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NOTICE

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16. Abstract

This report constitutes a summary of the results of the various phases of the Ballast and Foundation Materials Research Program. Data and information obtained from the technical literature and that developed in the project are summarized. Implications of the research data and findings are discussed and recommendations for further studies are presented.

Topics considered in the program were a) resilient and permanent deformation behavior of ballast and subgrade materials, b) track support system temperature regime, c) lateral stability of ballast, d) structural behavior of the track support system (including the development of the Illi-TRACK structural model), and e) an economic study of ballast and ballasting practices.

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PREFACE

This report has been generated as part of a sub-contract between the Association of American Railroads Research and Test Department and the University of Illinois.

This sub-contract is part of a larger contract which is a cooperative effort between the Federal Railroad Administration and the Association of American Railroads on improved track structures. The entire program is in response to recognition of the desire for a more durable track structure. To this end, the program is a multi-task effort involving (1) Mathematical modeling to develop equations that describe the behavior of the track structure under loading, (2) ballast and foundation material research to describe the behavior of ballast and foundation materials under repeated loads, (3) testing to develop information on the behavior of the components of the track structure under repeated loads and to validate the mathematical models, and (4) the design of a track research facility in which accelerated service tests can be carried out.

This report constitutes a summary of the results of the various phases of the Ballast and Foundation Materials Research Program.

A special note of thanks is given to Mr. William S. Autrey, Chief Engineer, Atchison, Topeka and Santa Fe Railway; Mr. R. M. Brown, Chief Engineer, Union Pacific Railroad; Mr. F. L. Peckover, Railway Geotechnical Consultant; Mr. C. E. Webb, Asst. Vice President, Southern Railway System, as they have served in the capacity of members of the Technical Review Committee for this Ballast and Foundation Materials Research Program; and Dr. R. M. McCafferty as the Contracting Officer's Technical Representative of the FRA on the entire research program.

W. So
Manager and Principal Investigator
Track Structures Research Program
Association of American Railroads

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 The Problem

Track stability is essential for the economical and safe operation of railroad systems. The provision and maintenance of stable track has become a subject of renewed interest because of the cumulative effects of deferred track maintenance over a long period of time and heavier traffic loading. The problem has been further worsened because of inadequate technology to perform engineering analyses of track support system response and performance. This limited technology plus the lack of methodology to assess the economic impact of providing better designed new track or converting poor track into good track has not provided any clear incentive to the railroads. Over the years, empirical or semi-empirical design methodologies have evolved which fail to explain the mechanistic behavior of the track support system assemblage consisting of rails, ties, ballast, subballast, and subgrade.

An idealized engineering design process for the track support system is shown schematically in Figure 1.1. Since the support system is a structural system, the basic and the most important aspects of the design process are the structural model (or models) and material characterization. Traffic loading, environmental conditions, and the subgrade support are the primary inputs to the design process. The structural model, after incorporating proper material characterization, is used to evaluate the primary structural response in terms of stresses, strains, and deflections of the track support system. Performance of the track support system is then predicted using transfer functions (relationships or correlations between the primary structural response and performance).

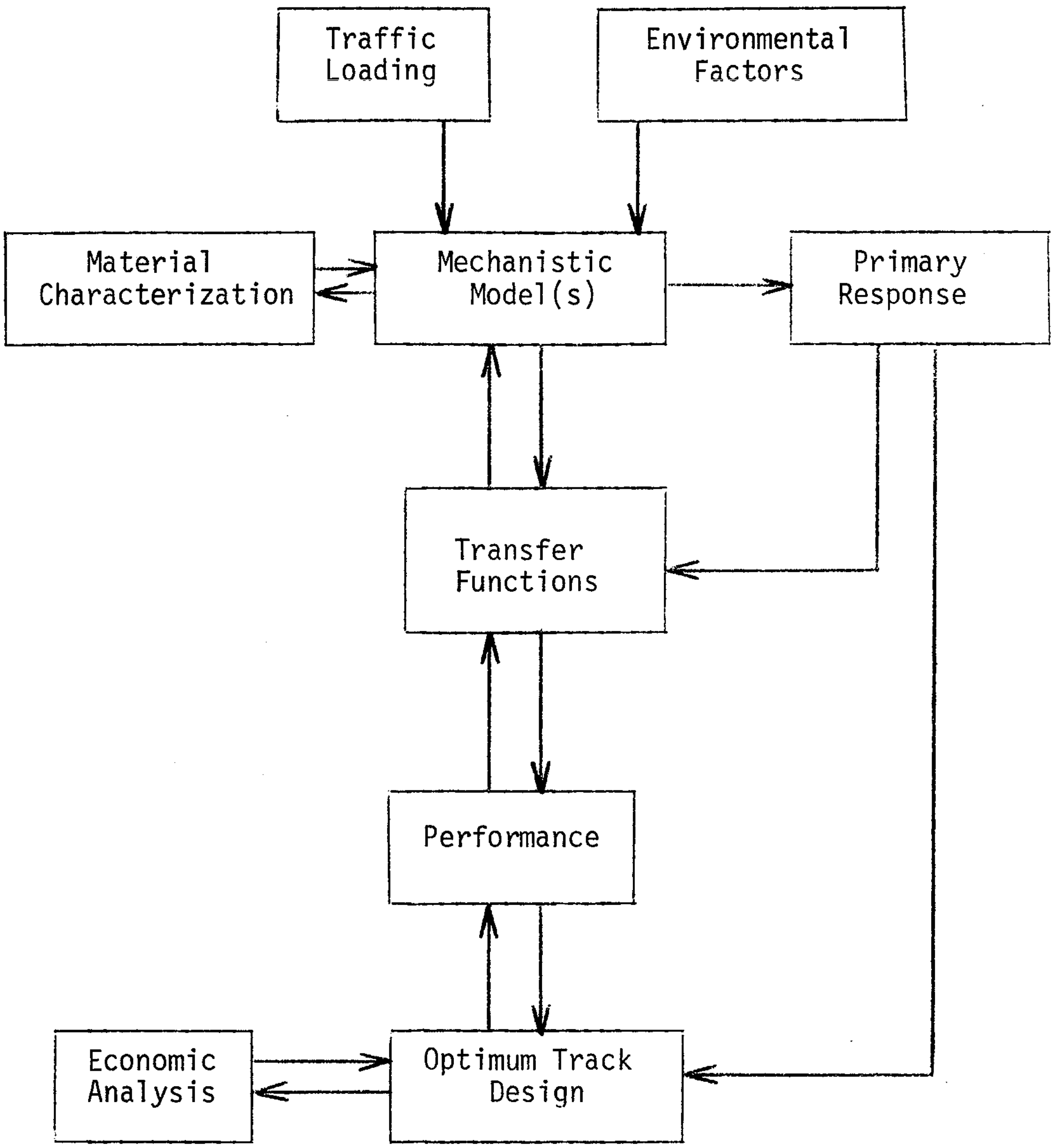


Figure 1.1. Track Support System Design Process.

Therefore, to facilitate the engineering design system for the track support system, it is essential to have adequate technology to:

1. Determine the primary response (stresses, strains, and deflections) of the track support system to the applied traffic loading.
2. Define the interactions among the various components (rail, tie, ballast, subballast, subgrade) of the track support system.
3. Evaluate the significant engineering properties and/or characteristics of the track support system components.
4. Develop transfer functions and material utilization criteria by which it is possible to predict performance based on track support system response.
5. Assess the effects of environment (primarily moisture and temperature) on track support system response and performance.
6. Evaluate field performance of the track support system.
7. Perform economic analyses of differing alternatives for providing an adequate system.

1.2 Project Research Objectives

The specific objectives of the "Ballast and Foundation Materials Research Program" are those tasks defined by the original work statement:

Task 1. Identify failure and other useful performance criteria for ballast and foundation materials.

Task 2: Identify relationships between loading environment and ballast and foundation material behavior.

Task 3: Identify environmental factors that influence ballast and foundation material behavior and the relative extent and importance of these.

Task 4: Identify material parameters that are meaningful for evaluating performance and test performance for determining these properties.

Task 5: For the total track structure performance, identify relationships between ballast and foundation material behavior, and environmental factors for combinations of materials, loadings, environment and track configuration.

Task 6: Perform rank ordering of the ballast, subballast, and subgrade materials according to their performance in service.

Task 7: Identify procedures where ballast and foundation materials properties may be modified to improve material performance.

Task 8: Identify the costs associated with the use of each type of ballast material.

1.3 Project Work Plan

The work plan outlined below describes the major phases of project activity. The manner in which the various phases of project activity contribute to the accomplishment of the specified tasks is indicated in Table 1.1.

Phase I Technical Data Bases

The relevant literature pertaining to the pertinent properties of granular materials, ballast materials, fine-grained soils, and structural models was reviewed. Based on the reviews and other available information sources, current technical data bases were developed (1).

Phase II Development of a Structural Model and Materials Evaluation Procedures

A "mechanistic structural analysis model" was developed and testing procedures established for evaluating the properties of the ballast and foundation materials needed as inputs to the structural model (2).

Table 1.1. Work Phases Contributing to the Achievement of the Designated Tasks.

Phase Number / Task Number	I	II	III	IV	V	VI
1	X					
2	X	X				
3	X	X				
4	X	X	X	X		
5	X	X	X	X		
6	X	X	X	X		
7	X	X	X	X		X
8	X		X	X	X	X

Phase III Parameter Studies and Sensitivity Analyses

The structural model developed in Phase II was utilized to establish the effects of various parameters on track support system response (3).

Phase IV Materials Evaluation Study

A series of laboratory tests were conducted with selected foundation soils, ballast, and subballast materials to determine their pertinent engineering properties as previously identified (4). The ballast, subballast, and foundation materials selected for use in the laboratory study represented a range in both engineering properties and types and sources of materials. Lateral stability tests were also conducted for different ballast materials using a 3-tie and a 1-tie test assembly (22).

Phase V Economic Evaluation

Costs associated with the use of different types of ballast materials were identified and the cost effectiveness of the various ballast materials ranked according to transportation costs (19).

Phase VI Preparation of Conclusions, Summary and Recommendations

Data and information obtained from the technical literature and that developed in the project are summarized and analyzed with respect to establishing definitive responses to the previously described tasks. Appropriate conclusions and recommendations are developed and areas of technological need identified.

1.4 Report Objectives and Organization

The primary objective of this report (Phase VI) is to summarize the data and information obtained from the technical literature and that developed in the project. The project activities were carried out in phases as described above. The contribution of each phase to the accomplishment of the specified tasks is indicated in Table 1.1.

The report has been divided into 6 chapters. Chapter 1 contains the introductory material. Chapter 2 contains a summary of ballast and foundation materials research (Phase IV) and includes the results of repeated load triaxial testing for evaluating resilient response and permanent deformation behavior. A discussion of track support system behavior under load (Phases II and III) is presented in Chapter 3. The results of a survey (19) conducted to determine various ballast costs (Phase V) are summarized in Chapter 4. Major conclusions developed during the course of the research program and recommendations for future studies are presented in Chapter 5.

CHAPTER 2

SUMMARY OF BALLAST AND FOUNDATION MATERIALS RESEARCH

2.1 General

Railroads have long used ballast to provide support for the rail-tie system and to provide a free draining medium. Two of the problems related to the performance of ballast materials are the excessive elastic deformations caused by the rapid application and removal of wheel loads and the accumulation of large permanent deformation in the ballast and subgrade resulting from many repetitions of individual wheel loads.

Excessive elastic deformations in the track support system may cause reductions in the fatigue life of the rail and tie components. In addition the ride quality of both freight and passenger cars is reduced if the elastic deformations in the conventional railway track support system (CRTSS) are excessive.

Permanent deformations in the ballast and subgrade necessitate continual realignment of the rail-tie system by addition or reworking of ballast. Present maintenance practice is to tamp only the portion of the ballast near the rail and to leave the center undisturbed. The practice results in the addition of ballast primarily in the proximity of the rails; ballast pockets result. The ballast pockets serve as potential traps for water; the result is high levels of subgrade saturation, thus worsening an already bad situation. Continued maintenance therefore is not a satisfactory solution.

The behavior of the subgrade soil (foundation material) is also important. Both elastic and permanent deformations are significant. Numerous factors have been found to have a significant effect on pertinent foundation material properties, including such factors as loading conditions, moisture-density, temperature, and certain inherent material characteristics.

This part of the report summarizes some of the important aspects of elastic and permanent deformation behavior of ballast and foundation materials as detailed in the Phase IV report entitled, "Material Evaluation Study" (4).

2.2 Resilient Response of Ballast

Modern analytical techniques for predicting the structural response of layered systems require better characterization of the dynamic response of materials than can be obtained from static testing methods. It is desirable to evaluate the response of granular materials under laboratory conditions which simulate the in-service conditions.

Several investigators have used the concept of resilient modulus to describe the behavior of granular materials subjected to repeated loading conditions. Resilient modulus is defined as the repeated deviator stress divided by the recoverable portion of the axial strain in a triaxial test. Values of resilient modulus, E_r, at several stress states are obtained from laboratory testing. To account for the stress dependent nature of the materials several predictive equations have been developed; two of the more widely used equations are the following:

$$E_r = K\theta^n \quad \text{and} \tag{2.1}$$

$$E_r = K' \sigma_3^m \quad \text{where} \tag{2.2}$$

K, K', n, and m are constants determined from regression analyses of laboratory data; σ_1, σ_2, and σ_3 are major, intermediate, and minor principal stresses, respectively, and θ is the first stress invariant, $\sigma_1 + \sigma_2 + \sigma_3$. $\theta = \sigma_1 + 2\sigma_3$ in the triaxial test.

Some of the more important findings of previous investigations and some of the factors affecting resilient response of granular materials are discussed in detail in References 1, 2, and 3. Most of the repeated load tests of granular materials have emphasized the characterization of the resilient behavior of sands or dense graded aggregates; little work has been done involving open graded aggregate such as ballast.

The results pertaining to the study of the resilient response of ballast follows.

2.2.1 Ballast Materials Used

Six materials commonly used for ballast were chosen so that comparisons of their repeated load behavior and natural properties could be made. The materials selected were dolomitic limestone from Kankakee, Illinois; blast furnace slag from Chicago; granitic gneiss from Columbus, Georgia; basalt from New Jersey; and crushed and uncrushed gravel from McHenry, Illinois. Blast furnace slag from the Kansas Test Track was also tested.

In order to relate the results of the repeated load tests to the physical properties of the materials, standard characterization tests were performed on each type of material. The standard tests and references are included in Table 2.1. The results of the tests are summarized in Table 2.2.

To examine the effects of different gradations on resilient response, three gradations were included in the testing program. Two standard AREA (American Railway Engineering Association) gradations, No. 4 and No. 5, were selected by using the center values of the recommended gradation bands. A third gradation was chosen based on the use of the Talbot equation using an exponent of 2/3. The Talbot equation is given below:

$$p = 100\left(\frac{d}{D}\right)^n$$

where

d = sieve size in question
p = percent of material finer than the sieve
D = maximum size of the aggregate
n = an exponent

Table 2.1. Standard Characterization Test References.

	Designation		
	ASTM[a]	AASHTO[b]	British Standard[c]
Particle Index	D3398		
Specific Gravity	C 127	T 85	
Los Angeles Abrasion	C 131	T 96	
Gradation Parameter[d]			
Flakiness Index			812-15
Soundness	C 88	T 104	
Crushing Value			812-34

(a) Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, 1975.

(b) AASHTO Materials, 11th ed., American Association of State Highway and Transportation Officials, Washington, D. C., 1974.

(c) British Standard 812, Methods for Sampling and Testing of Mineral Aggregates, Sands, and Filters, British Standards Institution, 1967.

(d) Hudson, S. B., and Waller, H. F., "Evaluation of Construction Control, Procedures - Aggregate Gradation Variations and Effects," National Cooperative Highway Research Program Report 69, 1969.

Gradation Parameter = $\overline{A}$

$$2^{\overline{A}} = \frac{54.8}{d} \quad \text{where:}$$

$$\overline{d} = \frac{0.443\ (d_1 - d_2)}{\log\ (d_1/d_2)}$$

d_1 = size of larger sieve, mm and d_2 = size of smaller sieve, mm. The gradation parameter of an aggregate is the weighted mean of the values of the various size fractions.

Table 2.2. Characterization Test Results.

Material	Gradation	Particle Index	Specific Gravity	Los Angeles Abrasion Loss, %	Gradation Parameter	Flakiness Index	Soundness Loss, %	Crushing Value
Limestone			2.626	34.2				22.7
	No. 5	13.80			1.846	17.52	12.3	
	No. 4	13.75			1.074	16.78	18.5	
	Well graded	14.09			2.039	17.33	15.3	
	n=1/2	14.07			2.295	17.04	14.5	
	n=1/2	14.07			2.178	17.04	14.5	
	CA-10	13.90			4.959	13.00	14.5	
Granitic Gneiss			2.679	34.7				26.1
	No. 5	13.61			1.846	15.60	0.23	
	No. 4	13.45			1.074	14.39	0.25	
	Well graded	13.68			2.039	15.71	0.26	
Chicago Blast Furnace Slag			2.133	37.8				37.3
	No. 4	15.68			1.074	3.59	0.75	
	Well graded	16.63			2.039	3.76	0.87	
Basalt			2.775	12.3				12.4
	No. 5	15.10			1.846	19.69	6.14	
	No. 4	15.40			1.074	17.33	4.93	
	Well graded	14.83			2.039	16.11	4.86	
Crushed Gravel			2.678	28.0				20.0
	No. 4	11.85			1.074	10.12	7.45	
Gravel			2.658	23.2				13.8
	No. 5	7.54			1.846	4.03	5.06	
	No. 4	10.17			1.074	5.79	5.78	
	Well graded	8.86			2.039	6.58	5.84	
Kansas Test Track Blast Furnace Slag			2.521	26.7				25.2
	No. 5	14.10			1.846	5.39	0.87	

Because one of the main considerations of ballast is that it be free draining, the results obtained through the use of the Talbot Equation were only maintained through the No. 4 sieve. To insure a high permeability, no material finer than the No. 16 sieve was used. The gradation determined through the above analysis was labeled "well graded". A conservative estimate of the permeability of the well graded material is 5000 ft (1500 m) per day.

For comparison purposes a dense-graded system (Illinois DOT CA-10 gradation)was also used for the limestone aggregate. The various gradations are shown in Table 2.2.

2.2.2 Test Equipment and Procedure

A U. S. Army Engineer Waterways Experiment Station triaxial cell design was modified, and the cell was fabricated at the University of Illinois. The confining pressure was supplied by air pressure and was not cycled during the tests. To satisfy the constraints of the equipment and to approximate in-service conditions, a frequency of 50 applications per minute and a haversine load pulse of 0.15 seconds duration were selected.

Because one of the objectives of this study was to determine the effects of gradation and maximum size on ballast behavior two different sample sizes were used. Samples 6 inches (152 mm) in diameter were used for the No. 5 ballast gradation which has a maximum particle size of 1 1/2 inches (38 mm). The No. 4 ballast gradation has a maximum particle size of 2 inches (51 mm), and therefore larger samples 8 inches (203 mm) in diameter, were used. Thus, a diameter to maximum particle size ratio of 4 was maintained. All of the prepared samples had a height to diameter ratio of 2:1 or more to minimize end effects on deformation measurements.

Because densities are generally not specified when ballast is placed and because no field data are available regarding in-situ ballast densities, no attempt was made to attain a predetermined density. Instead, three degrees of vibratory compaction were selected. For low density specimens, each layer of aggregate was placed and rodded 10 times. For medium density specimens each layer was compacted for 5 seconds with the vibratory hammer, and for the high density specimens each of the three layers was vibrated for 45 seconds. Little increase in density was attained for compaction times greater than 45 seconds and the gradation change (aggregate degradation) for limestone due to compaction was extremely small.

From finite element analyses of CRTSS (3), values were obtained for the stress at various points in the ballast layer. Representative values of deviator stress of 45 psi (310 kN/m^2) and confining pressure of 15 psi (130 kN/m^2) were selected as representative of the stress occurring approximately 2 inches (51 mm) beneath a crosstie. Each specimen was conditioned at those stress conditions for 5000 load applications. After conditioning, each specimen was tested for resilient modulus at each of 7 stress levels as follows:

Deviator Stress		Confining Stress	
psi	kN/m^2	psi	kN/m^2
60	414	15	103
30	207	15	103
40	276	10	69
20	138	10	69
20	138	5	34
15	103	5	34
10	69	5	34

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

2.2.3 Test Results

Table 2.3 is a summary of the physical properties of the specimens

Table 2.3. Summary of Primary Test Specimen Properties.

Material Type	Gradation	Compaction Level*	Compaction Density (pcf)	Void Ratio
Limestone	No. 5	Low	90.3	0.81
	No. 5	Med	103.2	0.59
	No. 5	High	106.8	0.55
	No. 4	Low	88.9	0.84
	No. 4	Med	95.9	0.71
	No. 4	High	99.0	0.66
	well graded	Med	111.9	0.46
	CA-10	Med	123.8	0.32
	CA-10	High	130.6	0.25
Granitic Gneiss	No. 5	Low	89.3	0.87
	No. 4	Low	93.0	0.76
	No. 4	Med	97.5	0.71
	No. 4	High	102.3	0.63
	well graded	Med	114.6	0.46
Chicago Blast Furnace Slag	No. 4	Low	66.7	1.00
	No. 4	Med	71.0	0.87
	No. 4	High	73.2	0.82
	well graded	Med	86.3	0.54
Basalt	No. 5	Med	107.5	0.63
	No. 4	Med	95.3	0.82
	well graded	Med	115.7	0.50
Crushed Gravel	No. 4	Med	100.8	0.66
Gravel	No. 5	Med	126.7	0.31
	No. 4	Low	102.4	0.62
	No. 4	Med	107.5	0.54
	No. 4	High	112.1	0.48
	well graded	Med	131.7	0.26
Kansas Test Track Blast Furnace Slag	No. 5	Low	90.8	0.73
	No. 5	Med	98.9	0.59
	No. 5	High	100.9	0.56

*Low - rodded 10 blows per layer
Med - 5 seconds per layer vibration
High - 45 seconds per layer vibration

tested. It is interesting that the most dense specimen, the well graded gravel, attained a density almost twice that of the least dense, the low compactive effort blast furnace slag.

The data collected from the resilient response testing was used in regression analyses to develop equations of the following type:

$$E_r = K\Theta^n$$

where

E_r = resilient modulus,

n, K = constants representing slope and intercept respectively, on a log-log plot, and

Θ = the first stress invariant, $\sigma_1 + \sigma_2 + \sigma_3$

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

Figure 2.1 presents typical resilient response of ballasts tested.

Correlation analyses were run to determine the effects of various parameters on the resilient response of ballast. The results are summarized below:

1. The resilient response of a specimen of open graded granular material is independent of stress history so long as the specimen has not been subjected to a stress level which would cause failure.
2. The resilient modulus of open graded materials is appreciably higher than that of dense graded aggregate for a given stress level.
3. The resilient modulus of open graded ballast materials is virtually insensitive to changes in gradation and compaction level. The dependence of resilient response on material type is weak and inconsistent, and therefore, no conclusion is drawn with respect to material type.

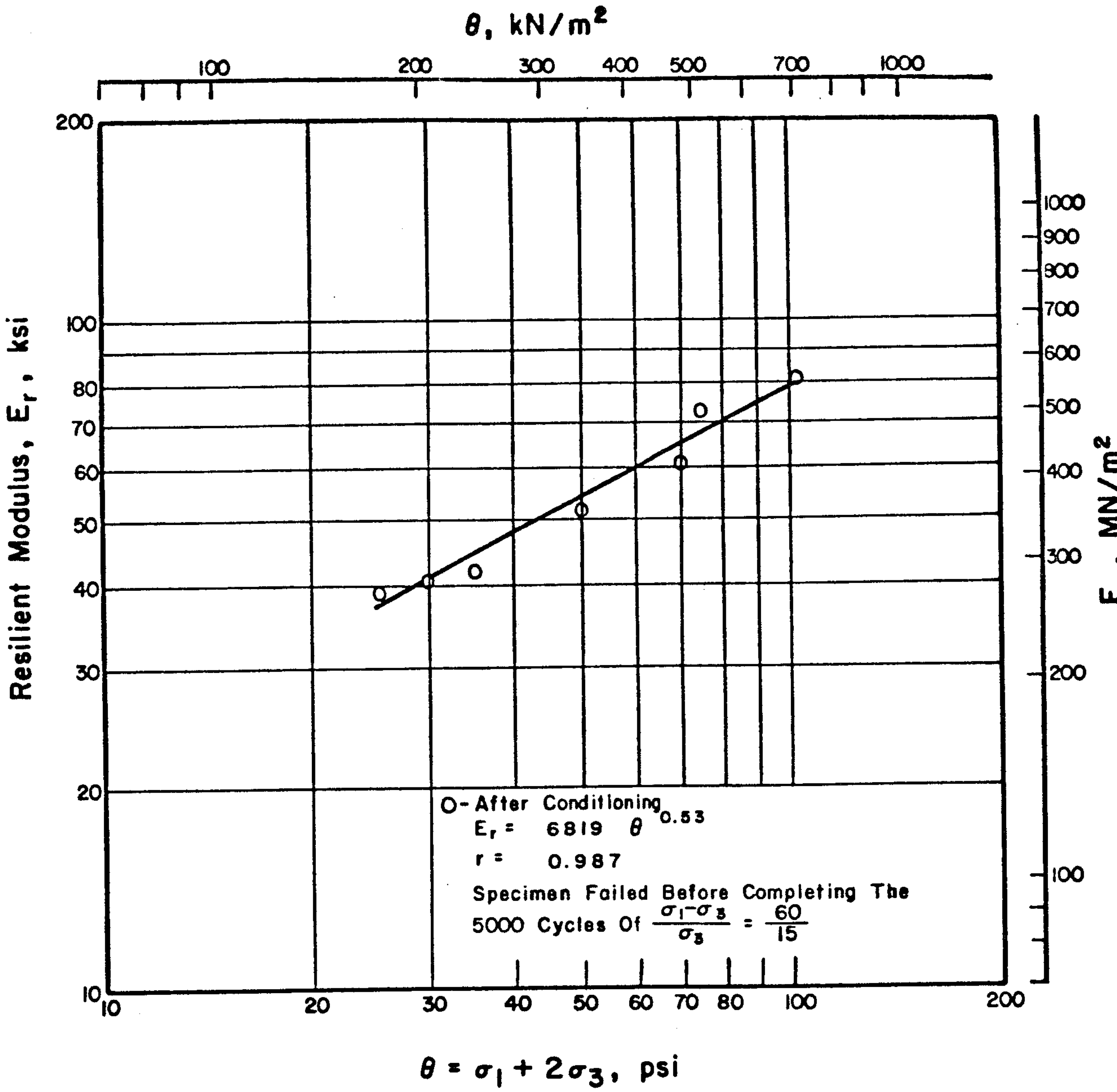


Figure 2.1. Typical Resilient Response of Ballasts Tested.

4. Stress level is the variable most directly influencing the resilient modulus of granular materials. The stress dependent nature of ballast type materials can be characterized by the predictive equation:

$$E_r = K\Theta^n$$

2.3 Permanent Deformation behavior of Ballast

Most of the factors affecting the resilient behavior of granular materials influence the repeated load permanent deformation behavior in similar manners. Some of the more important findings of previous investigations and some of the factors affecting the permanent deformation behavior of granular materials are discussed in detail in References 1, 2, and 4. Since little work has been done to evaluate the permanent deformation behavior of open graded ballast, a study was conducted with the seven ballast materials listed in Section 2.2.1 using the repeated load triaxial cell described in Section 2.2.2. The purpose of this study was to determine the effects of material type and gradation on the permanent deformation behavior and degradation under repeated load conditions of a variety of aggregates. The effects of stress history, degree of compaction, and stress level were also considered.

The study was conducted in two stages. In the first stage, which was part of the resilient response study, the test specimens of seven ballast material types were subjected to 5000 cycles at various stress states as shown in Table 2.4. In the second stage, specimens of six ballast material types were subjected to 10^6 cycles of loading at a constant state of stress to study the permanent deformation behavior and the mechanical breakdown of the aggregate after 10^6 loading cycles.

2.3.1 First Stage Study

Specimens 6 inches (152 mm) in diameter were used for the No. 5 ballast gradation and larger specimens 8 inches (203 mm) in diameter were

Table 2.4. Standard Test Sequence.

Phase	σ_3 psi	σ_D psi	σ_D/σ_3 psi	Number of Repetitions(1)	Readings(2)
I. Conditioning	15	45	3	5000	10 100 1000 5000
II. Primary					
a. Resilient	15	60	4		
	15	30	2		
	10	40	4		
	10	20	2		
	5	20	4		
	5	15	3		
	5	10	2		
b. Permanent	5	20	4	5000	(2)
	15	60	4	5000	(2)
c. Resilient (3)					
d. Permanent	5	30	6	5000	(2)
	5	40	8	5000	(2)
	15	90	6	5000	(2)
	15	120	8	5000	(2)

(1) 5000 or until failure
(2) same as for conditioning phase
(3) same as the first resilient

used for the No. 4 ballast gradation. A total of 32 specimens of the seven ballast material types was tested.

Before the primary tests were started, preliminary samples were tested to determine the effects of stress history on the permanent deformation behavior of open graded ballast. It was found that the total permanent strain obtained during the gradually increasing stress level sequence was less than that obtained when the specimen was first subjected to a high stress level.

After careful consideration of the preliminary test results, the primary test program was started. Figures 2.2 through 2.10 are the plots for permanent strain versus logarithm of the number of cycles for the data obtained during the conditioning phase of testing which have not been influenced by the effect of other stress levels (no stress history). The results obtained at stress levels other than conditioning are included in Reference 4.

Linear regression analysis was used to develop relationships between the plastic strain and the corresponding number of loading cycles. In general, the best results were obtained for plastic strain versus the logarithm of the number of cycles and for the logarithm of the plastic strain versus the logarithm of the number of cycles. Analysis of variance was also used to determine possible differences among the plastic strain responses of the samples due to gradation, compaction, and material effects. The important findings are summarized below.

1. In sharp contrast to the resilient behavior, plastic strain is affected by stress history. The effect can be explained in terms of primary loading, unloading, and reloading. Large plastic strain results during primary loading. During unloading and reloading elastic strain develops which is accompanied by a small amount of plastic strain.

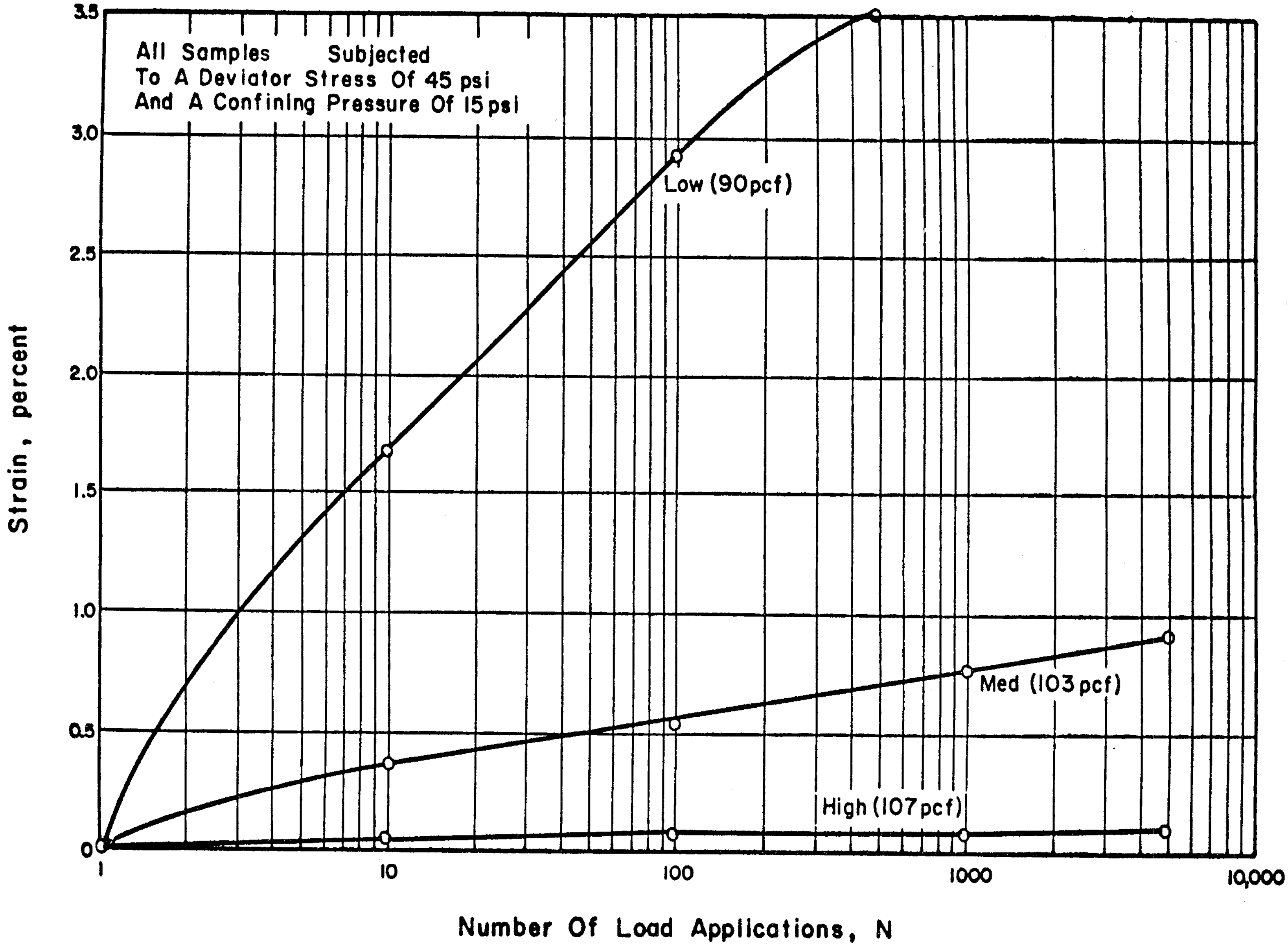


Figure 2.2. Effect of Density on Plastic Strain Response for No. 5 Gradation Limestone.

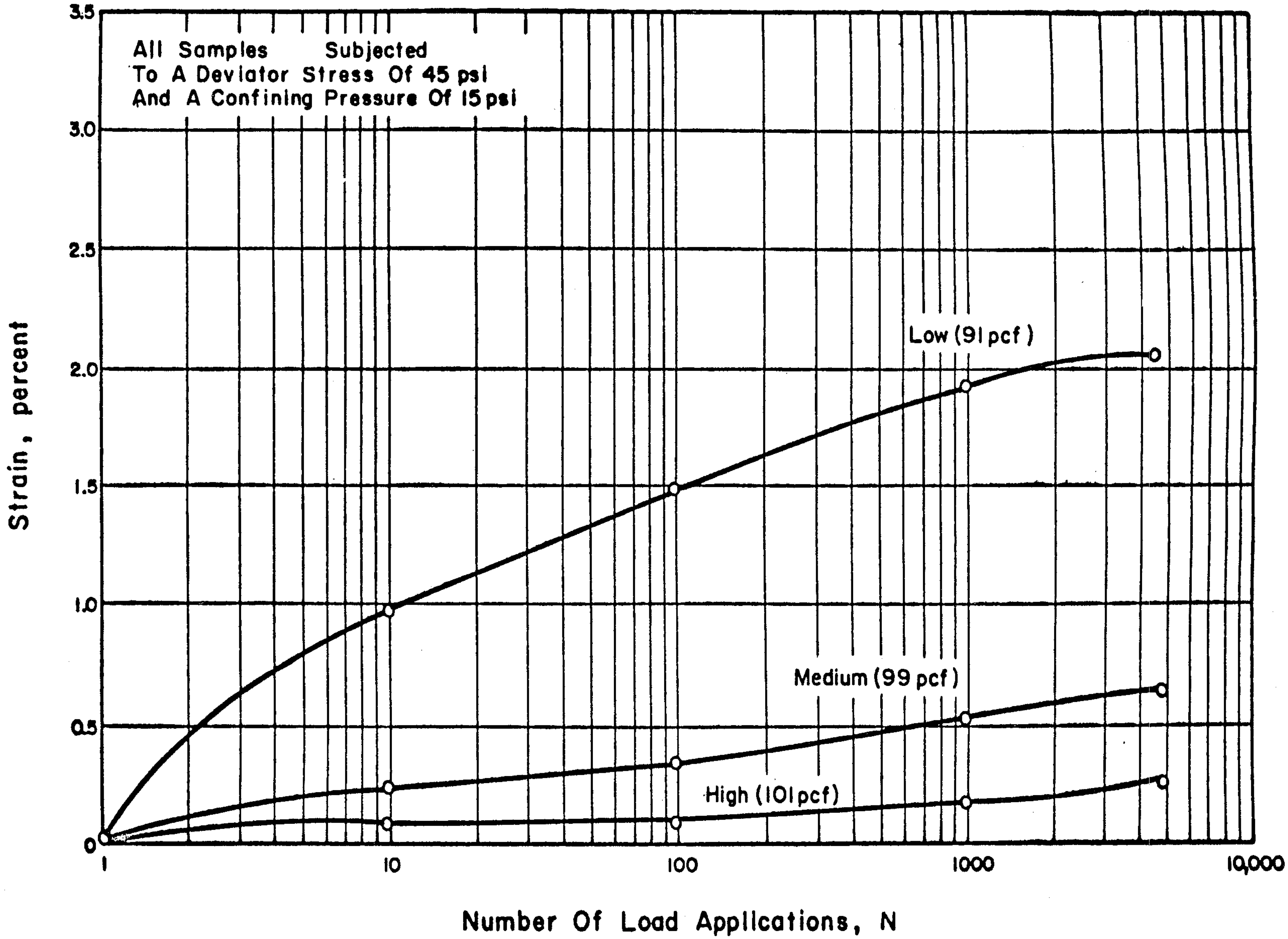


Figure 2.3. Effect of Density on Plastic Strain Response for No. 5 Gradation Kansas Test Track Slag.

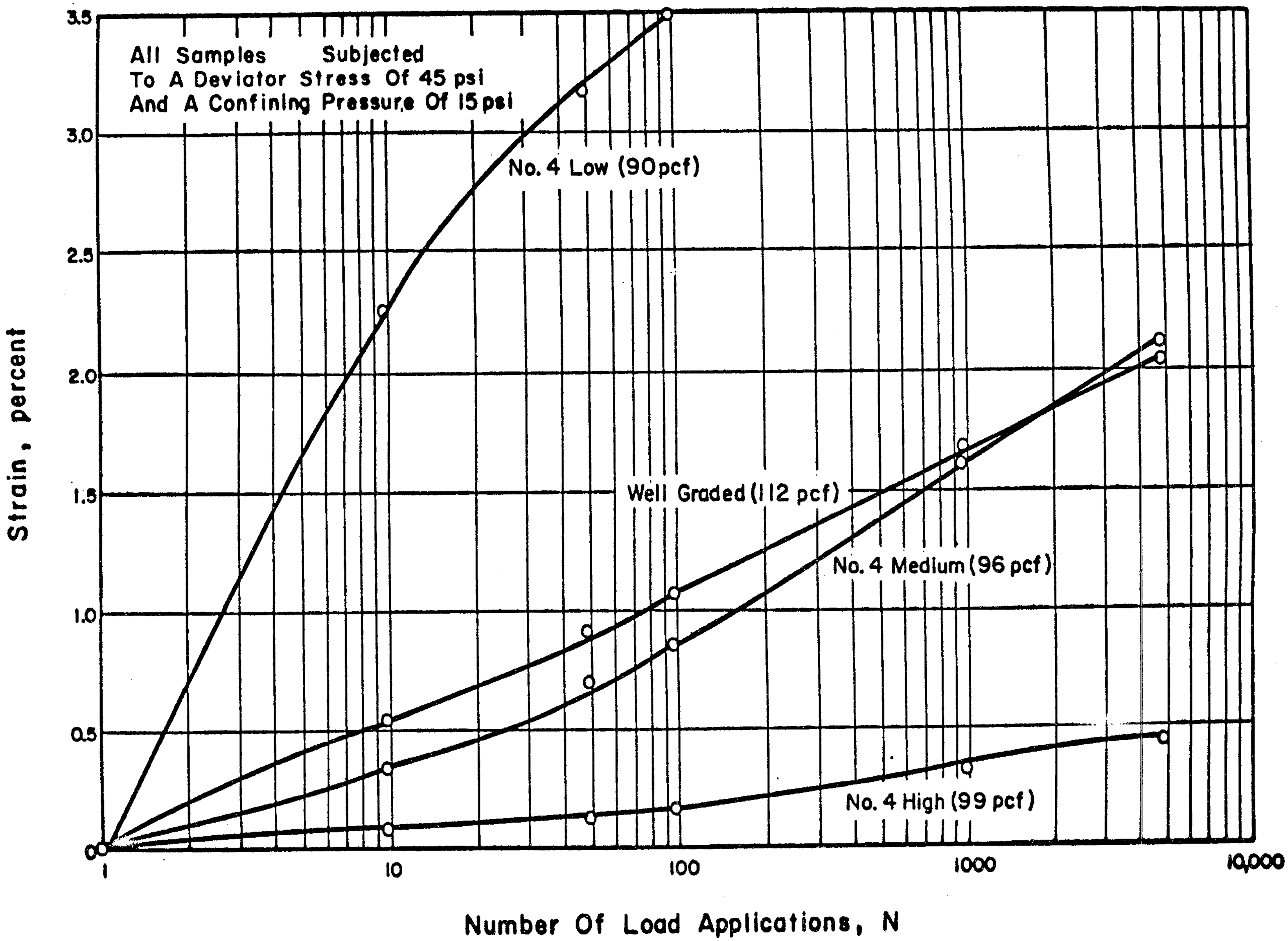


Figure 2.4. Effects of Gradation and Density on Plastic Strain Response for Limestone.

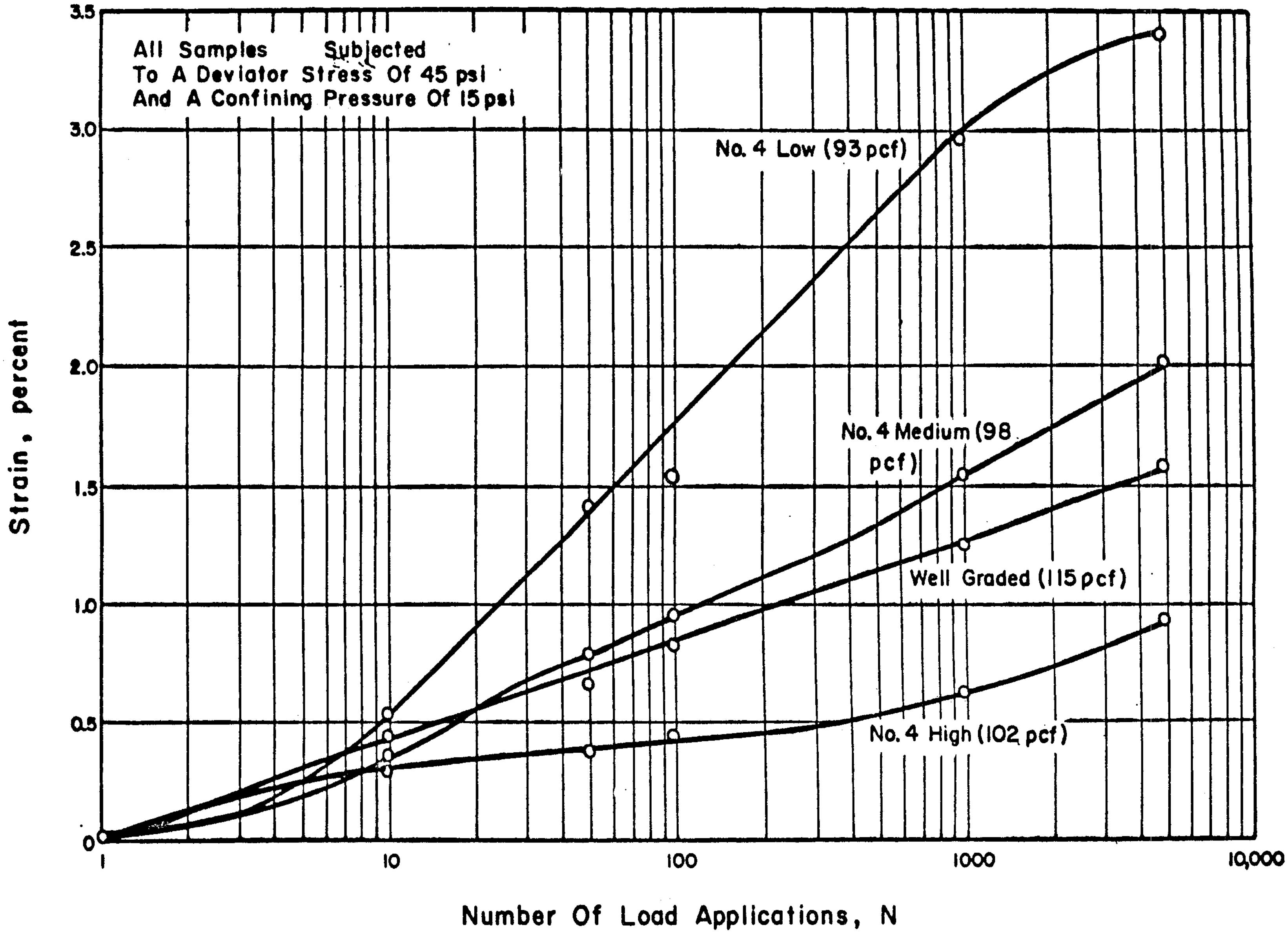


Figure 2.5. Effects of Gradation and Density on Plastic Strain Response for Granitic Gneiss.

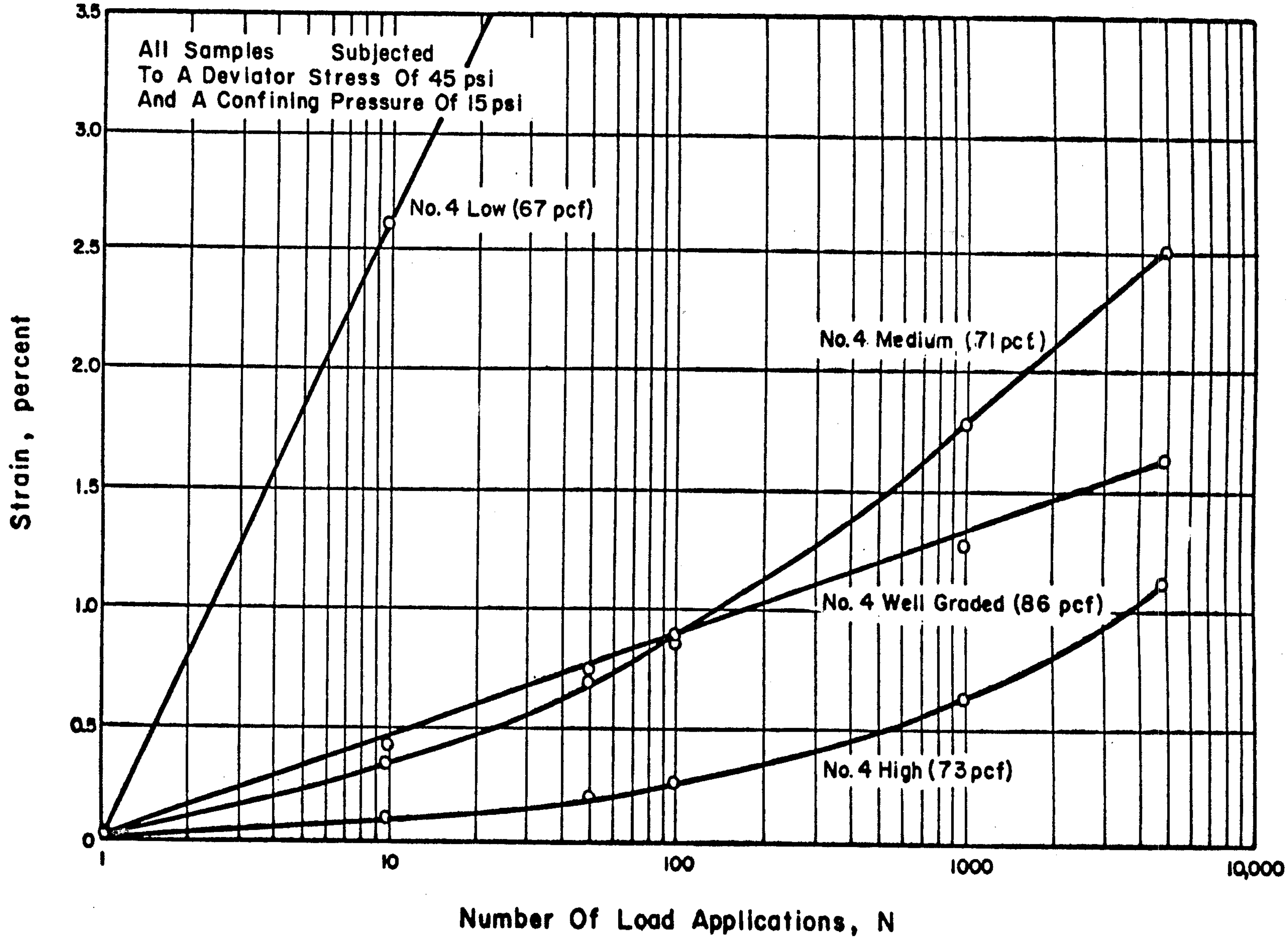


Figure 2.6. Effects of Gradation and Density on Plastic Strain Response for Chicago Blast Furnace Slag.

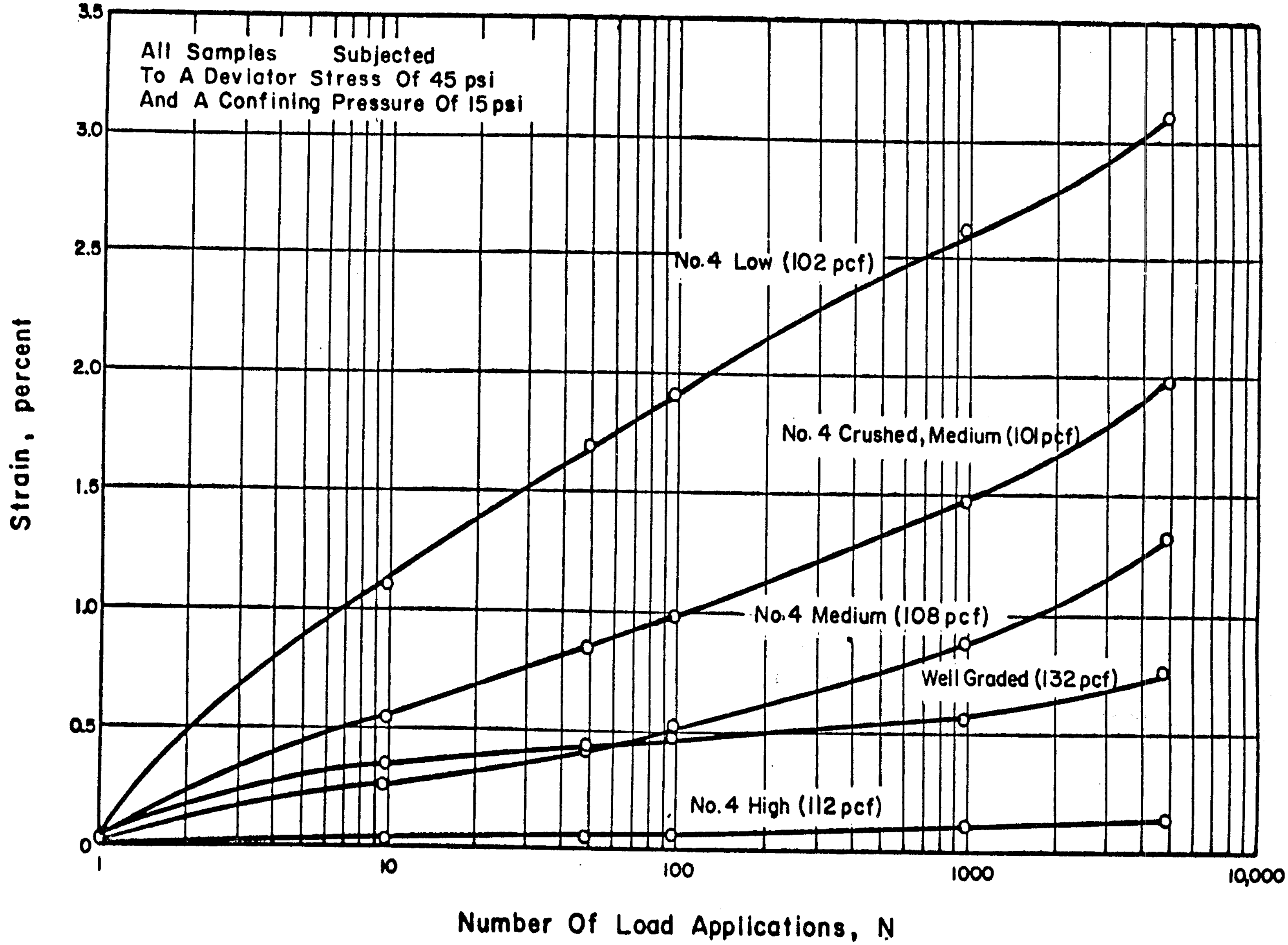


Figure 2.7. Effects of Crushing, Density, and Gradation on Plastic Strain Response for Gravel.

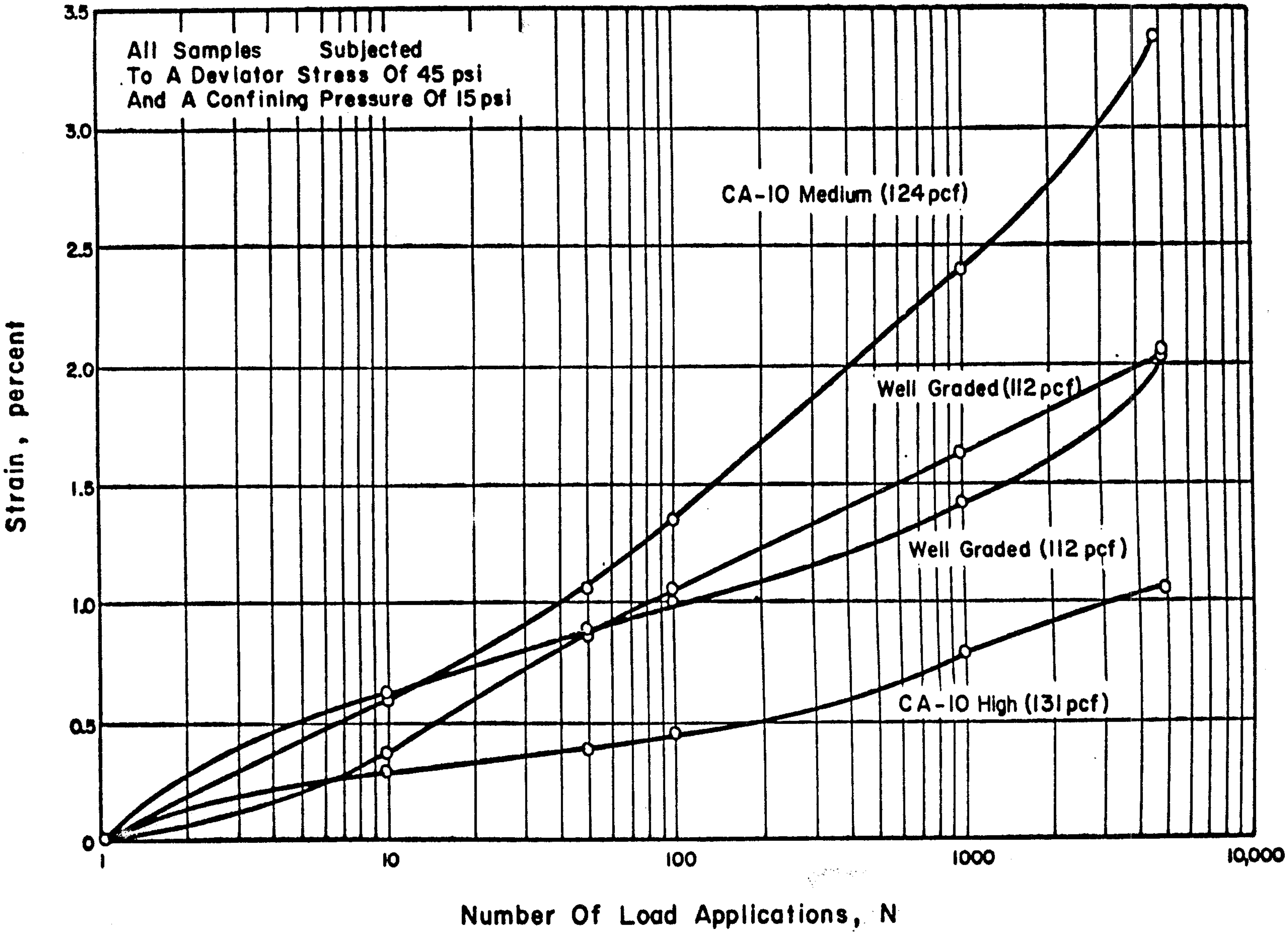


Figure 2.8. Effects of Density and Gradation on Plastic Strain Response for Limestone.

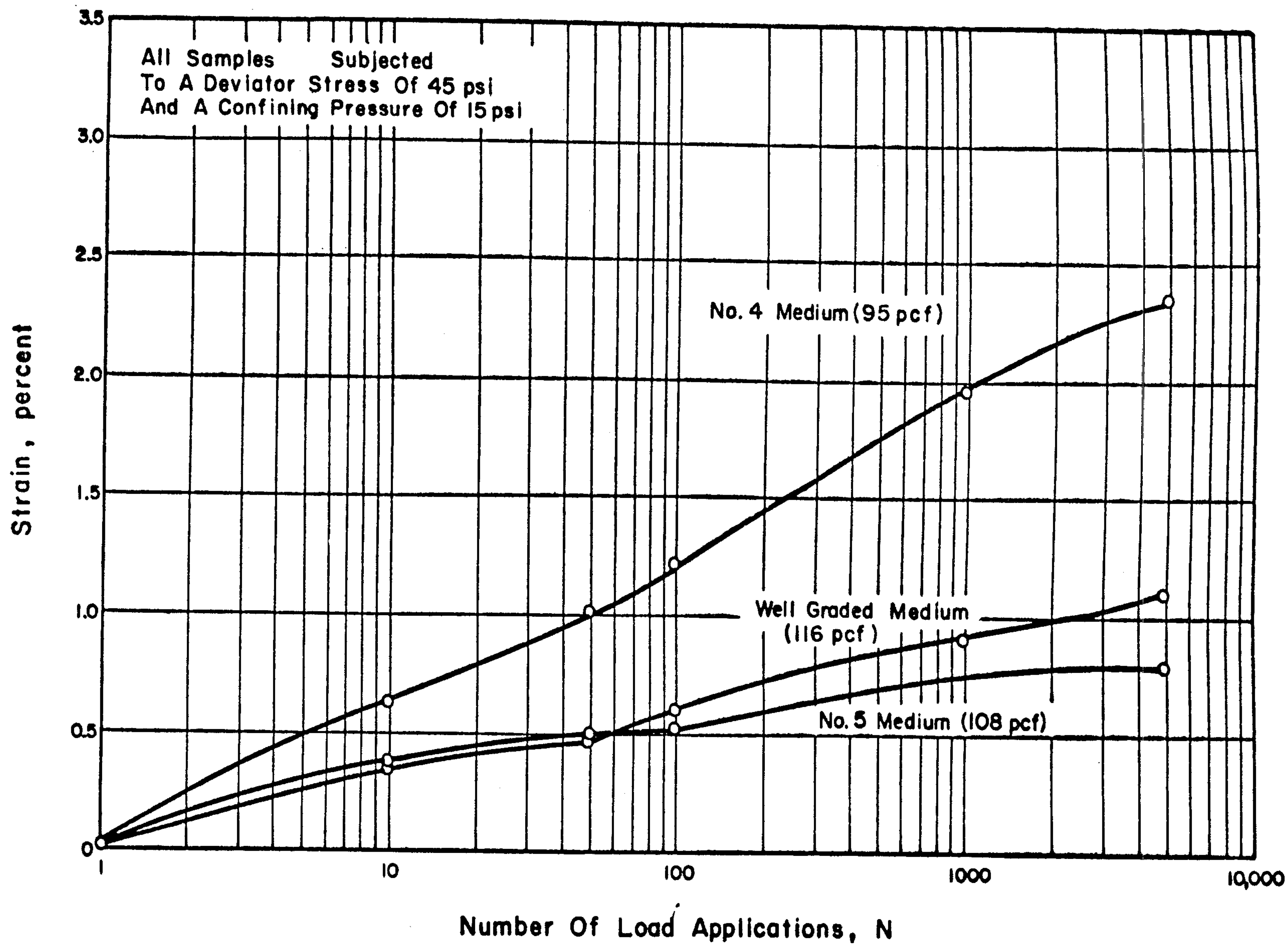


Figure 2.9. Effects of Gradation on Plastic Strain Response for Basalt.

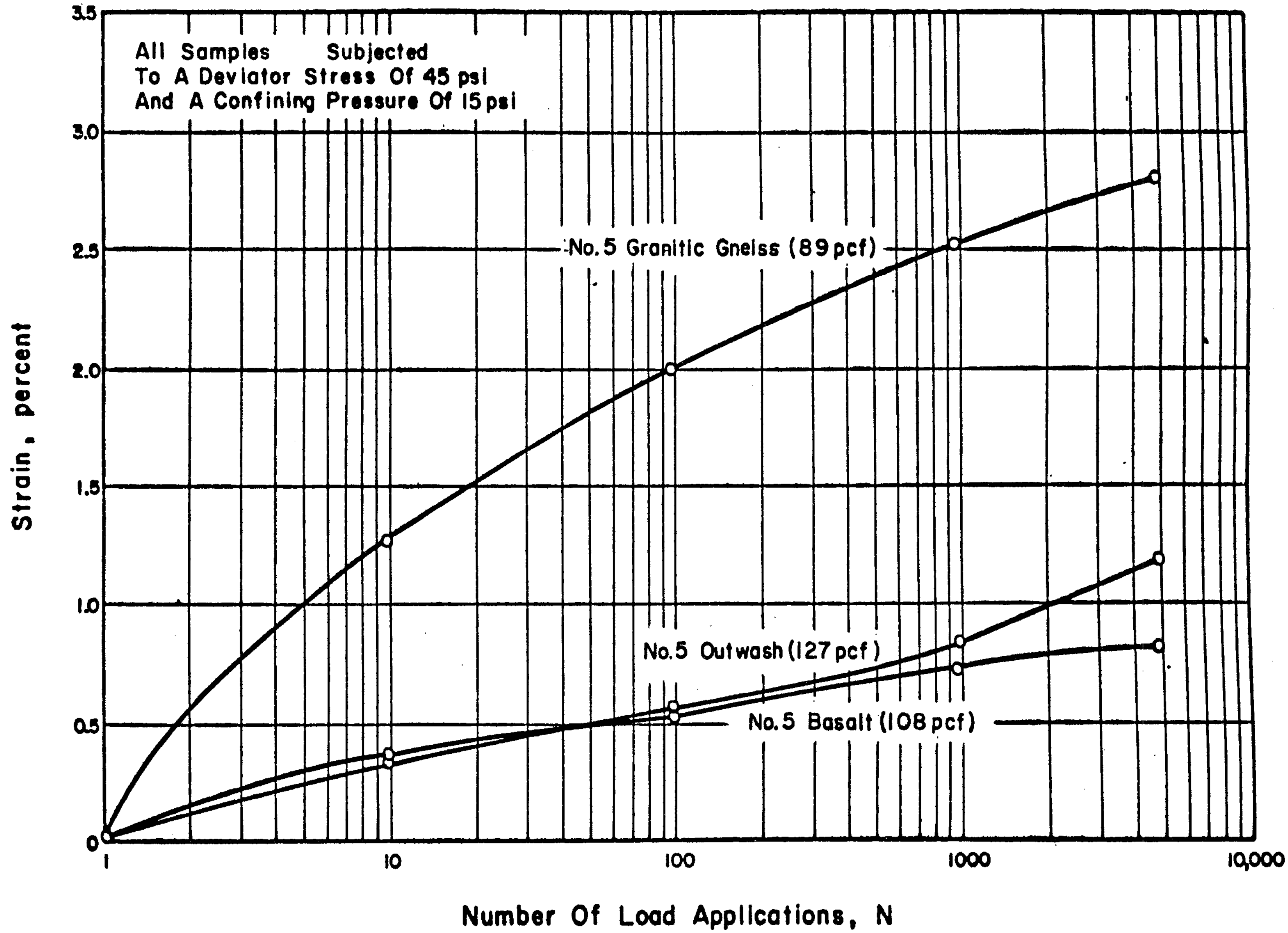


Figure 2.10. Effects of Material Type and Density on Plastic Strain Response.

2. For low stress levels, plastic strain is proportional to the logarithm of the number of cycles. As the stress level is increased a "critical value" is reached and the rate of plastic strain accumulation then increases.
3. Plastic strain accumulation is not solely a function of the repeated deviator stress but depends on both the deviator stress and the confining pressure.
4. In general, the AREA No. 5 ballast and the "well graded" specimens tended to resist permanent deformation better than did the AREA No. 4 gradation material.
5. There is a definite dependence of permanent strain behavior on compaction level. In every case the accumulated permanent strain was least for specimens compacted to the highest densities.
6. No definite conclusion can be made with respect to the affects on plastic strain behavior of material properties such as particle index, soundness, Los Angeles abrasion loss, and flakiness index.

2.3.2 Second Stage Study

The objective of this research was to determine the effects of 10^5 and 10^6 cycles of loading on the permanent deformation of six ballast material types. Also studied was the mechanical breakdown of aggregate after 10^6 loading cycles. The six ballast materials were dolomitic limestone from Kankakee, Illinois; granitic gneiss from Columbus, Georgia; blast furnace slag from Chicago; basalt from New Jersey; and crushed and uncrushed gravels from McHenry, Illinois. Ballast gradation corresponding to AREA No. 4 ballast gradation limits were selected for testing. The physical properties of the ballasts are summarized in Table 2.2. Specimens 8 inches (203 mm) in diameter and 16 inches (406 mm) in length were used. Each specimen was compacted by vibratory compaction in three layers for 5 seconds per layer.

Two series of tests were chosen. The first involved the application of one million loading cycles at a repeated deviator stress of 45 psi (310 kN/m^2) and 15 psi (103 kN/m^2) confining pressure.

To characterize the permanent deformation behavior of ballast at a low confining pressure, simulating ballast conditions near the ballast-subgrade interface, a second series of tests were run with limestone and gravel. A deviator stress of 12 psi (83 kN/m^2) was used. The testing procedure was started using a confining pressure of 3 psi (21 kN/m^2) and subjecting the specimen to 100,000 load applications; the confining pressure was then reduced to 2 psi (14 kN/m^2) and the specimen was subjected to another 100,000 load applications. The confining pressure was further reduced to 1 psi (7 kN/m^2) and an additional 100,000 load cycles were applied.

Typical results of the first series of tests are presented in Figure 2.11. To determine the trend of permanent deformation as the number of loading cycles increased, linear regression between the plastic strains and the logarithm of the corresponding number of cycles was accomplished. Correlation analyses were also conducted to determine the relationships of plastic strain to material properties.

For the degradation study, because the ballast gradation tested (AREA No. 4) contained no material passing the No. 4 sieve, the amount passing the No. 4 sieve after testing was defined as the "total degradation" of the ballast. The total degradation was subdivided into the amounts passing the No. 10, No. 40, and No. 200 sieves. The results are shown in Table 2.5. Correlation analyses were conducted to determine relationships between the material characterization test results and the amount passing the No. 4, No. 10, No. 40, and No. 200

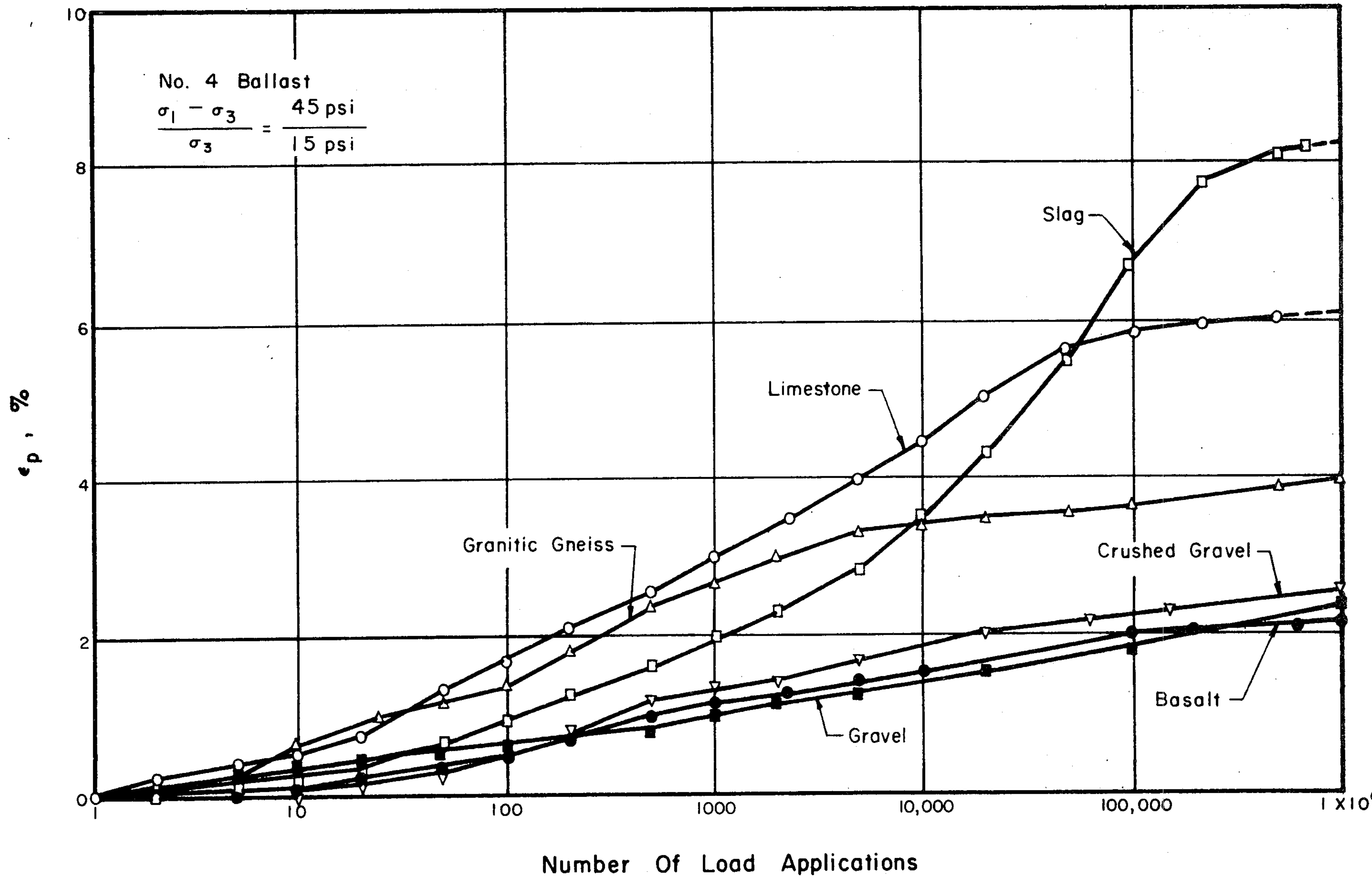


Figure 2.11. Effect of Numbers of Loading Cycles on Plastic Strain (σ_D/σ_3 = 45/15).

Table 2.5. Degradation Results for Long Term Testing.

Sieve Size	Original	Gravel	Granite Gneiss	Crushed Gravel	Limestone	Chicago Slag	Basalt
1 1/2"	95	95.83	97.60	95.00	96.70	96.40	95.51
1"	40	40.07	42.60	41.20	47.56	49.45	41.40
3/4"	7.5	9.37	11.90	11.93	15.22	16.62	12.48
3/8"	2.5	2.78	3.29	3.35	4.69	5.60	3.08
No. 4	0	0.33	0.75	0.74	1.52	2.22	0.43
No. 10	0	0.26	0.50	0.48	0.83	1.56	0.27
No. 40	0	0.23	0.40	0.37	0.56	0.97	0.20
No. 200	0	0.19	0.22	0.26	0.44	0.39	0.12

Note: Gradations are for the material following the application of one million loading cycles (σ_D/σ_3 = 45 psi/15 psi).

sieves and between permanent strain results and degradation. The results are given in Table 2.6.

Some of the significant results of the first series of tests are given below:

1. Permanent strain observed at 10^5 and 10^6 loading cycles correlated significantly with aggregate crushing value. Crushing value appears to be a promising test for predicting resistance to long term, permanent deformation in ballast.
2. Angular materials offer better resistance to permanent deformation at low confining pressures than do rounded materials.
3. Significant correlations for degradation were observed with crushing value, specific gravity (inverse), and density (inverse). No material property correlated significantly with the No. 200 degradation.
4. Long term permanent strain (10^5 and 10^6 loading cycles) correlated significantly with the degradation results.

The second series of tests involved low confining pressure tests for gravel and limestone. The results are presented in Figure 2.12. There was little difference between the behavior of the specimens at 3 psi (21 kN/m^2) confining pressure, but at the lower levels of confining pressure more plastic strain was observed for the gravel specimens.

2.3.3 Effects of Stress History

While the resilient response of ballast is independent of stress application sequence (stress history), the permanent deformation behavior is significantly influenced by stress history. Generally, the total permanent strain is less when a ballast specimen is subjected to gradually increasing stress levels than when the highest stress level is applied first.

Table 2.6. Correlations Between Degradation and Material Characterization Parameters.

A. Correlation Analysis

y Variable (Degradation)	Correlation Coefficient		
	Specific Gravity	Density	Crushing Value
% passing #4	-0.875*	-0.906*	0.888*
% passing #10	-0.945**	-0.949**	0.921**
% passing #40	-0.939**	-0.930**	0.944**
% passing #200	-0.620	-0.583	0.694

*Significant @ α = 0.05 **Significant @ α = 0.01

B. Regression Equations

$P_4 = -0.57 + 0.071\ \overline{CV}$ $R = 0.89$ $S_{\overline{X}} = 0.37$

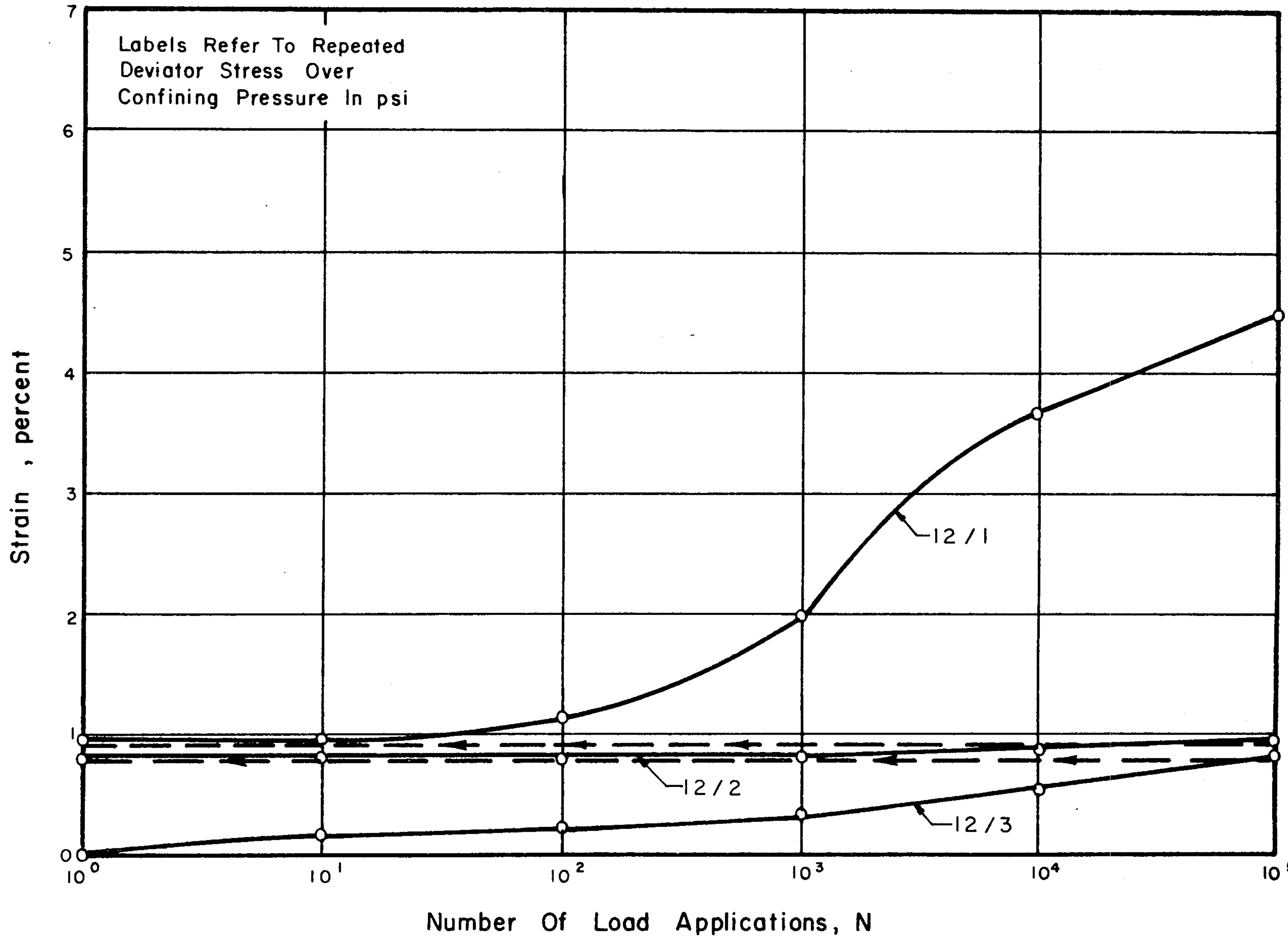
$P_4 = 6.31 - 0.057\ D$ $R = 0.91$ $S_{\overline{X}} = 0.34$

$P_4 = 8.20 - 2.78\ G$ $R = 0.88$ $S_{\overline{X}} = 0.39$

P_4 = % passing #4 D = Bulk Density, pcf

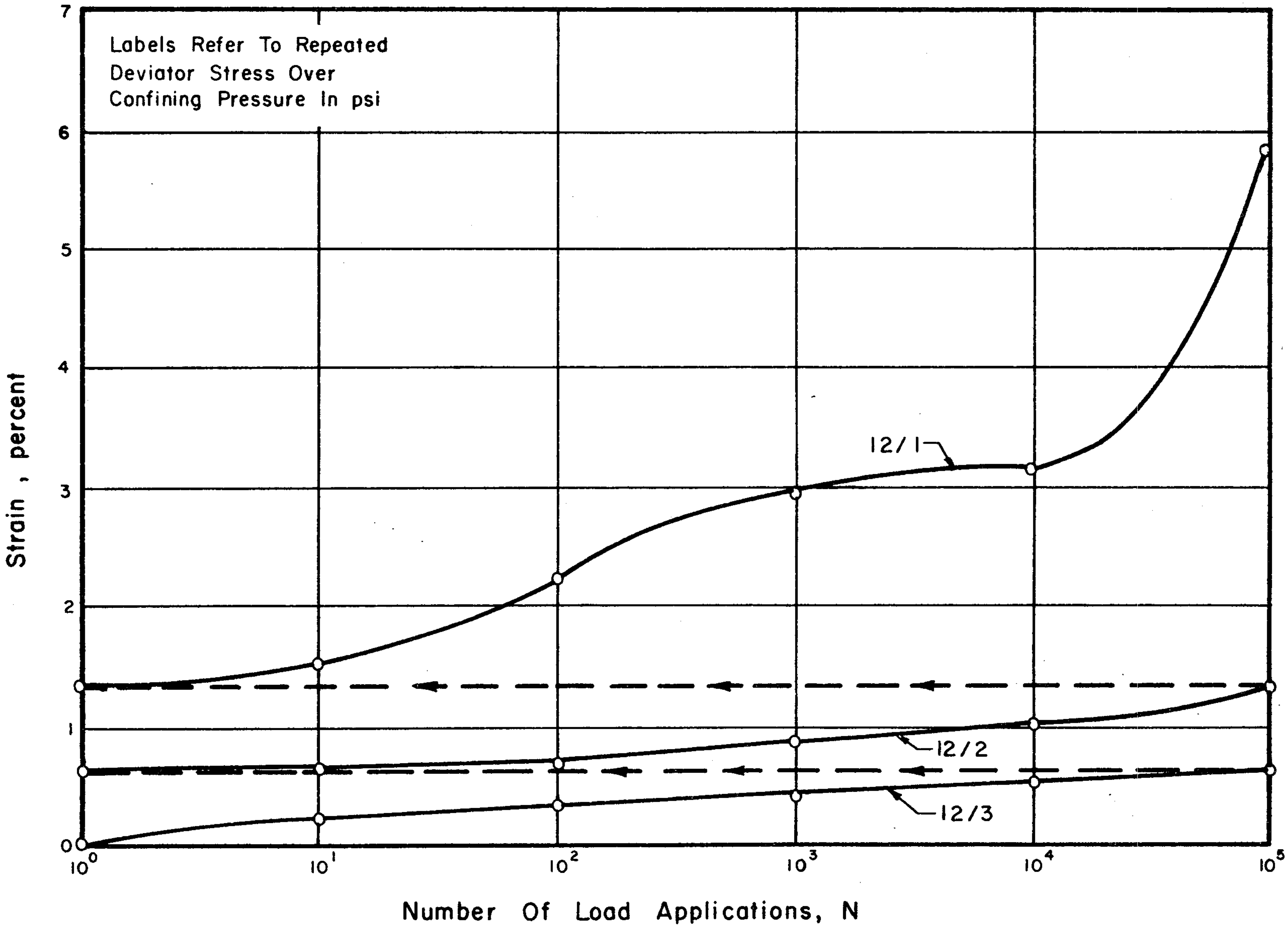
C_V = Crushing Value, % G = Specific Gravity

Note: Degradations were obtained for the six ballast materials following the application of 1×10^6 load applications ($\sigma_D/\sigma_3 = 45/15$).



(a) Limestone

Figure 2.12. Effect of Number of Loading Cycles on Plastic Strain at Low Confining Pressures.



(b) Gravel

Figure 2.12. Effect of Number of Loading Cycles on Plastic Strain at Low Confining Pressures.

The stress history effects were not investigated during this study. However, during the preliminary testing, two similar ballast specimens were used to determine stress history effects. One specimen was tested using gradually increasing stress levels and a second specimen was tested at a constant high stress level. The results are shown in Figures 2.13 and 2.14. The total permanent strain obtained during the gradually increasing stress level sequence was less than that obtained when the specimen was first subjected to a high stress level.

2.4 Resilient Response of Subgrade Soils

The soils selected for resilient response investigation are listed in Table 2.7. The selections were made to include soils ranging in anticipated engineering behavior from good to bad. Specimens measuring 2 in. (51 mm) in diameter by 4 in. (102 mm) in height were used. Repeated load triaxial test equipment was used. Figure 2.15 shows typical resilient response curves. A number of factors were found to significantly influence the resilient response of the fine-grained soils.

1. Reduced density leads to greater resilience (lower resilient modulus).
2. Increasing degree of saturation results in increased resiliency.
3. Resilient modulus is not constant, but is influenced by the magnitude of the repeated deviator stress.
4. Fine-grained soils exhibit substantially different resilient response characteristics due to inherent variations in soil properties such as plasticity, clay and silt contents and organic matter content.

2.5 Permanent Deformation Behavior of Subgrade Soils

The seven soils tested are listed in Table 2.7. Specimens measuring 2 in. (51 mm) in diameter by 4 in. (102 mm) in height were tested using repeated load triaxial equipment. Figure 2.16 shows typical curves of permanent

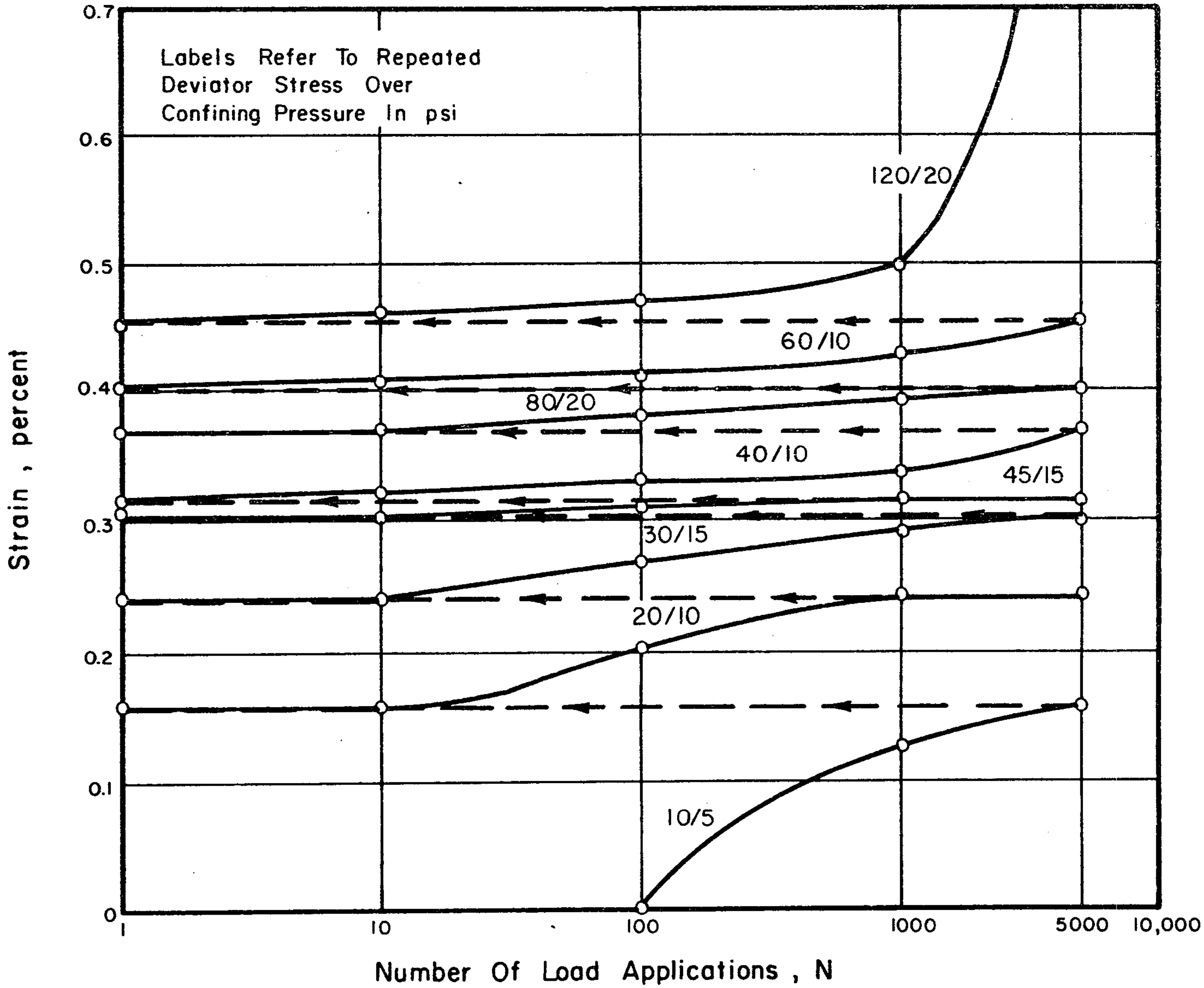


Figure 2.13. Stress History Effect for a No. 5 Gradation, Medium Density Limestone.

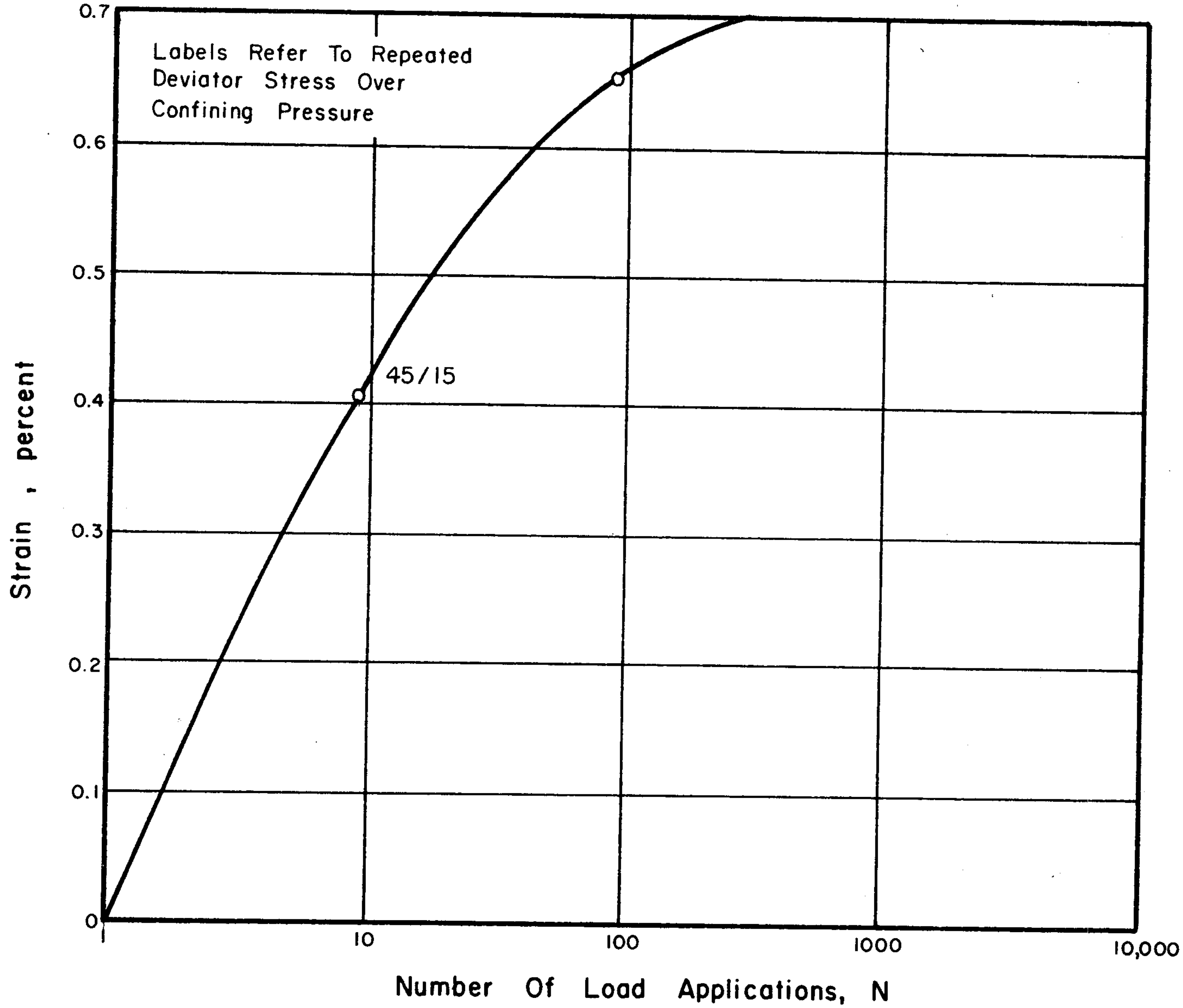


Figure 2.14. Single Stress State Effect for a No. 5 Gradation, Medium Density Limestone.

Table 2.7. Soils Used in the Laboratory Testing Program.

Foundation Sample Number	Pedological Name & Horizon	Parent Material	Sampling Location	Unified Soil Classification	Liquid Limit	Plasticity Index	% Clay (<0.002 mm)	Resilient Response Testing	Permanent Deformation Testing
1	Appling	Predominantly residuum from granite	Greenville County South Carolina	CH	71	38	50	Yes	
2	Cecil	Residuum from acidic rock (granite gneiss and granite)	Catawba County, South Carolina	CH	53	27	41	Yes	
3	Davidson B_2	Residuum developed over basic igneous and metamorphic rock	Spartanburg County, South Carolina	MH	70	34	54	Yes	Yes
4	Dickinson C	Fine sandy loam	Whiteside County, IL	SM	Non	Plastic	8		Yes
5	Drummer B	3-5 ft. of loess on Wisconsinan Till	Champaign Co, IL	CH	52	28	38	Yes	Yes
6	Fayette B	> 4-5 ft. of Peorian Loess	Henry County, IL	CL	43	21	31	Yes	Yes
7	Fayette C	> 4-5 ft. of Peorian Loess	Henry County, IL	ML	32	9	18	Yes	Yes
8	Greenville	Residuum from moderately fine and fine textured costal plain materials	Peach County, Georgia	CL	35	23	39	Yes	
9	(Kansas Test Track Soil)	Not available	Kansas Test Track	CH	58	38	—		Yes
10	Norfolk B_2	Residuum from thick beds of unconsolidated sandy loams and sandy clays of the costal plain	Peach County, Georgia	SC	28	18	27	Yes	Yes

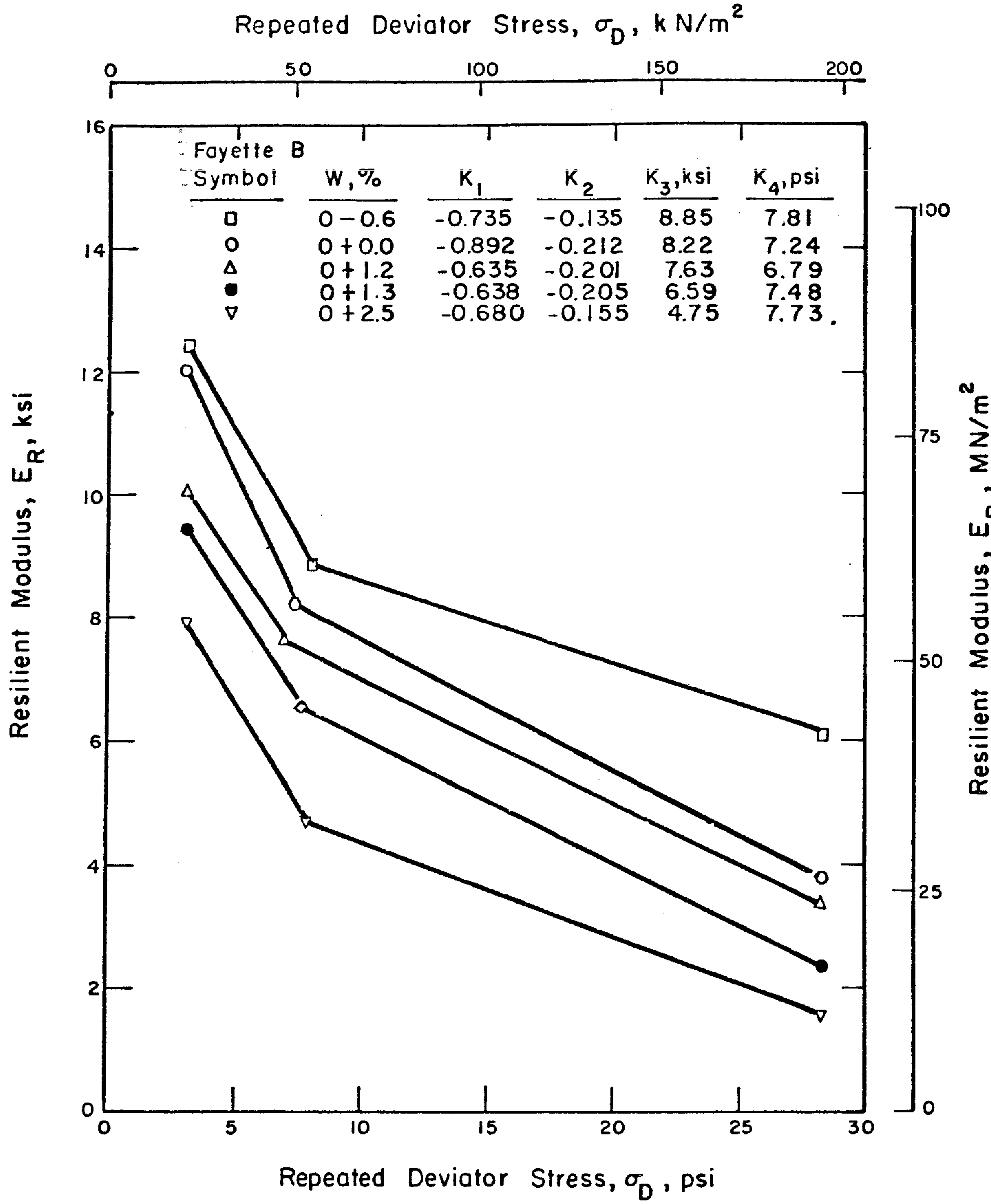


Figure 2.15. Resilient Modulus-Repeated Deviator Stress Relation for Fayette B.

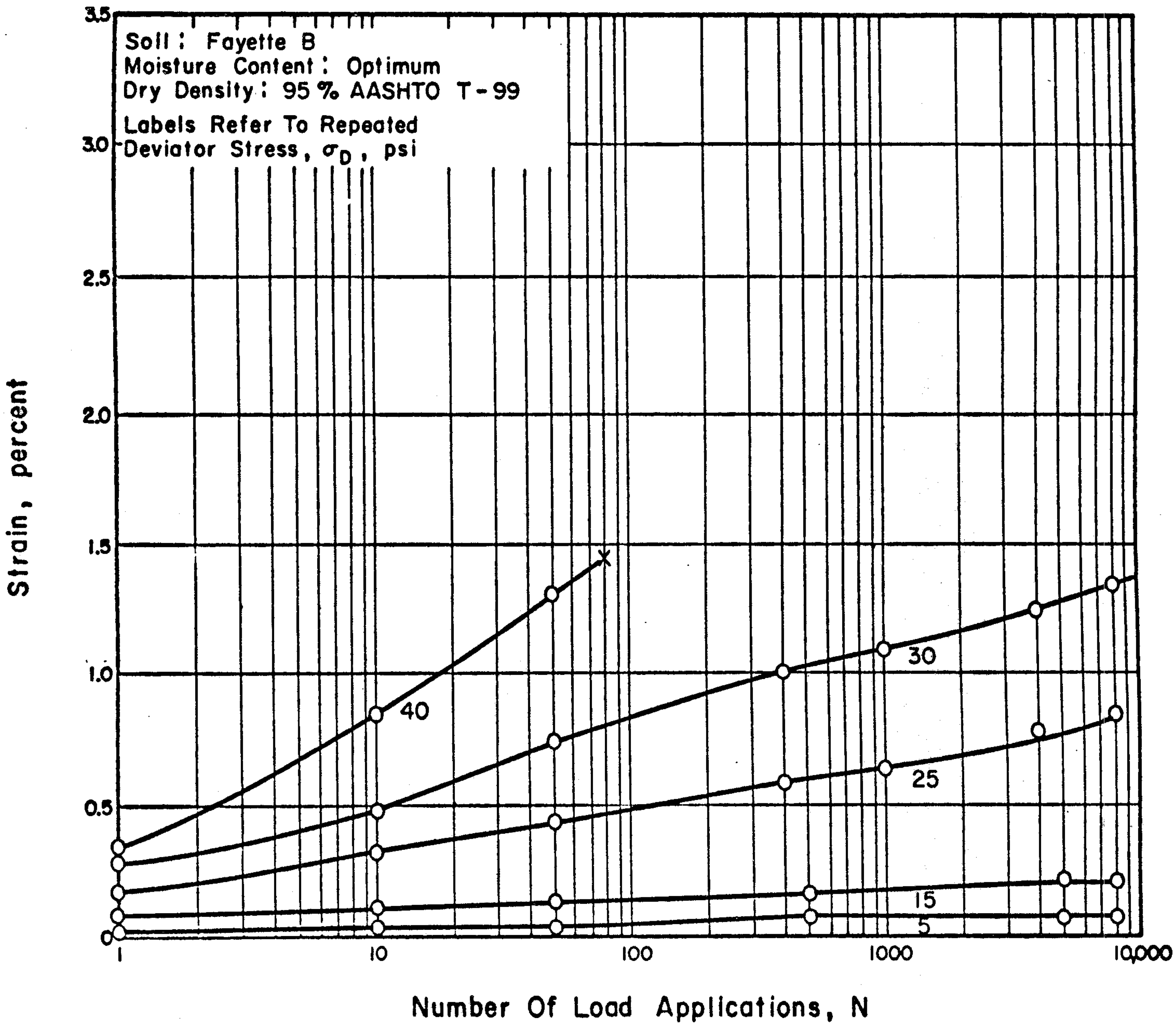


Figure 2.16. Permanent Strain-Number of Load Repetition Relation for Fayette B.

strain versus number of load applications at different stress states. The ε_p-N data for the soils tested were fit to the following equation using regression analyses:

$$\varepsilon_p = AN^b$$

where ε_p = permanent axial strain

N = number of load applications

A, b = experimentally determined coefficients

The effect of one cycle of freeze-thaw was also evaluated and is shown in Figure 2.17.

The factors that significantly influenced the permanent deformation test results are summarized below:

1. For most of the soils, increased moisture content and reduced density led to increased accumulation of permanent strain.
2. Permanent deformation response is stress-dependent with most of the soils exhibiting a pronounced increase in the rate of permanent strain accumulation with an increase in deviator stress.
3. Permanent deformation is also stress history dependent.
4. Cyclic freeze-thaw produces detrimental response in soils as compared to soils not subjected to any freeze-thaw cycles.

2.6 Track Support System Temperature Regime

Environmental exposure conditions have a substantial effect on the instantaneous-elastic behavior and the long term behavior and performance of track support systems. The nature of the ballast and subgrade materials and the track support system geometry make the materials sensitive to certain environmental exposure conditions; primarily temperature and moisture. Certain aspects of the temperature conditions such as freeze-thaw and frost heave are important not only in terms of design of the track support system

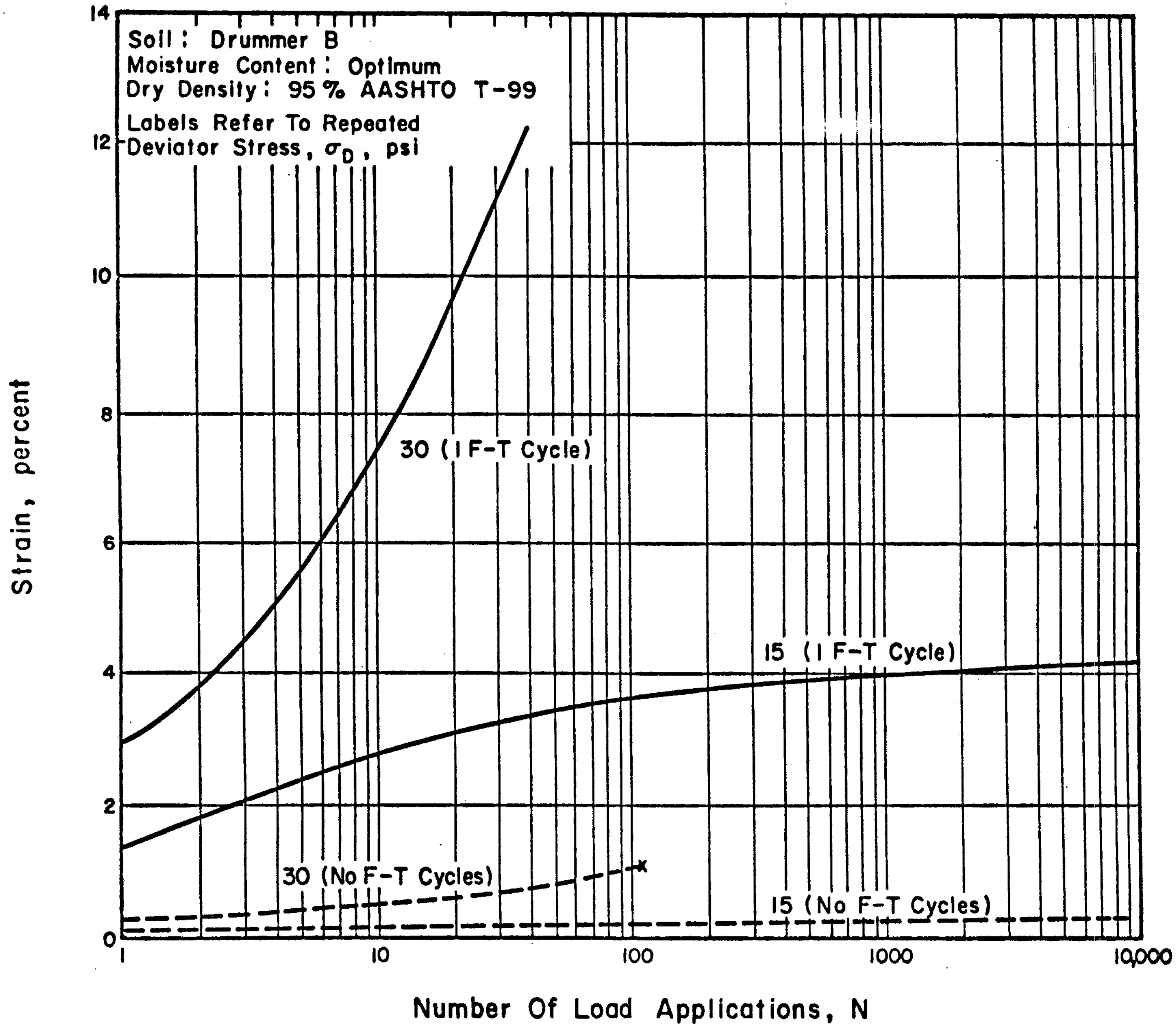


Figure 2.17. Effect of One Freeze-Thaw Cycle on Permanent Deformation for Drummer B.

but also in terms of material quality and property evaluation. The moisture regime in the track support system is also an important consideration. Factors such as precipitation, water table position, permeability of ballast and subgrade materials, and local drainage conditions have an influence on the moisture regime.

Improved CRTSS analysis and design procedures require the quantification of moisture regimes in the track support system both as a function of time and of space.

A study was conducted to characterize the temperature regime in the typical track section at two geographical locations: Chicago, Illinois, and Springfield, Illinois. The characterization was made by using a one-dimensional, forward-finite-difference heat-transfer computer model developed by Dempsey and Thompson (5). The computer model output can be presented as temperature depth profiles in multi-layer systems.

Laboratory tests and corresponding computer simulations were conducted to evaluate ballast thermal conductivity and to determine the relative importance of thermal conductivity, heat capacity, density, and water content with respect to heat transfer in ballast. A temperature regime study was conducted for a track support system with a 12 in. (30.5 cm) ballast layer for Chicago and Springfield, Illinois.

The results of the temperature regime study indicated that for the Chicago area the surface of the ballast is subjected to an average of 65-70 freeze-thaw cycles per year, with a 95 percent probability ($\pm$ 2 standard deviations) that during any one year there will be from 35 to 100 freezing and thawing cycles at the surface of the ballast. Higher numbers of freezing and thawing cycles lead to increasing weathering of ballast. Significant cyclic freezing and thawing also occurs below the surface of ballast, with 3.1 cycles per year occurring at the ballast-subgrade interface.

The freezing and thawing activity in Springfield, Illinois is not as intense as in Chicago, An average of 50.4 and 1.6 freezing and thawing cycles occur at the surface and the ballast-subgrade interface, respectively.

From this study, the following conclusions can be drawn:

1. The heat transfer model (5) is an excellent tool for the characterization of the temperature regime in an idealized ballast subgrade track support system.
2. Further investigations identifying and measuring the effects of rainfall, internal moisture movement, and snow cover on frost action are needed so that the heat transfer model can be modified and updated to more accurately simulate CRTSS field conditions.
3. More accurate estimates of the thermal conductivities of ballast materials under field conditions are needed as input for the heat transfer model.
4. Further investigation relating the degradation of ballast materials to cyclic freezing and thawing is needed. Information generated by the heat transfer model can be used to determine warming and cooling rates, durations of freezing and thawing cycles, freezing and thawing temperatures, and the number of freezing and thawing cycles. The results could be used in controlled, long term cyclic freezing and thawing tests to examine and determine weathering characteristics of ballast materials.

2.7 Lateral Stability of Ballast

Full-scale lateral stability tests were conducted with a 2-rail, 3-tie system using slag, crushed limestone, and gravel as ballast(22). The tests were conducted under conditions of:

1. Various vertical loads
2. Various ballast shoulder configurations
3. Various rates of horizontal loading (displacement)

The following parameters were chosen as possible measures of lateral stability:

1. Peak resisting force
2. Displacement at peak resistance
3. Yield Force
4. Displacement at yield
5. Yield force as percentage of peak resisting force
6. Slope of the initial portion of the stability curve
7. Resistance at 0.1 inch (2.54 mm) and 0.25 inch (6.35 mm) displacements
8. Resistance with zero vertical load, and corresponding displacements

Typical lateral stability curves are shown in Figure 2.18. The results of the lateral stability study indicate that differences in the lateral stability behavior of the three ballasts tested are not significant. Also, the results indicate a peak L/V (lateral resistance/vertical force) ratio of about 0.8. The lateral resistance of a tie developed in the unloaded track condition is only a small fraction of the lateral resistance developed when the track is vertically loaded.

For a loaded track, no significant increase in lateral resistance was found for a 12 in. (30.5 cm) shoulder over that of a 6 in. (15.2 cm) shoulder. However, the unloaded track tests with a 12 in. (30.5 cm) shoulder showed an increase in peak resistance of almost 20 percent over that of tests with no ballast shoulder.

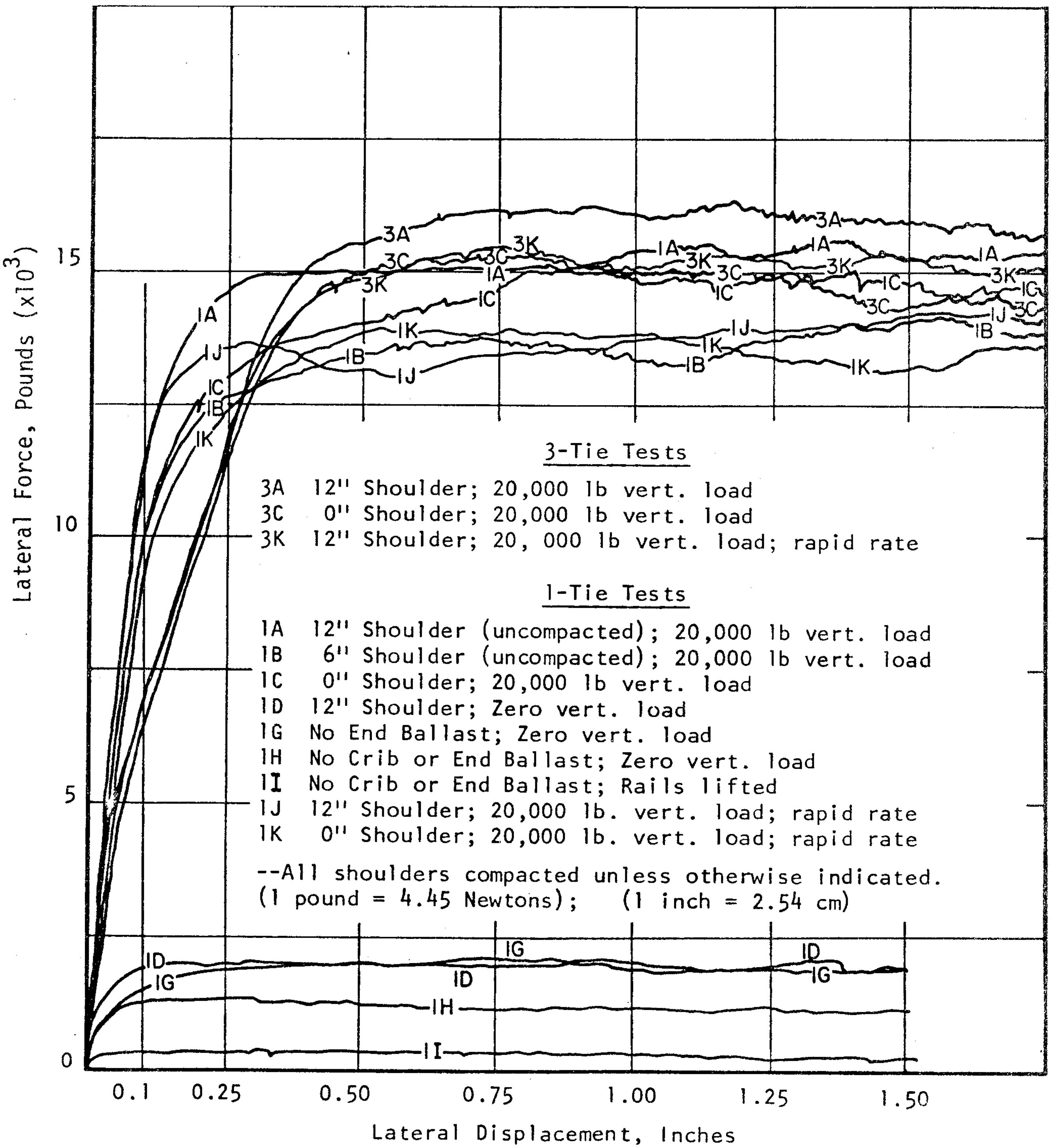


Figure 2.18. Lateral Stability Curves for AREA No. 4 Crushed Limestone.

CHAPTER 3

TRACK SUPPORT SYSTEM BEHAVIOR UNDER LOAD

3.1 General

The major factors that affect the structural behavior of the track support system can be categorized as follows:

Extrinsic Factors

1. Dynamic Train Loading (vertical, lateral, longitudinal)
2. Environmental Factors (temperature, moisture)

Intrinsic Factors

1. Rail Properties (type, joints, etc.)
2. Tie Properties (type, tie-spacing, etc.)
3. Ballast and Subballast Properties
4. Subgrade Properties

The track support system behavior under load can be defined in terms of structural response and performance.

The structural response of the track support system is usually determined in terms of the "instantaneous elastic" response which is the response of the track support system to applied loading at any given time, and can be evaluated in terms of stresses, strains and deflections.

Performance of the track support system is a measure of the ability of the track support system to fulfill its functional requirements. In other words, performance is a measure of the "degree of failure". For the track support system, failure is not a catastrophic occurrence; failure is a condition that develops over a period of time, generally measured in years, and is usually referred to in context of level of service or the degree to which the functional requirements of the track support system have been fulfilled.

In the United States, the level of service is generally denoted by FRA's designation of Track - Class 1 track being the poorest and Class 6 track being the best.

Optimum engineering design requires that design methodologies should incorporate the limiting response patterns of every component of the transportation support system. For the track support system, the limiting response patterns of the ballast, the subballast and the subgrade should be carefully considered together with those for the rails and ties. For example, under repeated loading fine-grained soils can deform substantially if the stress level exceeds a certain value. On the other hand, open-graded ballast materials can resist only minimal tensile stresses and have allowable limits of principal stress ratio, σ_1/σ_3 (where σ_1 and σ_3 are the major and minor principal stresses respectively) that it can resist. In general, the limiting response criteria can be written as

$$[\sigma_{ij}] < [\sigma_{ij}]_A$$

where

$[\sigma_{ij}]$ = stress tensor at any point in the track support system due to applied load

$[\sigma_{ij}]_A$ = allowable stress tensor at that point in the track support system

3.2 Behavior Predicted by Analytical Methods

For optimum design of track support system, it is required to determine the primary response (stresses, strains, deflections) of the system under the expected loading conditions. The three-dimensional geometry of the track support system compounded by the non-uniform nature of the traffic loading make it difficult to rationally analyze the system without making many assumptions. Other normally existing field conditions, such as gaps between rails and tie plates, seating of ties on ballast, variable subgrade support conditions and method of ballast tamping further complicate attempts at rational analysis. Recently, because of the cumulative effects of deferred maintenance of the roadbed and heavier freight and tank car loadings, the need has become apparent to examine more fully the ballast, subballast, and subgrade systems and to incorporate their response in new track designs as well as for rehabilitation design of existing tracks.

A list of some currently available methods for the analysis of the track support system is presented below. Both theoretical and empirical methods are listed.

1. Beam on Elastic Foundation (6, 7)
2. Finite Beam on Elastic Foundation (8, 9, 10, 11, 12)
3. Analytical Method for Track Structure Subjected to Moving Loads (13)
4. General Boussinesq Method (14)
5. Semi-Empirical Methods, e.g., the Japanese National Railways Equation (15)
6. Finite Element Methods (2, 16, 17, 18)

A realistic analytical model for the track support system should be capable of:

1. Evaluating a system comprised of the basic structural components of the system, viz, rails, tie-plates, ties, ballast, subballast, and subgrade.
2. Considering realistic material characterization for each system component.
3. Considering the finite horizontal extent of the ballast and subballast in a typical cross section of a track support system.
4. Considering arbitrary loading conditions including non-uniform, non-symmetrical and dynamic loading conditions.
5. Evaluating the response of the system to changes in material properties caused by changing environmental conditions (viz, the effect of degree of saturation of the subgrade, etc.)

The analytical procedures that have been developed for calculating stresses, strains, and deflections have concentrated on "realistic" representation of the rail-fastener-tie systems while representing the ballast, the subballast, and the subgrade as either springs (Winkler foundation) or linear elastic or viscoelastic, homogeneous materials.

3.3 The ILLI-TRACK Model

Recognizing the major limitations of the existing methods of analysis and the requirements of a realistic analysis methods, a finite element model of the track support system was developed. While it is possible to formulate a three-dimensional finite element model that would more accurately represent the track support system, the amount of "discretization" and the computer costs required for solution of the problem would be high and probably impractical. Therefore the model was divided into two stages wherein a longitudinal analysis of the track support system is performed followed by a transverse analysis. The modelling is shown in Figures 3.1 and 3.2. Details of the development of the model have previously been reported (2). The finite element model, called "ILLI-TRACK", has been validated using measured responses from Section 9 of the Kansas Test Track (2). Good agreement was obtained between the measured response and that calculated using ILLI-TRACK. As more field data becomes available, the model will be further validated. In its present version, ILLI-TRACK is not a design model but rather an analysis tool. Stress dependent material characteristics have been incorporated into ILLI-TRACK. However, failure criteria and constitutive response models for granular materials subjected to stress states in which the confining stress is near zero or tending to "go into tension" are not well defined. Presently, when any granular material element in the structural model reaches the failure criteria, it is assigned a low modulus value to be used in the next step loading analysis.

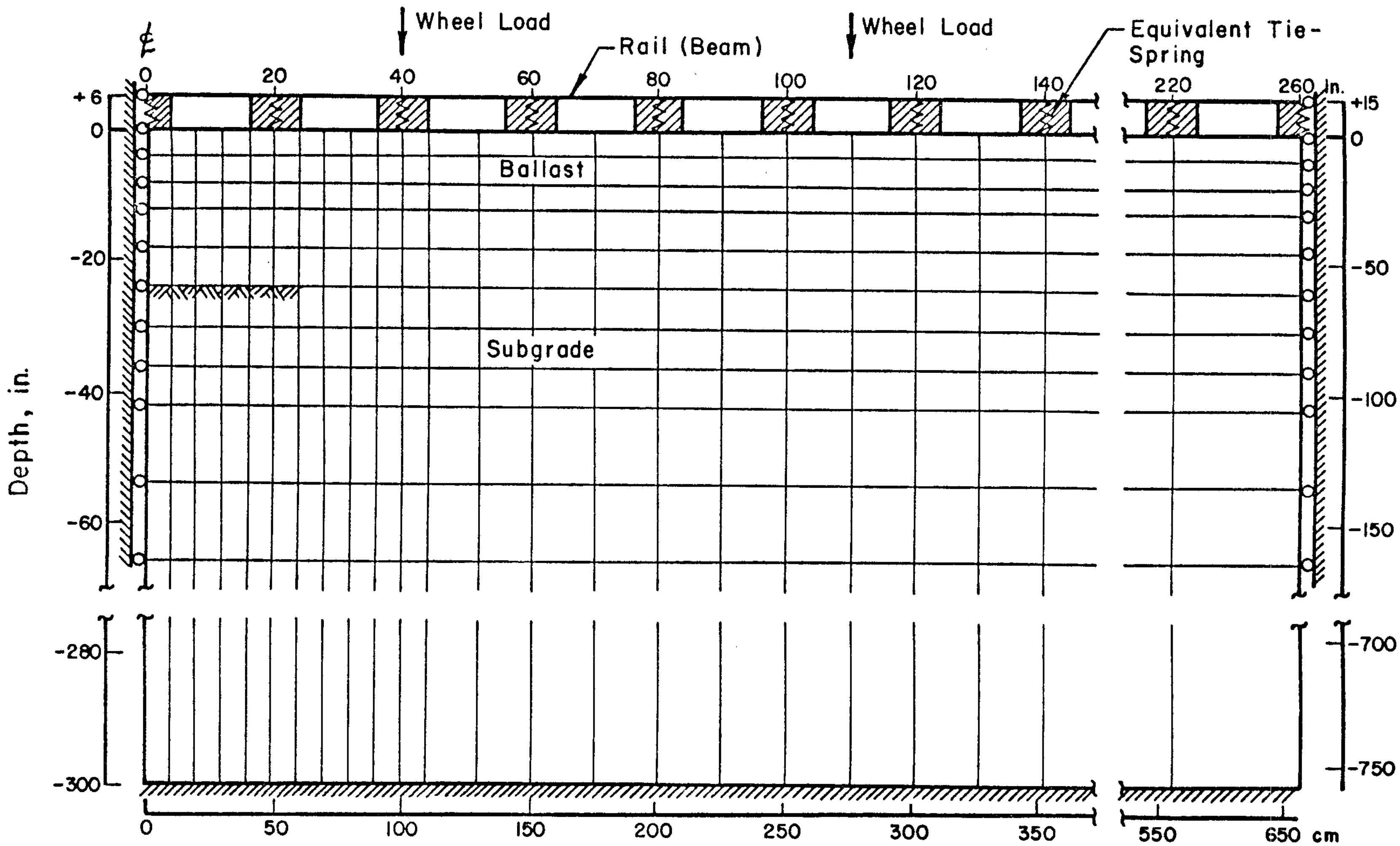


Figure 3.1. A Typical Finite Element Mesh Used for Longitudinal Analysis.

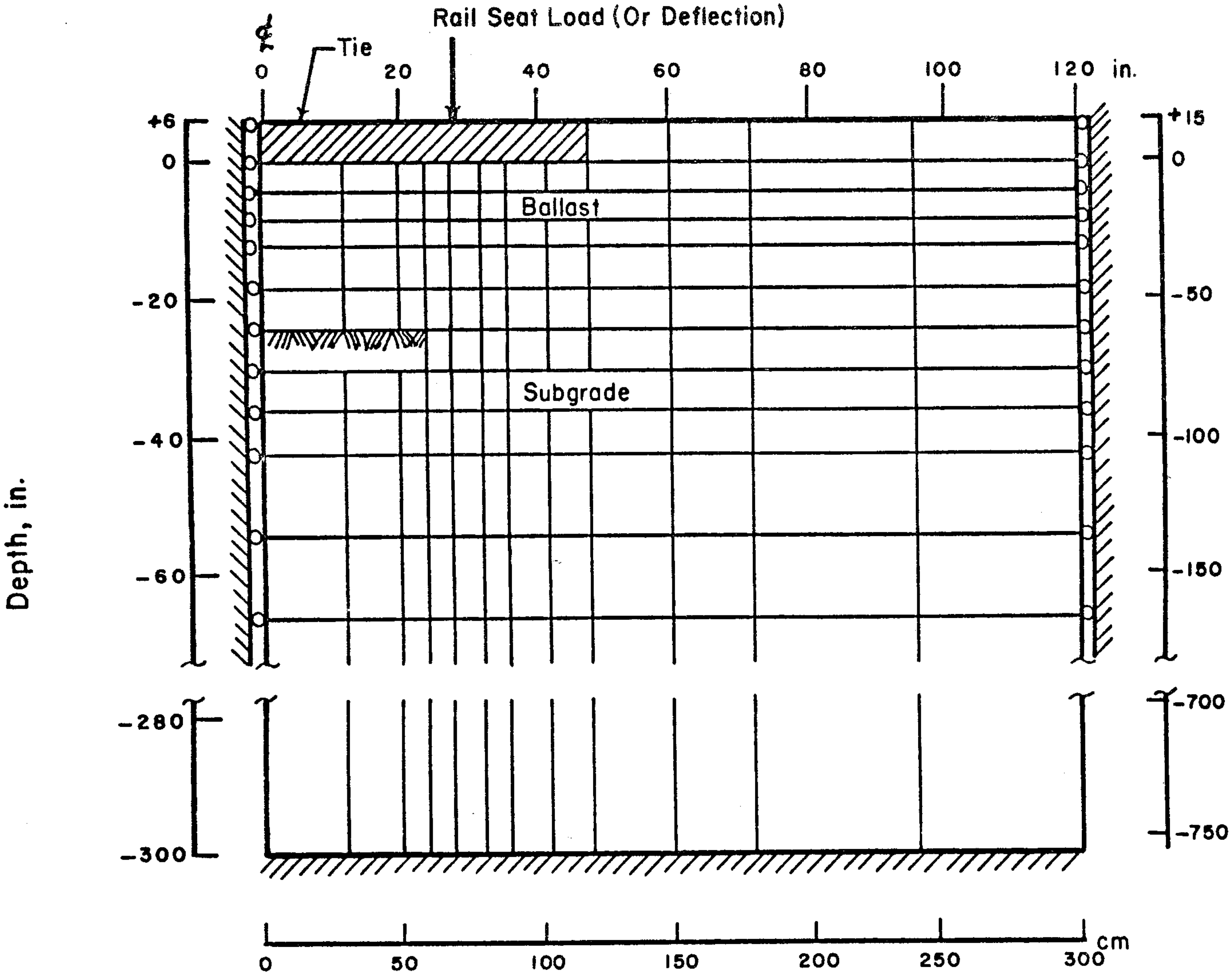


Figure 3.2. A Typical Finite Element Mesh Used for Transverse Analysis.

3.4 Parameter Study

A parameter study was conducted using ILLI-TRACK to establish the effects of various parameters on the instantaneous-elastic response of CRTSS subjected to loading in vertical plane (3). The parameters studied were ballast (type and depth), subballast (type and depth), subgrade support conditions, rail size, tie width and tie spacing, wheel loading, and missing ties. The major findings from the parameter study are given below:

1. Basically, the stiffness of the CRTSS is derived from two sources - the rail subsystem and the foundation subsystem which includes the ballast, the subballast, and the subgrade. When the stiffness of the rail subsystem is high as in the case of a 136 lb/yd (68 kg/m) rail, the variability in the stiffness of the foundation subsystem has less influence on the response of the CRTSS than for a less stiff rail (e.g., 115/lb/yd (57 kg/m) rail). Thus, for a poorly maintained track with substantial foundation subsystem variability and poorly maintained ties the use of a stiffer rail might be beneficial. Also a stiffer rail might be more beneficial for lateral stability considerations.
2. The resilient response of the CRTSS is not very dependent on the type of ballast used. Laboratory testing has shown that the E_R-θ resilient response curves for most ballasts lie in a very narrow band. Thus, it appears that for evaluation of transient response of CRTSS, standardized E_R-θ resilient response curves for various ballast types may be used in analyzing the resilient response of the CRTSS. However, the long term behavior of ballast under repeated (traffic) loading and changing environmental conditions is significantly dependent on ballast type, and this should be considered when evaluating different ballast types.

3. The effect of a variable foundation subsystem can be reduced by using a stabilized subballast. The stabilized subballast aids in distributing the load more uniformly on the subgrade and maintains the ballast aggregate matrix in a more confined state allowing the ballast to develop higher stiffness. The development of stiffness at the bottom of the ballast layer is very much dependent on the stiffness of the layer under it. With the use of a stabilized layer a very low modular ratio can be maintained resulting in horizontal compressive stress at the bottom of the ballast layer. Thus, the ballast layer can develop higher stiffness and the response of a CRTSS with a stabilized layer is more favorable under traffic loading than that of a CRTSS without a stabilized layer.
4. One of the most variable components in the CRTSS is the subgrade. Variation in the subgrade support can be a result of soil type, moisture content, frost action, compaction conditions, etc. The variation in the strength of the subgrade soils was found to be one of the most important parameters influencing the response of the CRTSS. Thus, on a given track section with non-uniform (in terms of stiffness) subgrade the response due to traffic loading can be very erratic. The desirability for uniform and stable subgrades is apparent.
5. The results of the parameter study indicate that rail type and tie base width has little influence on the system response of the CRTSS. Increase in tie base width does result in reduction in maximum ballast vertical pressure and maximum subgrade strain. On the other hand, increasing tie spacing leads to a

detrimental response in terms of increased maximum rail deflection and patterns of higher subgrade vertical stress. Increased tie spacing leads to localized concentration of stress on the subgrade (below the ties).

6. Over the years tracks in the United States have been deteriorating due to increased traffic frequency, heavier wheel loads and deferred maintenance of the CRTSS. Increased wheel loading leads to an increasingly detrimental response of the CRTSS which may result in early failure. When increased loading is anticipated on a given line, it is necessary to evaluate the CRTSS to insure that the response patterns in all of the track components are acceptable.

CHAPTER 4

ECONOMIC EVALUATION OF BALLAST MATERIALS

4.1 General

For railroads to develop sound maintenance policies and procedures, a methodology is needed to perform rational economic evaluation of ballast materials. Research efforts in ballast costing have been numerous, but much of the effort has merely involved analysis of piecemeal data derived from the opinion and experience of maintenance personnel. Ballast costing is complicated because of complexity of ballast loading environment, variances in policies and conditions prevailing on different railroads, the incompleteness and inadequacies of railroad record keeping (including lumping of figures into system averages), and other compounding factors. Efforts directed toward the establishment of more precise in-track performance tests have met with other difficulties, such as, the lack of quantitative measures of the need to perform track maintenance operations, the long time base required to conduct meaningful tests, and the variability of such important factors as environment and subgrade stability.

In absence of a workable guide, most railroads have predicated their ballast decisions primarily upon purchase price, durability, and transportation costs. In recent years, a renewed drive for a more rational ballasting policy has been generated. The consideration of service life as an important ballast selection criteria is gaining use.

4.2 Ballast Economics

The principal goal of the economic evaluation phase was the development of an overall economic cost model of ballast use. The overall economic cost of ballast is a function of the following:

1. Purchase price
2. Transportation cost
3. Unloading cost
4. Cost of spotting operations
5. Cost and frequency of lining and surfacing operations
6. Cost and frequency of ballast renewal operations
7. Ballast's effects on the cost and frequency of renewing rail, ties and other track materials
8. User costs associated with delays and accidents.

The study of ballast economics requires assembly of a detailed data base. Therefore, as part of the Ballast and Foundation Materials Program, a review of pertinent literature and the development of a detailed cost survey were undertaken. This part of the report summarizes some of the important aspects of the economic evaluation of ballast materials as detailed in the Phase V report entitled, "A Study of Railroad Ballast Economics" (19).

4.3 Ballast Costs Survey

A ballast cost survey was prepared and submitted to seventy American and Canadian railroads during the fall of 1975. The results of the data obtained from the survey respondents and from the review of pertinent literature are summarized below:

1. Statistically, no discernible purchase price difference was found to exist among ballast types.
2. Few railroads have quantified even the simple charges for on-line movements and fewer still assign such costs to their maintenance budgets. The method of conveying ballast from source to point of placement is a major factor in the overall cost of ballast. From the survey replies, the average cost of ballast transport

was found to be \$0.009 per cubic yard per mile (\$0.0073 per cubic meter per kilometer) for blocks of cars assigned to ballast service which are shuttled between ballast source and yard near point of usage by revenue trains. The average cost was \$0.0081 per cubic yard per mile (\$0.0066 per cubic meter per kilometer) for blocks of cars which are released to general revenue service after delivering ballast to yard near point of usage. Cost of ballast transport by unit trains ranged from \$0.004 to \$0.0092 per cubic yard per mile (\$0.0033 to \$0.0076 per cubic meter per kilometer) depending on the number of cars used. The off-line charges, on the average, were 5 times greater than those for on-line ballast movement. Ballast transport costs are also influenced by ballast density.

3. Most railroads use work trains for all ballast unloading exercises. Work train costs ranged from \$400 to \$450 per 8-hour day and \$485 to \$560 per 10-hour day. Table 4.1 gives a summary of output data for unloading operations. The costs assigned to this activity varied markedly among the railroads, indicating that many did not assess all of the appropriate elements of the unloading cost. No difference was experienced in unloading by ballast material type or by ballast gradation. Ballast density, on the other hand affects the number of cars unloaded in the placement of a given ballast volume.

4. Spotting work practices are so variable that neither the operations' cost nor the relative performance of various ballasts can be determined at this time.

Table 4.1. Summary of Output Data for Unloading Operations.

For Work Train Unloading Blocks of Cars Hauled by Revenue Train

Railroad	Simple Mean Daily Unloading Rate[a] (cars)	Simple Mean Car Capacity (cubic yards)	Simple Mean Daily Output[a] (cubic yards)
B	10	55	550
C	16[b]	65	1024
D	9	56	504
E	15	55	825
F	12	72	864
G	26	80	2080
I	10	32	320
P	22	50	1100
O	30	40	1200
S	25	40	1000
U	15	50	750
V	20	56	1120

Simple Mean Daily unloading Rate[a] = 18 cars

Simple Mean Car Capacity = 54 cubic yards

Simple Mean Daily Output[a] = 970 cubic yards

Note: See Appendix , Reference 19 for description of the railroads.

For Work Train unloading Large Blocks of Cars Hauled by Unit Train

Railroad	Simple Mean Daily Unloading Rate[a] (cars)	Simple Mean Car Capacity (cubic yards)	Simple Mean Daily Output[a] (cubic yards)
H	50	50	2500
R	40	68	2720
Z	47[c]	68	3195

Simple Mean Daily Unloading Rate[a] = 46 cars

Simple Mean Car Capacity - 64 cubic yards

Simple Mean Daily Output[a] = 2850 cubic yards

[a] Per 8 hour day

[b] 20 cars unloaded in 10 hours

[c] 62 cars unloaded in $10\frac{1}{2}$ hours

5. The cost per unit of output of a lining and surfacing operation is very strongly linked to the manner in which that operation is performed, and is the sum of labor cost and machinery's capital and operating costs. Railroads responding to the survey indicated a great diversity in equipment organization. Most railroads reported no correlation between ballast gradation and output for lining and surfacing operations.

   Table 4.2 gives a summary of data for lining and surfacing operations and Table 4.3 gives a summary of cost data for lining and surfacing operations.

4.4 Frequency of Lining and Surfacing Operations

The need for track lining and surfacing is primarily related to the deterioration of track geometry. The point at which the procedure is performed, however, is a subjective matter. Each company establishes its own basis for undertaking maintenance operations. Furthermore each track officer applies these rules based on his personal track appraisals and judgment. Of the eighteen respondents discussing lining and surfacing frequency, thirteen reported that their decisions are based primarily upon inspection and evaluation of field conditions. Of the remaining 5 railroads two chose to line and surface only with tie and rail renewal operations, two adhered to a predetermined cycle regardless of field conditions and the remaining railroad based its frequency upon a desire to keep all gangs working continuously. In addition, cycle lengths are affected by the maintenance goals of the various railroads and the budget conditions at any point in time. Thus, even for identical traffic, subgrade and climatic conditions an individual ballast material may exhibit vastly differering cycle lengths on different railroads.

Table 4.2. Summary of Data for Lining and Surfacing Operations.

Equipment Used	Railroad	Labor: Foremen	Labor: Operators	Labor: Laborers	Cost ($) per Productive Hour	Ties Raised	Ties Tamped	Number of Tamping Head Insertions Per Tie	Output (ft.) per Productive Hour
Tamper, Liner and Ballast Regulator	F	2	3	1	N.A.	All	All	3	763
	Q	2	3	3	N.A.	All	All	N.A.	583
	W	1	3	2	179	All	All	2	800
	W	1	3	2	179	All	All	1	600
Tamper, Liner and 2 Ballast Regulators	D	1	4	1	200	All	All	1	640
	D	1	4	1	165	All	All	1	570
	R	1	4	2	218	All	All	2	900
	R	1	4	2	197	All	All	2	900
	Mean of Above				190				720
Tamper, Liner, Tandem Tamper, and Ballast Regulator	F	1	4	2	N.A.	All	All	2	1048
	W	1	4	2	N.A.	All	All	2	500
Tamper-Lines	E	1	1	4	N.A.	All	All	3	775
Tamper-Liner Tandem Tamper and 2 Ballast Regulators	C	1	2	2	142	All	All	1.5	900
	E	1	2	5	N.A.	All	All	3	677
	F	1	2	3	N.A.	All	All	2	632
	J	1	2	1	101	All	All	2	586
	M	1	2	3	150	All	All	1	600
	V	2	2	4	148	All	All	1	726
	V	1	2	1	N.A.	All	All	1	475
	Mean of Above				135				657

Table 4.2. (Continued)

Equipment	Railroad	Labor			Cost ($) per Productive Hour	Ties Raised	Ties Tamped	Number of Tamping Head Insertions Per Tie	Output (ft.) per Productive Hour
		Foremen	Operators	Laborers					
Tamper-Liner, Tandem Tamper, and Ballast Regulator	H	1	3	2	N.A.	Even	Odd	2	910
	S	1	3	2	210	Even	Odd	2	993
	S	1	3	2	191	Even	Odd	2	910
	Mean of Above				200				938
Tamper-Liner, Tandem Tamper and 2 Ballast Regulators	0	2	4	2	N.A.	All	All	2	1200

See Appendix B, Reference 19 for description of the railroads.

Table 4.3. Summary of Cost Data for Lining and Surfacing Operations.

From Data of Table 4.2.

Machine Organization	Mean Cost ($) Per Productive Hour	Mean Output (Ft) Per Productive Hour	Mean Cost ($) Per Track Foot
Tamper, Liner and one or more ballast regulators	190	720	0.26
Tamper-Liner and one ballast regulator	135	657	0.21
Tamper-Liner, tandem tamper, and one ballast Regulator	200	938	0.21

From Data of Exhibit 4.5, Reference 19.

Machine Organization	Mean Cost ($) Per Productive Hour	Mean Output (Ft) Per Productive Hour	Mean Cost ($) Per Track Foot
Tamper, Liner and one ballast regulator	178	700	0.25
Tamper-Liner and one ballast regulator	122	743	0.16

The survey requested the railroads to provide information on sections of high traffic density (10 to 30 million gross tons annually), well-maintained track with relatively clean, uncemented ballast on a stable, well-drained subgrade. The data derived from the survey are shown in Figure 4.1, which includes a reference curve of average cycle lengths reported in a 1959 AREA questionnaire (21). In order to provide a basis for comparison between ballast materials, the data were normalized as explained in Reference 19. The normalized data are shown in Table 4.4 and Figure 4.2. Even after normalization, it is still difficult to recognize any major differences in performance of various ballast materials.

From the evaluation of the data, it appeared that a cycle length model of the form given below might be appropriate:

$$T = D^{0.5} \; R^{0.5} \; I_2^{1.5}$$

where

T = length of surfacing cycle (MGT)

D = annual tonnage density (MGT)

R = height of raise (in.)

I_2 = lateral moment of inertia of rail (in^4)

4.5 Major Ballast Renewal Operations

The cost of major ballast renewal operations is largely a function of the type of renewal operation utilized. The so-called surface treatments, cribbing and shoulder cleaning, were reported as having the lowest costs $0.36 and $0.10 per track foot, respectively). Heavy raises were reported as having costs of about $1.00 per track foot, but ranging from $.40 to $1.61. The more sophisticated renewal methods (plowing, sledding, undercutting and undercutting-cleaning) generally were reported as having higher costs, although several railroads reported costs comparable to heavy raises.

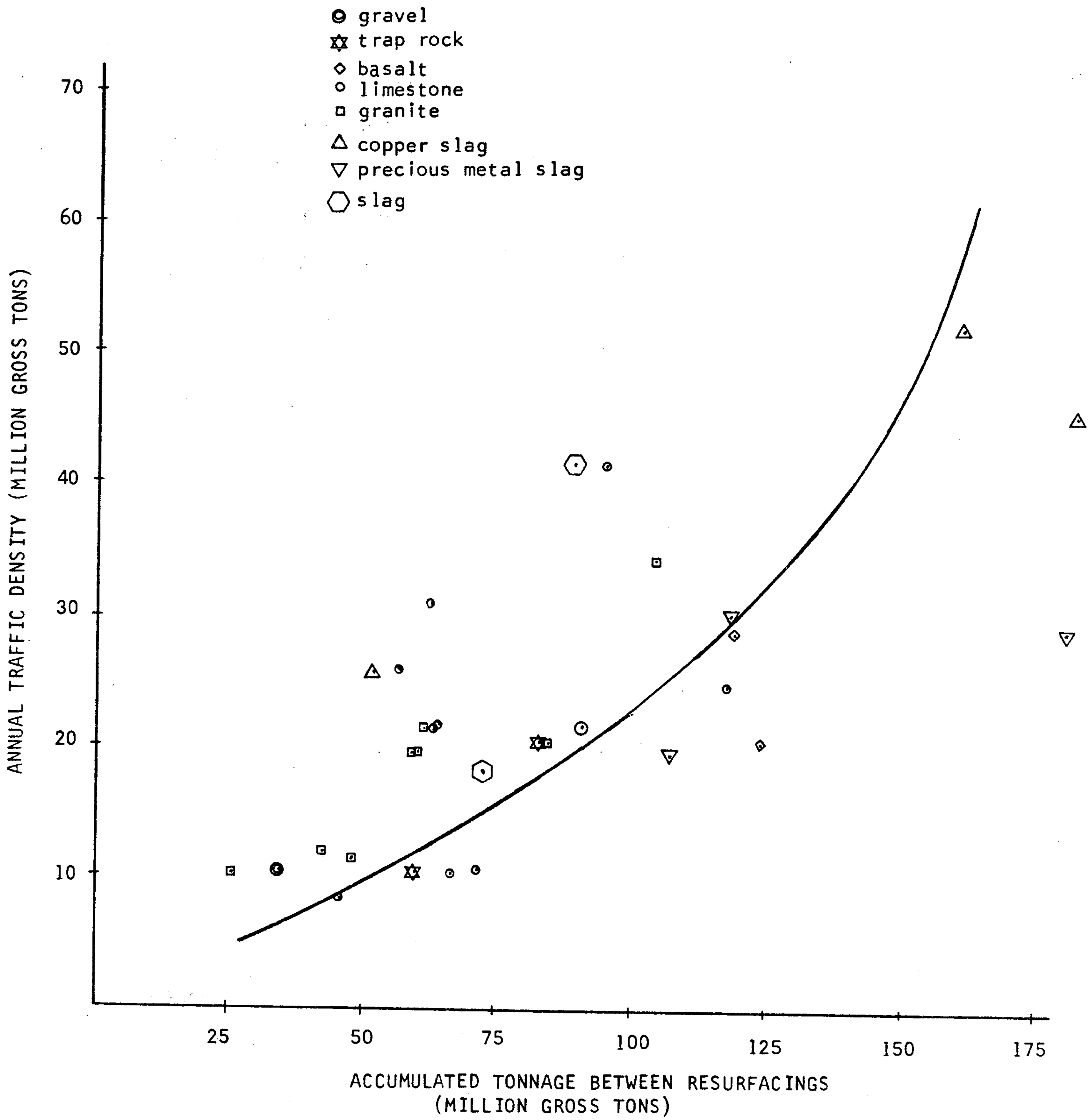


Figure 4.1. Surfacing Cycles as Reported by Survey Respondents.

Table 4.4. Normalized Frequency of Lining and Surfacing Operations.

Railroad Ballast Type	Cycle Length (Years)	FRA Track Class	% Wheel Loads Over 26,000 lbs	Ballast Depth (in.)	Rail Type	Rail Weight	Normalized Cycle Length (Years)
C-LMS	2	4	75	20	CWR	140	1.87
D-TRR	4	3	35	12	CWR	115	3.38
D-TRR	6	3	35	12	Jointed	112	6.09
E-LMS	4	3	--	6	Jointed	112	4.29
E-BST	6	4	--	10	Jointed	115	6.34
F-SLG	4	4	--	12	Jointed	115	4.23
F-LMS	3	4	--	24	Jointed	140	2.9
F-LMS	3	4	--	8	Jointed	115	3.5
G-LMS	6.5	4	65	12	CWR	112	6.38
J-LMS	2	3	40	24	Jointed	132	1.68
K-PMS	7	5	17	12	CWR	136	8.07
K-PMS	4	5	18	12	Jointed	136	4.619
K-PMS	6	5	10	12	Jointed	115	7.26
N-LMS	5	4	40	16	Jointed	132	5.37
N-LMS	6	4	30	16	Jointed	115	6.68
N-LMS	5	2	40	12	Jointed	115	4.07
O-GRN	2.5	4	70	12	CWR	132	2.24
P-DNA	4	2	10	6	CWR	132	3.04
Q-GRV	3	3	5	6	Jointed	115	3.25
R-GRN	4	4	1	12	CWR	132	3.7
R-GRN	3	4	1	12	CWR	132	2.77

Table 4.4. (Continued)

Railroad -Ballast Type	Cycle Length (Years)	FRA Track Class	% Wheel Loads Over 26,000 lbs.	Ballast Depth (in.)	Rail Type	Rail Weight	Normalized Cycle Length (Years)
R-GRN	3	4	1	12	CWR	119	2.89
S-LMS	2.33	4	25	15	CWR	132	2.25
S-SLG	2	4	25	15	CWR	132	1.93
T-DNA	3	--	100	10	CWR	132	3.26
V-GRN	3	5	3.4	18	Jointed	132	3.41
V-GRN	4	4	5.8	16	CWR	132	3.38
V-GRN	3	5	7.6	24	CWR	132	3.27
W-CSL	5	5	15	9	CWR	136	4.83
W-CSL	3	5	25	10	CWR	136	2.92
W-CSL	4	5	11	8	CWR	136	3.84
2-GRN	3	5	10	--	Jointed	133	3.82
2-CSL	2	5	20	--	Jointed	133	2.58
2-BST	4	5	6	--	Jointed	133	5.05

Ballast Types:

LMS - Limestone

BST - Basalt

PMS - Precious Metal Slag

DNA - Data Not Available

CSL - Copper Slag

TRR - Trap Rock

SLG - Slag

GRN - Granite

GRV - Gravel

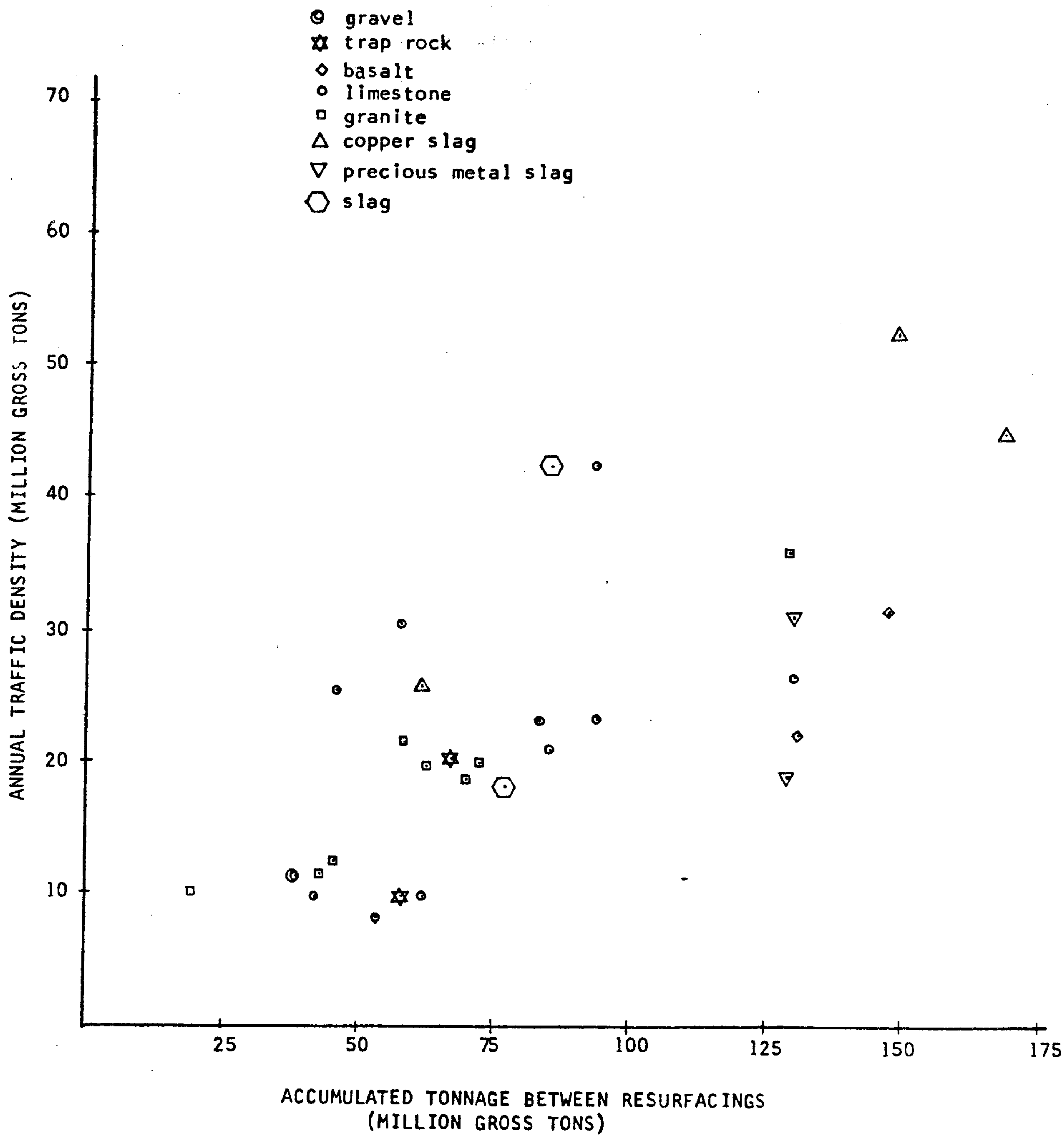


Figure 4.2. Normalized Surfacing Cycles.

The information provided on the length of the major ballast renewal cycles is insufficient to relate these cycles to ballast type, track class or other conditions. The length of the major renewal cycles varied from 7 to 30 years, with most in the 20 year range. The accumulated tonnage between major renewals was usually in the 200 to 300 million gross tons range.

CHAPTER 5

IMPLICATIONS OF THE RESEARCH PROGRAM

5.1 General

Since the objective of ballast selection procedure is "to determine the durability and stability of various types of gradations of ballast materials with the purpose of obtaining information which will help reduce ballast costs by rational selection of available types and gradations which will produce the best service records and the lowest maintenance expenditures" (20), it is imperative that the selection process be objective.

Ballast selection process requires two types of analyses:

1. Ballast Suitability Analysis
2. Ballast Economic Analysis

Ballast suitability analysis can be performed by using the results of laboratory testing and field experience. Field experience is mostly successful if the ballasts being considered were subjected to similar field conditions (subgrade, climate, traffic loading, etc.). Therefore, it is obvious that there is a great need for an approach or a methodology for evaluating ballasts by considering how well a ballast will satisfy its functional requirements. The evaluation process should be able to identify and quantify those pertinent ballast material properties that relate to total track support system performance.

It was towards these ends that the efforts of the Ballast and Foundation Materials Research Program were directed. Major areas of the research program were ballast and foundation materials testing and evaluation using repeated load tests, development of a structural model for analyzing track support systems, and a study of ballast costs.

5.2 Results and Findings

The various phases of the Ballast and Foundation Materials Research Program have been reviewed in the previous chapters. Results and findings of particular significance are summarized below.

Ballast and foundation materials play a critical role in track support systems and must be given adequate consideration during design or rehabilitation. A large portion of the structural strength of the track support system is derived from the ballast, subballast, and subgrade. Like other structural materials, the ballast, subballast, and subgrade have limiting (or allowable) response patterns. For example, under repeated loading the permanent deformation of a ballast material increases at an increasing rate when the principal stress ratio, σ_1/σ_3, exceeds a certain value. Fine-grained soils also exhibit a similar behavior.

The resilient (instantaneous-elastic) behavior of the ballast materials tested were similar. Permanent deformation behavior under repeated loading was influenced by ballast type, gradation, density, stress state, and stress history. Physical degradation under extended repeated loading (10^6 load applications) differed for the various ballast types. It is apparent that the permanent deformation and physical degradation responses of ballast must be considered in the ballast selection process.

Most of the commonly used ballast characterization tests, except for the Crushing Value Test, showed no correlations with the repeated load tests. However, since most of the ballasts tested were of "above average" quality, it is felt that characterization tests may still be of value to identify ballasts of poor quality.

Density was found to be very critical to ballast performance. Ballast specimens compacted to higher density levels showed improved resistance to permanent deformation. This verifies field observations regarding ballast settlement in the initial period following ballast reworking or ballast addition. Traffic during the initial period densifies the ballast. Subsequent load applications produce reduced amounts of permanent deformation.

Ballast behavior is a function of the total state of stress and not just the vertical stress. The establishment of ballast failure criteria based on vertical stress alone is not justifiable. Ballast failure criteria that appear most promising are the principal stress ratio, σ_1/σ_3, for a given σ_3, and the minimum confining stress, σ_3. Repeated triaxial laboratory testing is required to develop the appropriate criteria for a given material.

The behavior of the ballast (subballast) at the ballast/subgrade interface is important with regard to the total performance of the track support system. With weak (soft) subgrades, adequate confinement of the ballast (subballast) cannot be developed at the interface. This results in accelerated permanent deformation accumulation in the ballast (subballast) materials.

For a given fine-grained subgrade soil, density and degree of saturation are critical factors. Since existing rehabilitation techniques do not readily allow for the modification of subgrade densities, consideration should be given to the possible effects of improved subsurface and surface drainage. Subgrade soils also exhibit the phenomenon of limiting (or allowable) responses. Most soils show a pronounced increase in the rate of permanent strain accumulation with increase in deviator stress. Thus, the need to minimize the stress level in the subgrade. Cyclic freeze-thaw is detrimental to fine-grained soils. The reduction of the intensity of freeze-thaw activity (number of freeze-thaw cycles, depth of frost penetration) in the subgrade should be given consideration during design.

The importance of the subgrade as a major structural component of the track system should not be overlooked. The parameter study conducted using the ILLI-TRACK program (3) demonstrated that subgrade stiffness was the major factor influencing the instantaneous-elastic response of the track support system.

Program ILLI-TRACK, the finite element model developed for the analysis of track support systems, shows great potential for use in a track support system design methodology. Considering the developmental state of material characterization procedures and lack of availability of pertinent field response data, it is felt that ILLI-TRACK adequately characterizes the instantaneous-elastic response of the track support system subjected to loading in the vertical plane. The mechanistic behavior of the whole track support system can be easily "visualized" using the results of ILLI-TRACK; thus the trends effected by changes in track support system components are readily apparent. It should be emphasized that the ILLI-TRACK program has enough flexibility to incorporate future developments in ballast and foundation material characterization (material constitutive relationships).

5.3 Ballast Selection Metholodogy

Ballast selection methodology, to be objective, has to incorporate different levels of ballast performance required for different types of traffic conditions and class of track. For example, ballast performance requirements would be different for a line carrying 20 MGT per year than for a line carrying 50 MGT per year if permanent deformation or physical degradation after a given "time period" were used as performance criteria. Obviously factors such as magnitude and number of load repetitions are important.

An important factor that needs to be considered is the increased level of track performance required to justify the higher price that may be associated with the use of a "better quality" ballast. Guidelines need to be established, based on each railroad's practice, to determine the minimum level of improvement required in the frequency of lining and surfacing operations to justify purchasing a "better quality" (and generally a more expensive) ballast. Use of the "best" ballast is not necessarily the right choice for all track and traffic situations. In certain cases, it may be more economical to use locally available ballast which is cheaper but may require an increased frequency of lining and surfacing or even perhaps undercutting and cleaning.

Thus, analyses should be conducted to compare the rates of return on incremental investments for an expensive ballast with the minimum attractive rate of return for a locally available ballast. The major difficulty in using the above type of analysis is to categorize the savings due to incremental investment; but this could be achieved by accumulating a data base for performance of track support systems and/or using performance trends, based on material testing and ILLI-TRACK analyses. It must be emphasized that ballast surface and lining frequency is not a ballast quality phenomenon alone.

5.4 Recommendations for Future Studies

The mechanistic behavior of ballast and foundation materials as components of track support system is very complex. Progress has been made in understanding this behavior as detailed in this report; however, additional technology needs to be developed and/or refined. The ultimate goal should be the development of suitable technology for rendering rational engineering decisions regarding the optimum use of ballast and foundation materials in CRTSS to provide desired levels of performance.

It is emphasized that the lack of adequate technology for considering ballast and foundation materials is not a problem unique to the railroad industry. Extended and costly research efforts concerning the use of aggregates and subgrade soils in highway and airfield pavements have been and are being conducted. Many of the areas of inadequate technology are common to all modes (railroad, highway, airfield). This study adequately summarized the present state of the art during its early phases and as a result of various subsequent phases of activity developed highly significant technological advances, particularly in the areas of ballast and foundation material evaluation and CRTSS structural analysis (ILLI-TRACK Model).

Based on the results of this investigation and the expertise of the Project Staff, the following subject areas are in need of immediate further study and investigation.

1. Permanent deformation behavior of ballast needs to be further investigated. Testing conducted during the course of the Ballast and Foundation Materials Research Program demonstrated the considerable influence of stress history on permanent deformation accumulation in ballast. Thus, the effect of stress history needs to be more fully investigated. Stress history effects can also influence improvement in ballast compaction technology.

2. Ballast behavior at low levels of confining stress (or the minimum principal stress) needs to be further investigated. Analyses using the ILLI-TRACK model has shown that at the ballast/subgrade interface ballast materials (under a tie) exhibit a tendency of low confining stress or "going into tension". The same tendency is observed in the ballast in the crib area.
3. The "cementing potential" of ballast materials is an area of inadequate technology. Laboratory procedures and criteria should be developed for evaluating "cementing potential".
4. Further work needs to be done to evaluate the degradation of ballast materials subjected to repeated loading. During the present research program, degradation was evaluated for a single state of stress and 10^6 load applications. Degradation potential should be evaluated for a range of stress states and different numbers of load applications.
5. Comprehensive studies should be conducted in the areas of durability testing and durability criteria. Characterization of the field environment (moisture and temperature) and the development of "realistic" testing procedures should be the initial focus of activity. Subsequently, appropriate ballast and subballast durability quality criteria should be developed.
6. The ILLI-TRACK Model and the procedures developed for ballast, subballast, and subgrade characterization should be incorporated into an overall "design model". The "design model" would significantly contribute to the development of improved decisions regarding both new construction and rehabilitation activities.

7. The present study has demonstrated the need for <u>reliable</u> field response and field performance data. Laboratory testing and evaluation as well as structural analysis models need to be correlated with actual field behavior and performance of the track support system.

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