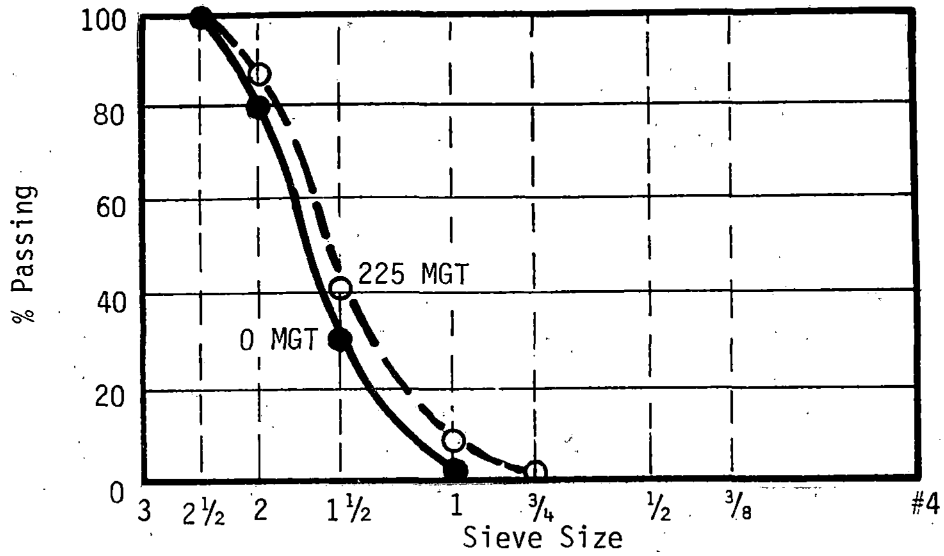
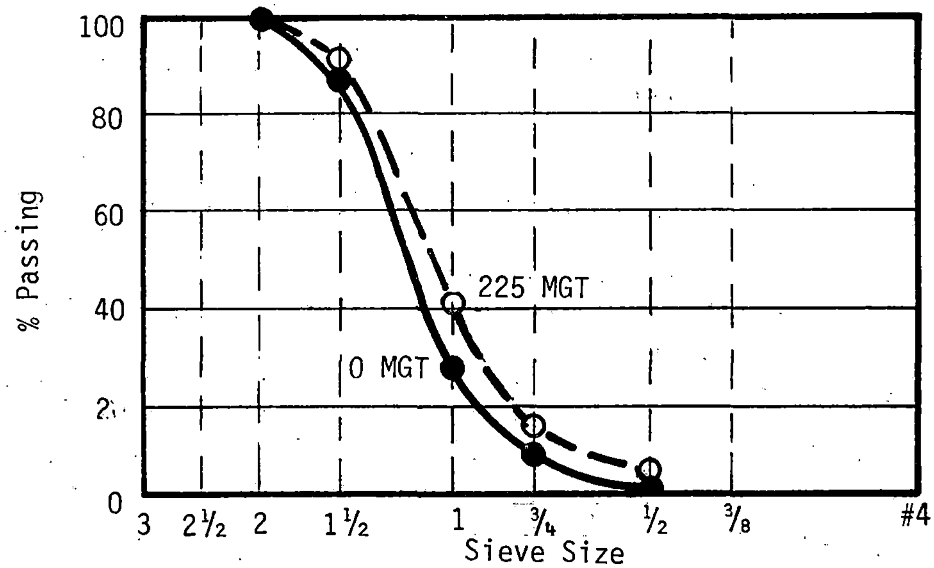


FIGURE B-4. (CONTINUED).

Granite III,
Section 03,
Wood Ties



Granite IV,
Section 03,
Wood Ties



Granite V,
Section 03,
Wood Ties

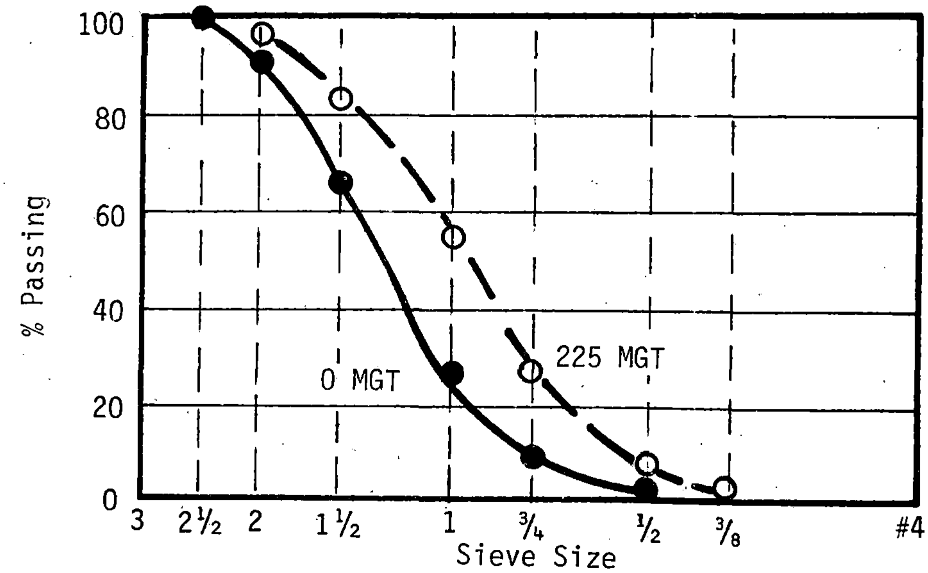


FIGURE B-4. (CONTINUED)

SHAPE FACTOR TESTS FOR THE SECOND BALLAST EXPERIMENT

Two separate sets of tests were used for evaluating the shape characteristics of the test ballasts.

BS 812 Tests

The first set of tests were the Flakiness and Elongation Index tests, based on the British Standard 812 test of the same name but modified to accommodate American gradation sieve sizes. These test procedures are published by the British Standards Institute.*

The flakiness index of the ballast is the percentage by weight of those particles whose least dimension is less than three-fifths of their mean dimension. To make this determination, the ballast sample is screened using the standard ballast gradation test. The portions retained on the individual sieves are weighed. The individual particles are then fitted through the slot in the flakiness gauge (Figure A), corresponding to the sieve on which the particle was retained. Those particles passing through the slot are classified as "flaky". The "flaky" particles are weighed at the end of the test and compared with the original weight to calculate a percentage. This percentage is the flakiness index.

The elongation index is similar to the flakiness test but finds particles whose greatest dimension is more than 1-8/5 times its mean dimension. For the

----

* British Standards Institute
101 Pentonville Road
London N1 9ND, U.K.

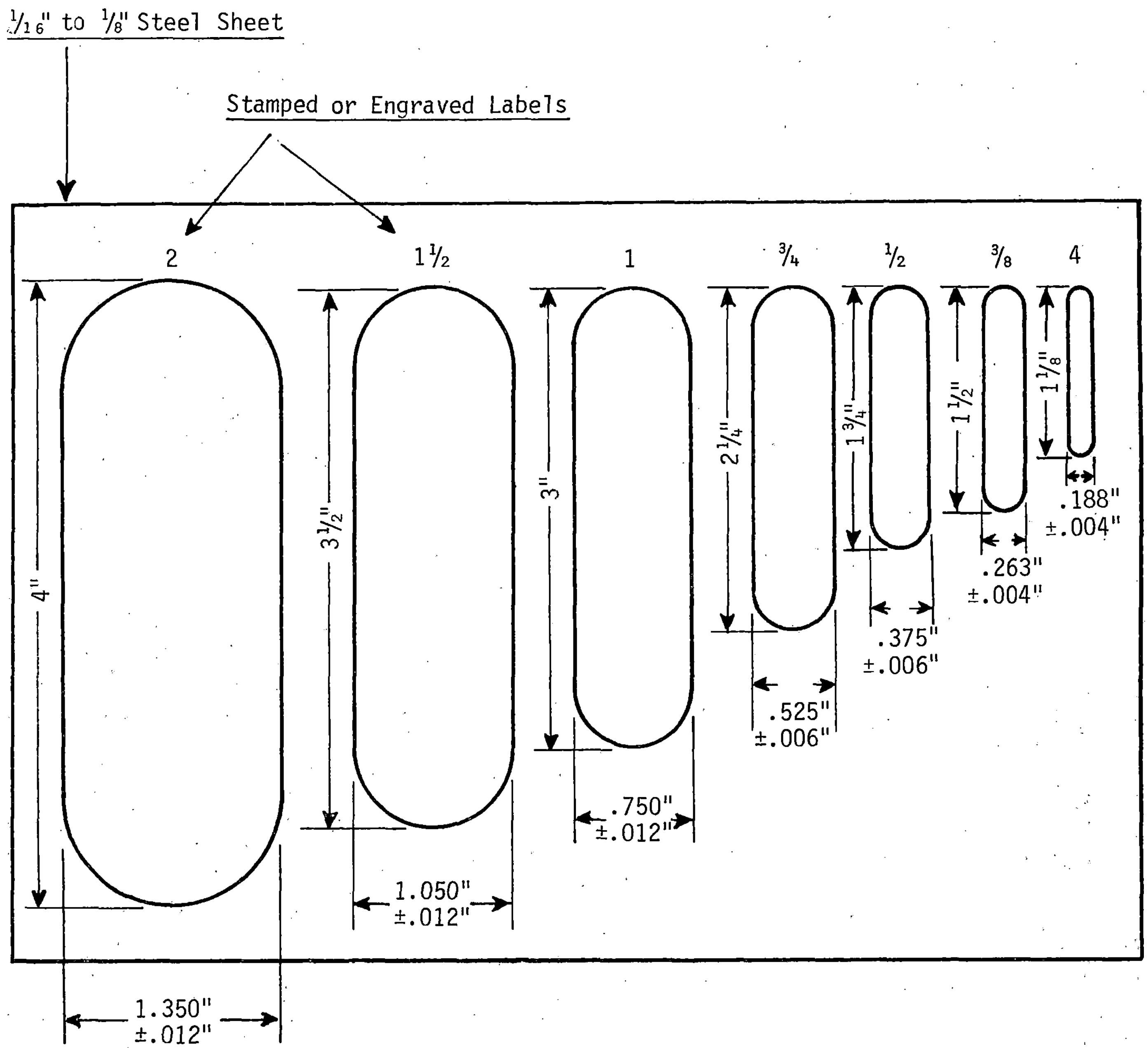


FIGURE B-5. MODIFIED FLAKINESS GAUGE, SECOND BALLAST EXPERIMENT.

test, the particles are hand fitted between the appropriate pair of pins on the gauge (Figure 5). Those particles whose greatest dimension will not pass between the pins are classified as "elongated".

CIGGT Shape Factor Test

The other shape test used for the second experiment is the shape factor test as described by the Canadian Institute of Guided Ground Transport. Their text describing the test is as follows:

"A representative sample of about 100 coarse ballast particles which are retained on a specified grading sieve designated to have 50-70 percent passing shall be used to obtain the ballast shape factor. Using a pair of calipers, each particle shall be measured to the nearest mm (0.04 inch) to determine its longest dimension and its least width. The least width is defined as the least dimension of an infinitely long slot with parallel sides which will just allow the particle to pass through.

The shape factor is the ratio of the sum of the longest dimension to the sum of the least width:

$$\text{shape factor} = \frac{\Sigma \text{ longest dimension}}{\Sigma \text{ smallest dimension}}$$

Where required, a linear plot of least width divided by sieve size passing versus sieve size passing divided by longest dimension of each test particle shall be prepared to allow a visual indication of the distribution of particle shapes to the client."[1]

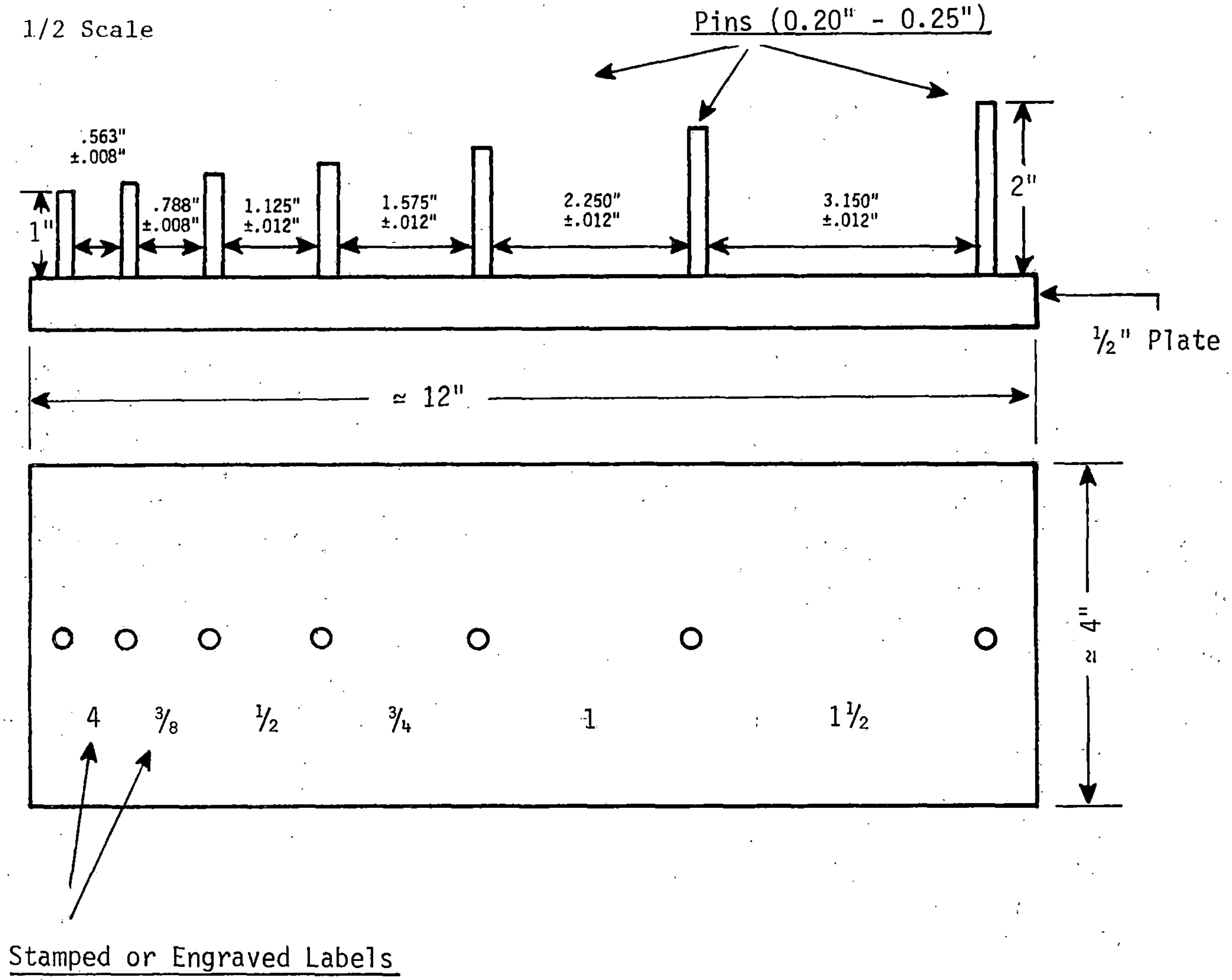


FIGURE B-6. MODIFIED ELONGATION GAUGE, SECOND BALLAST EXPERIMENT.

----
[1] Raymond, G. P., Boon, C. J., Lake, R. W., "Ballast Selection and Grading - A Summary Report" CIGGT Report #79-4, April, 1979.

APPENDIX C

BIBLIOGRAPHY OF RELATED MATERIALS

APPENDIX C

BIBLIOGRAPHY OF RELATED MATERIALS

<u>FAST Reports</u>*

TM 79/01	"Ballast Consolidation Test"
TN 79/09	"Ballast Physical Properties Tests"
TN 79/10	"Section 17 Ballast Quality Tests"
TN 79/15	"Lateral Track Instability"
TN 80/05	"Evaluation of Lateral Track Strength Measurements at FAST"
TM 80/08 (See Note)	"Data Supplement to Ballast Experiments Intermediate (175 MGT) Stress and Strain, Status Report" (This supplement now part of TM 81/03)
TM 80/11	"Ballast and Subgrade Instrumentation, 1979 Rebuild, Section 22"
TM 81/03	"Ballast Experiments Intermediate (175 MGT) Stress & Strain, Status Report"
TM 81/04	"Summary of the Subsurface Exploration Program Performed Prior to the 1979 FAST Rebuild, Sections 03, 17 and 22"
TM 81/06	"Documentation of Ballast and Subgrade Aspects of 1979 Rebuild of FAST, Sections 03, 17 and 22"
TM 81/07	"Track Settlement Predictions at FAST"
TN 81/03	"Ballast Shoulder Width Experiment"
FRA/TTC-82/01	"Proceedings, FAST Engineering Conference, 1981"
FRA/TTC-82/08	"Ballast Experiments at FAST, Status Report"

----

* FAST reports may be obtained by writing to:

Technical Librarian
The Association of American Railroads, TTC
P. O. Box 11130
Pueblo, CO 81001 U.S.A.

Other Reports

Adegoke, C.W., "Elastic and Inelastic Deformation Response of Track Structures under Train Loads," Ph.D. Dissertation, Department of Civil Engineering, State University of New York at Buffalo, Buffalo, N.Y., December, 1978.

Adegoke, C.W., and Chang, C.S., "Initial Evaluation of the Burmister/Load Combination Track Model--MULTA," Department of Civil Engineering, SUNYAB, October, 1977.

Alva-Hurtado, J.E., "A Methodology to Predict the Elastic and Inelastic Behavior of Railroad Ballast," Ph.D. Dissertation, Department of Civil Engineering, University of Massachusetts, Amherst, Mass., May, 1980.

Alva-Hurtado, J.E. and McMahon, D.R., "Static Triaxial Testing of FAST Granite Ballast," Internal Report, Department of Civil Engineering, University of Massachusetts at Amherst.

Berard, J., "Petrographic Study of Ballast," Ecole Polytechnique, Montreal, Quebec, Canada, 1973.

Bishop, C., "Some Vibration and Repeated Loading Tests on Railway Ballast," Undergraduate Report, Queen's University, Kingston, Ontario, 1975.

Blacklock, J.R., "An Investigation of Stresses and Deflections in Railroad Track Soil Support Systems Using the Nonlinear Finite Element Method of Analysis," Soils Laboratory, University of Arkansas, Little Rock, Ark., Special Report No. 78-1, August, 1978.

Chang, C.S., Adegoke, C.W., and Selig, E.T., "A Study of Analytical Models for Track Support Systems," Transportation Research Board Record 733, Washington, D.C., 1979, pp. 12-19.

Chang, C.S., Adegoke, C.W., and Selig, E.T., "The GEOTRACK Model for Railroad Track Performance," Journal of the Geotechnical Engineering Division, ASCE, Vol. 106, No. GT11, Proceedings Paper 15819, November, 1980, pp. 1201-1218.

Chang, I.C., "Track Foundation Stresses Under Horizontal Loads," M.S. Thesis, Department of Civil Engineering, Illinois Institute of Technology, May, 1975.

Chung, K.M.P., "Some Triaxial Tests on Railway Ballast," Undergraduate Report, Queen's University, Kingston, Ontario, 1974.

Clarke, C.W., "Track Loading Fundamentals 1," Railway Gazette, 106, 2 pp. 45-48, January 11, 1957.

Clarke, C.W., "Track Loading Fundamentals 3," Railway Gazette, 106, 6 pp. 157-160, January 11, 1957.

Cunney, E.G., May, J.T., and Jones, H.N., "Effects of Accelerated Ballast Consolidation," FRA/ORD 76/274, March, 1977.

Dalton, C.J., "Field Durability Tests on Ballast Samples as a Guide to the Significance of the Specification Requirements," Canadian National Railways Technical Research Centre, St. Laurent, Quebec, 1973.

Dalton, C.J., "Freeze-Thaw Tests on Ten Ballast Samples," Canadian National Railways, Montreal, Quebec, Canada, June, 1976.

Dean, F.E. and Prause, R.H., "Evaluation of Selected FAST Track Performance Measurements," Technical Directive No. 2 of Contract DOT-TSC-1044, July, 1978.

"Deformation of Railway Ballast under Repeated Loading (Triaxial Tests)," Office for Research and Experiments of the International Union of Railways Report D 117/RP 5, Utrecht, Netherlands, 1974.

"Documentation Report for Ballast and Subgrade Instrumentation, 1979 Rebuild, FAST Section 22," Report prepared by Haley and Aldrich, Inc., Cambridge, Mass., for DOT/TSC, Cambridge, Mass., March, 1980.

"Documentation of Ballast and Subgrade Aspects of the 1979 Rebuild of FAST Sections 3, 17 and 22," Report prepared by Haley and Aldrich, Inc., Cambridge, Mass., for DOT/TSC, Cambridge, Mass., June, 1980.

Dowart, B.C. and Panuccio, C.M., "Lateral Tie Push Tests on the FAST Site," Field Test Report, State University of New York at Buffalo, January, 1978.

Dowart, B.C. and Panuccio, C.M., "Plate Load Tests at FAST Site," Field Test Report, State University of New York at Buffalo, February, 1978.

Doyle, N.F., "Railway Track Design, A Review of Current Practice," Australian Government Publishing Service, Canberra, 1980.

"Field Testing of Machine Induced Ballast Consolidation," Department of Transportation, December, 1973.

Goldbeck, A.T., "Mineral Aggregates for Railroad Ballast," ASTM STP No. 83, 1948.

Goto, H., and Konishi, J., "On Attenuation of Vibrations and Deformation in Railway Ballast," Proceedings, Japan Society of Civil Engineering, Aug., 1973, pp. 69-78 (Translated by BHP Research, Melbourne, Australia).

Harrison, H.B., "General Computer Analysis of Beams on Elastic Foundations," Proceedings of the Institution of Civil Engineers, 55, Pt. 2, pp. 605-618, September, 1973.

Hay, W.W., Baugher, R., and Reinschmidt, A.J., "Study of Railroad Ballast Economics," FRA/ORD 77/64, September, 1977.

Hay, W.W., Peterson, H.C., Plotkin, D.E., and Bakas, P.T., "Lateral Stability of Ballast," Foundation Materials Research Program, FRA/ORD 77/61, September, 1977.

Heath, D.L. and Coltram, M., "Stresses Beneath a Railway Track," The Railway Gazette, Vol. 124, 1966.

Heath, D.L., Shenton, M.J., Sparrow, R.W., and Waters, J.M., "Design of Conventional Rail Track Foundations," Proceedings, Institute of Civil Engineers (London), Vol. 51, 1972.

Heath, D.L. and Shenton, M.J., "The Behavior of Track Ballast Under Repeated Loading Conditions," British Railways Report No. E.610D, 1968.

Hetenyi, M., Beams on Elastic Foundation, University of Michigan Press, 1946.

Ho, D.C., Selig, E.T., and Chang, C.S., "Variation of Parameters Study of Track Response Using GEOTRACK Model," Report No. FRA80-239I, Department of Civil Engineering, University of Massachusetts, Amherst, Mass., March, 1980.

Hoffmann, Pfarrer, "Influence of Various Measures on the Lateral Displacement Resistance of the Unloaded Track," DT44/D117/D, Research and Testing Laboratory of the International Railroad Association (ORE), Utrecht, May, 1976.

Huang, E.Y., "A Test for Evaluating the Geometric Characteristics of Coarse Aggregate Particles," ASTM Proceedings, Vol. 62, 1962.

Huang, E.Y., "An Improved Particle Index Test for the Evaluation of Geometric Characteristics of Aggregates," Michigan Highway Research Project No. 86546, Houghton, Michigan, July, 1965.

"Investigation of the Lateral Resistance of Concrete Tie Track," Interim Report No. 2, Project Agreement No. 4a, Task 1, Polish National Rail Research Institute (COBIRTK), Warsaw, April, 1979.

Ireland, H.O., "Railroad Subgrade Stesses," Proceedings of the AREA, Bulletin No. 641, pp. 641, pp. 382-386, January-February, 1973.

Johnson, J.I. and Yoo, T.S., "Follow-up FAST In-Situ Ballast Density Measurements and Gradation Tests," Field Test Report, Department of Civil Engineering, State University of New York at Buffalo, February, 1978.

Kennedy, J.C. and Prause, R.H., "Development of a Multilayer Analysis Model for Tie/Ballast Track Structures," Paper presented at 57th Transportation Research Board Annual Meeting, Washington, D.C., January, 1978.

Kennedy, J.C., "Lateral Resistance of Unoccupied Track," Battelle-Columbus Laboratories, March 8, 1979.

Knutson, R.M., "Factors Influencing the Repeated Load Behavior of Railway Ballast," Ph.D. Thesis, University of Illinois, Urbana, 1976.

Knutson, R.M., Thompson, M.R., Mullin, T., and Tayabji, S.D., "Material Evaluation Study - Ballast and Foundation Research Program," FRA/ORD 77-02, January, 1977.

Kondner, R.L. and Zelasko, J.S., "A Hyperbolic Stress-Strain Formulation for Sands," Proceedings, Second Pan-American Conference on Soil Mechanics and Foundations Engineering, Vol. I, pp. 289-324, Brazil, 1963.

Lundgren, J.R., Martin, G.C., and Hay, W.W., "A Simulation Model of Ballast Support and the Modulus of Track Elasticity," University of Illinois, Urbana, 1970.

Lynch, J.K., "Factors Which Affect the Stability, Testing, Selection and Performance of Suitable Aggregates for Railroad Ballast," AREA Bulletin 668, Vol. 79, June-July, 1978, pp. 368-377.

Ma, C.C., "Mathematical Models for Stress Analysis of Track Structure Foundations Subjected to Vertical Loading," AAR Report.

Magee, G.M., "Stabilized Ballast Investigation," DOT/FRA/OHSGT Report, August, 1969.

Mann, M.J., "Parametric Study of Track Response Using GEOTRACK Model," Track Maintenance Life Prediction Study, Dept. of Civil Engineering, SUNYAB, January, 1979.

Meacham, H.C., et al, "Study of New Track Structure Designs," BCL, Summary Report to USDOT, August, 1968.

Nichols, F.P., "Toward Better Evaluation of Railroad Ballast Aggregate," National Crushed Stone Association.

Norman, G.M., "Ballast Box Experiments for Evaluating Ballast Field Performance," University of Massachusetts, Department of Civil Engineering, March 1982.

Okabe, Z., "Laboratory Investigation of Railroad Ballast," Japan Railway Civil Engineering Association, Permanent Way No. 13, 1961.

Olowekere, D.O., "Strength and Deformation of Railway Ballast Subject to Triaxial Loading," M.S. Thesis, Queen's University, Kingston, Ontario, 1975.

Optimum Adaptation of the Conventional Track to Future Traffic, Question D117, Report No. 2, Office for Research and Experiments of the International Union of Railways, Utrecht, April, 1973.

Panuccio, C.M., Yoo, T.S., and Selig, E.T., "Mechanics of Ballast Compaction: Vol. 3, Field Test Results for Ballast Physical State Measurements," Department of Civil Engineering, State University of New York at Buffalo, Contract No. DOT/TSC/1115, Final Report to Transportation Systems Center, Cambridge, Mass., September, 1980.

Peckover, F.L., "Railway Ballast Material," Canadian National Railways, Office of the Chief Engineer, Montreal, Quebec, Canada, 1973, p. 97.

Prause, R.H. and Kennedy, J.C., "Parametric Study of Track Response and Performance," Battelle Columbus Laboratories, Columbus, Ohio, September, 1977.

"Railway Roadbeds for Tomorrow," Information Series No. 137, The Asphalt Institute, College Park, MD, July, 1966.

Raymond, G.P., "Research on Rail Support Improvement," Transportation Research Board, January, 1977.

Raymond, G.P., "Design for Railroad Ballast and Subgrade Support," ASCE Journal of the Geotechnical Engineering Division, Vol. 104, No. 1, January, 1978.

Raymond, G.P., "Railroad Ballast Prescription: State of the Art," ASCE Journal of the Geotechnical Engineering Division, February, 1979.

Raymond, G.P., Boon, C.J., Lake, R.W., and Diyaljee, V.A., "Characteristics of Acceptable Railroad Ballast," Transportation Research Board, January, 1977.

Raymond, G.P., Boon, C.J., and Lake, R.W., "Ballast Selection and Grading - A Summary Report," Canadian Institute of Guided Ground Transport, Report No. 79-4, April, 1979.

Raymond, G.P. and Davies, J.R., "Triaxial Tests on Dolomite Railroad Ballast." Journal of the Geotechnic Engineering Division, ASCE, GT6, pp. 737-751, June, 1978.

Raymond, G.P. and Gaskin, P.N., "Contribution to Selection of Railroad Ballast," Transportation Engineering Journal, ASCE, Vol. 102, May, 1976, pp. 377-394.

Riessberger, K.H., "Evaluation and Measurement of Ballast Consolidation by the Use of Compacting Machines," March, 1973.

Rixner, J.J. and Sluz, A., "Update FAST Experiment Plan for Ballast Replacement in Sections 3, 17 and 22," TSC, March, 1979.

Robnett, Q.L. and Thompson, M.R., "Interim Report - Resilient Properties of Subgrade Soils, Phase I - Development of Testing Procedure," Civil Engineering Studies, Transportation Engineering Series No. 5, Illinois Cooperative Highway Research Program Series No. 139, Department of Civil Engineering, University of Illinois at Urbana-Champaign, 1973.

Robnett, Q.L., Thompson, M.R., Knutson, R.M., and Tayabji, S.D., "Development of a Structural Model and Materials Evaluation Procedures," Ballast and Foundation Materials Research Program, University of Illinois, Report to FRA of U.S. DOT, Report No. DOT-FR-30038, May, 1975.

Robnett, Q.L., Thompson, M.R., and Hay W.W., "Technical Data Bases Report - Ballast and Foundation Materials Research Program Summary Report," FRA/ORD 76/138, July, 1975.

Robnett, Q.L., Thompson, M.R., and Hay, W.W., "Ballast and Foundation Materials Research Program," University of Illinois at Urbana, July, 1975.

Rostler, F.S. and Newton, J.W., "Study of Methods of Stabilizing Conventional Ballast Using Polymers," Materials Research and Development, Inc., 1968.

Salem, M.T. and Hay, W.W., "Vertical Pressure Distribution in Ballast Section and the Subgrade Beneath Statically Loaded Ties," University of Illinois, Urbana, 1966.

Scalzo, P.A., "Laboratory Testing of Railway Ballast," Department of Civil Engineering, Queen's University, Kingston, Ontario, Canada, April, 1972.

Selig, E.T., "Soil Strain Measurement Using Inductance Coil Method," ASTM STP 584, Performance Monitoring for Geotechnical Construction, August, 1975, pp. 141-158.

Selig, E.T. and Adegoke, C.W., "FAST Inductance-Coil Instrumentation Installation," State University of New York at Buffalo, Progress Report, U.S. Department of Transportation, Transportation Systems Center, Contract DOT-TSC-1115, February, 1977.

Selig, E.T., Chang, C.S., Alva-Hurtado, J.E., Adegoke, C.W., "A Theory for Track Maintenance Life Prediction." Final Report on First Year of Study, prepared for USDOT, Report number DOT-RSPA/DPB-50/79/22, August, 1979.

Selig, E.T., Chang, C.S., Alva-Hurtado, J.E., Adegoke, C.W., "A Theory for Track Maintenance Life Prediction." Final Report, prepared for USDOT, Report number DOT-RSPA/DPB-50/81/25, June, 1981.

Selig, E.T., Yoo, T.S., and Panuccio, C.M., "Mechanics of Ballast Compaction, Volume I: Field Methods for Ballast Physical State Measurement," State University of New York at Buffalo, November, 1977.

Selig, E.T., Yoo, T., and Adegoke, C.W., "Mechanics of Ballast Completion," IL, SUNYAB, May, 1978.

Selig, E.T. and Sluz, A., "Ballast and Subgrade Response to Train Loads," Transportation Research Board Record 694, Washington, D.C., January, 1978, pp. 53-60.

Selig, E.T., "FAST Substructure Dynamic Stresses, Strains and Deflections from 3 to 300 MGT," Report No. TSC80-270I, Department of Civil Engineering, University of Massachusetts, Amherst, Mass., prepared for U.S. DOT, Transportation Systems Center, Cambridge, Mass., December, 1980.

Shenton, M.J., "Deformation of Railway Ballast Under Repeated Loading," Soil Mechanics Section, British Railways Research Department, 1974.

Sinha, H., "Ballast in Railway Track," Indian Railway Technical Bulletin IS-26, 1967.

Siriwardane, H.J., "Nonlinear Soil-Structure Interaction Analysis for One-, Two- and Three-Dimensional Problems Using Finite Element Method," Ph.D. Dissertation, Department of Civil Engineering, Virginia Polytechnic Institute and State University, Blacksburg, W. Va., 1980.

Snaith, M.S. and Bell, A.L., "The Filtration Behavior of Construction Fabrics under Conditions of Dynamic Loading," Geotechnique, Vol. 28, No. 4, December, 1978.

So, W., Martin, G.C., Singh, B., Chang, I.C., Chang, E.H., "Mathematical Models for Track Structures," Association of American Railroads, Final Report to U.S. DOT/FRA, Report No. DOT-FR-30038, June, 1978.

So, W., "Ballast Characteristics and Selection: The State of the Art," Association of American Railroads, Report No. R-402, December, 1979.

"Stabilization of Ballast by Chemical Methods, Report No. 11," Question D117, Optimum Adaptation of the Conventional Track to Future Traffic, ORE, Utrecht, October, 1978.

"Stabilization of Ballast by Chemical Methods, Report No. 17," Question D117, Optimum Adaptation of the Conventional Track to Future Traffic, ORE, Utrecht, April 1981.

Stewart, H.E., "Index and Property Testing at FAST Subgrade," Report No. OUR80-240I, Department of Civil Engineering, University of Massachusetts, Amherst, Mass., March, 1980.

Stewart, H.E., "One-Way Analysis of Variance Applied to Dynamic and Static Track Foundation Responses at FAST," Report No. FRA80-244I, Department of Civil Engineering, University of Massachusetts, Amherst, Mass., May, 1980.

"Stresses in the Rails, the Ballast and in the Formation Resulting from Traffic Loads, Summary of the Results Given in Reports Nos. 1-12," Office for Research and Experiments of the International Union of Railways Report D 71/RP 13 (Final Report), Utrecht, Netherlands, 1970.

Svec, O.J., et al, "Analytical and Experimental Investigation of a Rail Track Structure," Proceedings of Second Symposium on Applications of Solid Mechanics, June, 1977.

Talbot, A.N., "Stresses in Railroad Track, The Talbot Report," AREA.

Tayabji, S.D. and Thompson, M.R., "Track Support Systems Parameter Study," Foundation Materials Research Program, FRA/ORD 76-256, July, 1976.

Tayabji, S.D. and Thompson, M.R., "Finite Element Analysis of Railway Track Support System: User's Manual," Report No. FRA-OR&D-76-257, July, 1976.

Tayabji, S.D., "Consideration in the Analysis of Conventional Railway Track Support Systems," Ph.D. Thesis, University of Illinois, Urbana, 1976.

Tiedemann, D.A., "Dynamic Soil Properties, UMTA Rapid Rail Test Track," U.S. Bureau of Reclamation, Denver, Colorado, June, 1973.

Thompson, M.R. and Robnett, Q.L., "Resilient Properties of Subgrade Soils," Final Report, Civil Engineering Studies, Transportation Engineering Series No. 14, Department of Civil Engineering, University of Illinois at Urbana-Champaign, 1976.

Thompson, M.R., "FAST Ballast and Subgrade Materials Evaluation," Interim Report Prepared by University of Illinois for U.S. Department of Transportation Federal Railroad Administration, Report No. FRA/ORD-77/32, December, 1977.

Thompson, M.R., Hay, W.W., and Tayabji, S.D., "Summary Report - Ballast and Foundation Materials Research Program," FRA-ORD 78/10, June, 1978.

Turcke, D.J. and Raymond, G.P., "Three-Dimensional Analysis of Rail Track Structures," Transportation Research Board Record 733, Washington, D.C., 1979, pp. 1-6.

Waters, J.M. and Shenton, M.J., "Track Foundation Design," The Railway Gazette, Vol. 124, 1968.

Wong, R.C.T., "One Dimensional Repeated Loading Test of Railway Ballast," M.S. Thesis, Queen's University, Kingston, Ontario, 1974.

Yoo, T.S. and Chen, H.M., "FAST In-Situ Ballast Density Measurements," Field Test Report, Department of Civil Engineering, State University of New York at Buffalo, February, 1977.

Yoo, T.S. and Selig, E.T., "Field Observations of Ballast and Subgrade Deformations in Track," Transportation Research Board Record 733, Washington, D.C., 1979, pp. 6-12.

Zarembski, A.M. and Choros, J., "On the Measurement and Calculation of Vertical Track Modulus," AREA Bulletin 675, November-December, 1979, pp. 156-173.