MICHIGAN
STATE HIGHWAY DEPARTMENT
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State Highway Commissioner

ABNORMAL CRACKING AND SETTLEMENT OF PAVEMENT SLABS IN THE WILLOW RUN AND DETROIT INDUSTRIAL EXPRESSWAY SYSTEMS

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Research Project 46 B-20

Research Laboratory
Testing and Research Division
Report F-97
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FOREWORD

This report describes the work and findings of an investigation concerning the abnormal cracking and settlement of slabs in the Willow Run and Detroit Industrial Expressway systems.

A major portion of the field and laboratory work were performed by and under the supervision of Gail Blomquist and Samuel Cardone, formerly with the Research Laboratory. Messrs. R. Thurm and W. O. Fremont have been intimately associated with the study of slag aggregate and the theoretical aspect of the problem.

In the absence of Mr. Cardone, the author has assumed the responsibility of assembling and interpreting the data, as well as preparing the report.

INVESTIGATION OF ABNORMAL SLAB CRACKING AND PAVEMENT SETTLEMENT ON WILLOW RUN AND DETROIT INDUSTRIAL EXPRESSWAYS

During an inspection of the Willow Run and Detroit Industrial Expressways in November, 1945 by Harry C. Coons, Deputy Commissioner and Chief Engineer, in company with Messrs. A. M. Davis, A. Anderson and E. Wenger of the Portland Cement Association, it was observed that throughout both Expressways many of the pavement slabs in the outer lane of both roadways had cracked between transverse joints, and also that abnormal faulting and settlement had occurred at both transverse and longitudinal joints at certain locations. It was the general opinion of the group that the abnormal cracking and settlement of the pavement in these locations could have been caused by differential consolidation of the subbase under the passing and traffic lanes due to concentration of heavy truck traffic in the outer lane.

At the request of Mr. Coons an investigation has been made of prevailing conditions on the Willow Run and Detroit Industrial Expressways to determine the factors contributing to these irregularities in pavement performance with the view of recommending steps to overcome such conditions on future construction. The investigation afforded an opportunity to determine by observations and studies in the field the following: first, a correlation of pavement failures with pavement design, subgrade and subbase construction; second, subbase consolidation as related to concentrated traffic and; third, performance of concrete made from different types of aggregates.

The investigation has included in particular the following work:

1. A general crack survey of projects in that part of the Willow Run and Detroit Industrial Expressways located between US 12 and Michigan Avenue with the exception of

pavement sections associated with bridge or grade separation projects.

2. A detailed condition survey of projects DPW 82-93,C1; 82-93,C3; 82-96,C3; 82-96,C5 and 82-96,C1 located between Belleville Road and Middle Belt Road for comparative study of cracking in relation to aggregate types and foundation construction.

3. A special study of both roadways located between Wayne and Merriman Roads (project 82-96,C1) which has undergone unusual settling especially in the outside traffic lanes.

4. A crack survey of projects 82-74,C6; 82-74,C7; 82-74,C4 and 82-74,C8 located between Greenfield Road and Michigan Avenue for comparative study of cracking in relation to type of subbase material.

5. A study of the physical properties of the concrete from cores and laboratory data.

6. The determination of subbase densities in relation to traffic conditions.

The condition surveys were started in November 1945 and continued intermittently until March 1946. In addition to the field surveys original construction and laboratory data have also been reviewed and analyzed.

This work has been prepared in the nature of a progress report for the purpose of presenting factual data relative to conditions disclosed by the investigation so far and to present conclusions and recommendations which are believed to be warranted at this time.

In brief the investigation has disclosed that for the projects surveyed, cracking in the traffic lane is on an average 4.5 times as severe as that in the passing lane. Furthermore, cracking of slabs on projects constructed with slag aggregate is approximately 6 times as great as that occurring on gravel aggregate projects and, furthermore, the limestone aggregate projects have on an average approximately 3 times as many cracked slabs as appear in the gravel aggregate projects.

In the special sections surveyed, more than 75 percent of the transverse joints in the traffic lanes have faulted from 1/8 to 3/8 inches. On the same project the slabs in the traffic lane have faulted along the longitudinal joint as much as 3/4 inch in certain locations.

A comparison of subbase densities revealed that, under sections of the traffic lane where faulting along the longitudinal joint was observed, density values ranged from 1 pound to 12 pounds per cubic foot higher than those found under the passing lane. Where no longitudinal faulting was observed, density values under both lanes were very much the same.

In view of the evidence obtained from the investigation it may be stated that the general abnormal structural deterioration of the pavement on the Willow Run and Detroit Industrial Expressways is for the most part due to lack of appropriate slab design and construction considerations in face of conditions under which the projects had to be constructed. More specifically, the sporadic settling of the traffic lane with respect to the passing lane is definitely caused by subsequent consolidation of the subbase by the vibratory and load effect of concentrated heavy truck traffic augmented by the absence of tie bars at the longitudinal joint. The faulting of slabs at the transverse joints and at cracks is no doubt due to a combination of factors including the lack of subgrade support at the slab ends in conjunction with the absence of load transfer devices across the joints, the omission of mesh reinforcement which would have held the slabs together when cracks developed and the spacing of expansion joints at 120 foot intervals which permitted the cracks and contraction joints to open and thus destroy any load transfer from aggregate interlock which might have existed. The more pronounced cracking of slabs in the traffic lanes as compared to the passing lanes is obviously due to inadequate slab thickness in view of the factors setforth above. The reason that the slabs in the slag projects have cracked considerably more than those in projects containing limestone aggregate or natural aggregate has not been ascertained at this time. Additional study is necessary before this phenomenon can be conclusively explained.

The report presents the work of the investigation by first discussing the results of the general condition surveys and laboratory studies of materials associated with the work. General construction conditions which prevailed during construction of the Expressways as well as traffic conditions are reviewed. Analysis of failures is treated separately in the light of the results obtained from the condition surveys. Conclusion and recommendations are also included.

THE CONDITION SURVEYS

As previously mentioned in the introduction, the scope of the general condition survey included all major pavement projects located in that portion of the Willow Run and Detroit Industrial Expressway systems lying between US 12 and Michigan Avenue. The projects included in the survey are indicated by project numbers on the sketch shown in Figure 1. Sections of pavement included in bridge projects, grade separations, or traffic interchange projects were not included in the survey. The survey included 21.87 miles of slag aggregate, 10.7 miles of limestone aggregate and 24.0 miles of gravel aggregate concrete pavement including both roadways.

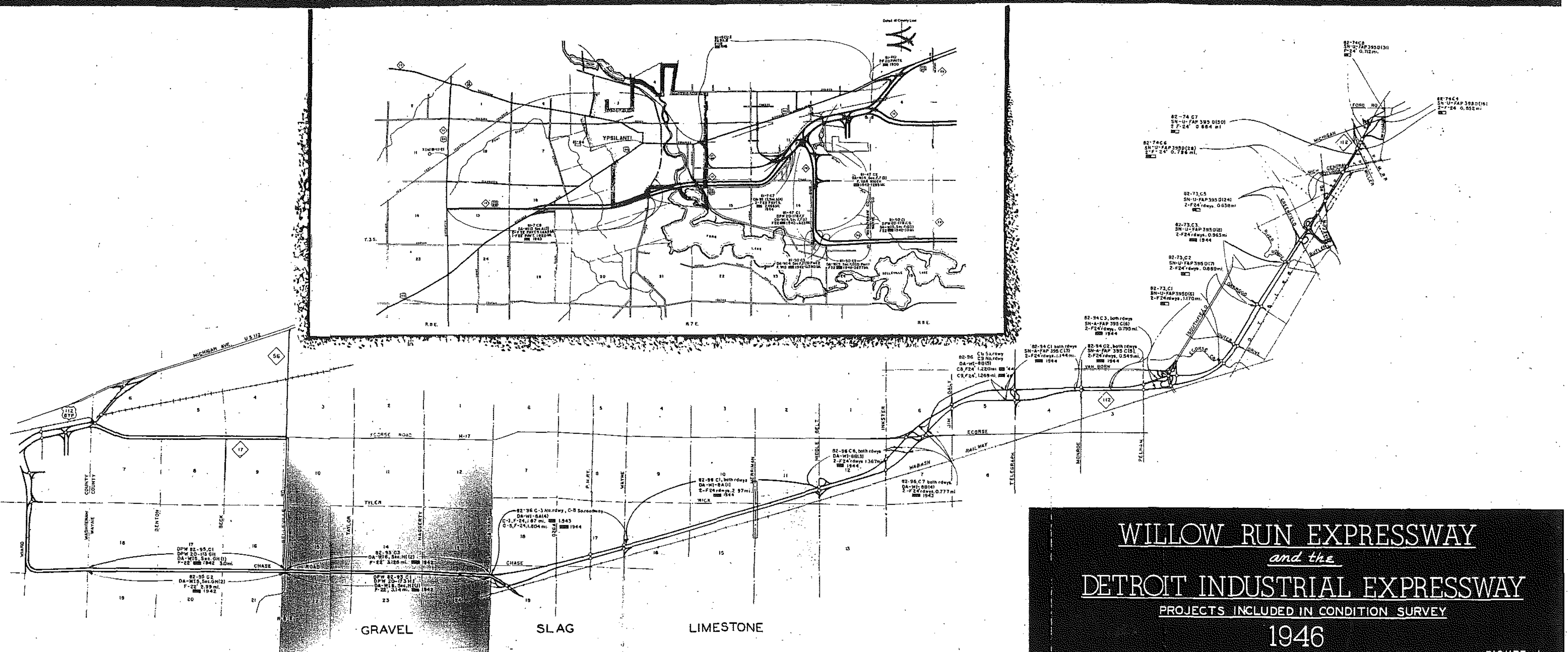
The general condition survey consisted of a visual observation and recording of the number of cracked slabs in each project irrespective of the number of cracks per slab. Many of the slabs contained two or more transverse cracks. When the slabs contained only one crack, invariably the crack was located approximately in the center section of the slab, while in the case of two cracks, they usually occurred at approximately the third points.

Results Revealed by Survey

A summary of crack data in relation to projects is presented on a percentage basis in Table I.* A study of these data indicates that:

1. The amount of cracking in the traffic lane is on an average approximately 4.5 times as severe as that occurring in the passing lane.
2. There is no apparent relation between the amount of cracking and the time of year that the project was constructed.

* See Appendix for all Tables



WILLOW RUN EXPRESSWAY

and the

DETROIT INDUSTRIAL EXPRESSWAY

PROJECTS INCLUDED IN CONDITION SURVEY

1946

FIGURE 1.

3. There is a definite correlation between type of aggregate and degree of cracking. The relation found at the time of survey is shown graphically in Figure 2.

4. The percentage of cracked slabs in the different projects varied considerably.

Other factors brought out by the survey are:

1. Apparent rocking of the slabs under traffic and general faulting of slabs at transverse joints and cracks.

2. Abnormal settlement of pavement in some sections of the traffic lanes.

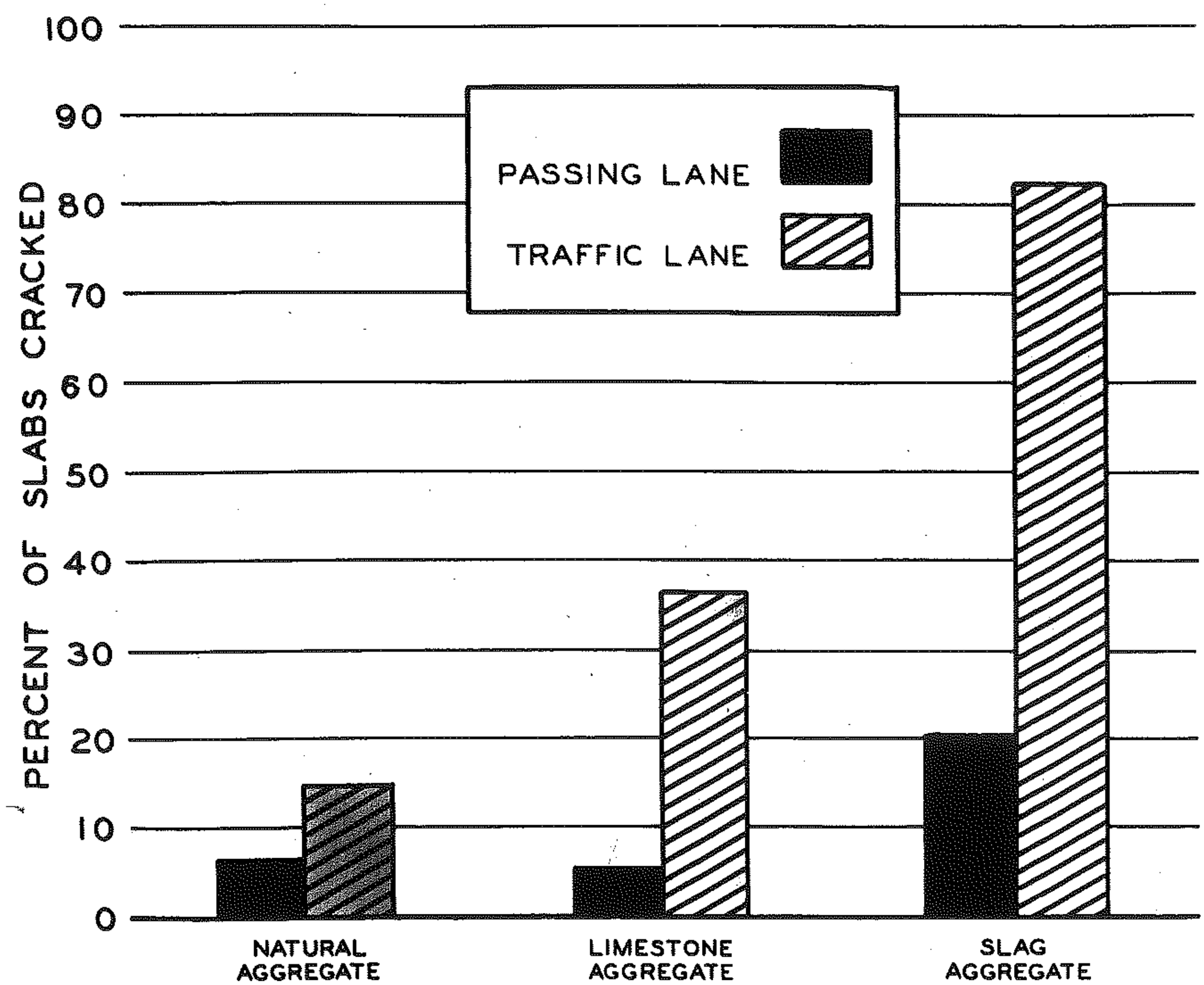
In order to obtain more pertinent and specific facts concerning the physical characteristics of the concrete in relation to various conditions stated above, a detailed survey was made of five adjacent representative projects constructed to a certain degree upon similar subbase material and subjected to the same traffic condition. The projects selected include concrete made from gravel, limestone and slag aggregates.

<u>Study of Selected Projects Constructed with Slag, Limestone and Gravel Aggregates</u>

The projects selected for special study are located in that part of the Willow Run and Detroit Industrial Expressways lying between Belleville and Merriman Roads (See Figure 1). By number, the projects are 82-93,C1 and C3, 82-96,C3 and C5 and 82-96,C1 both roadways. Project 82-93,C1 was constructed under Wayne County specifications and supervision.

The special studies associated with the projects just mentioned, were conducted for the primary purpose of determining specific information concerning:

1. Subbase conditions under a section of project 82-96,C1



PERCENTAGE *of* SLABS CRACKED *in* RELATION *to* TYPE *of* AGGREGATE

FIGURE 2.

between Wayne and Merriman roads which has developed excessive faulting along the longitudinal joint.

2. The physical characteristics of the concrete in passing and traffic lanes of the projects containing slag, limestone and gravel aggregate which might throw some light on the relative cracking experience of the three projects and in turn the whole expressway system.

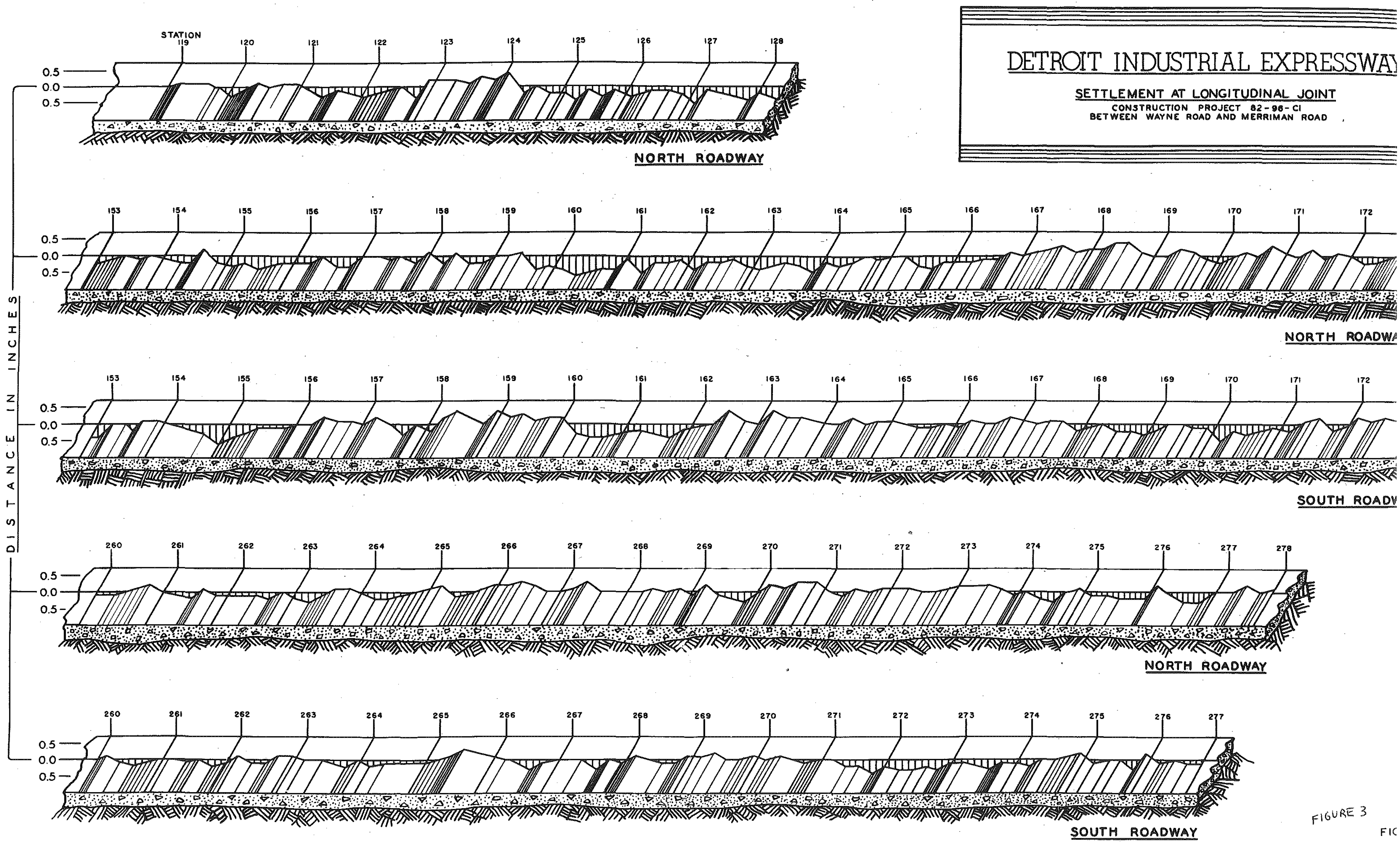
3. Relative consolidation of the subbase under passing and traffic lanes due to traffic.

4. Pavement foundation characteristics in relation to pavement performance.

The studies included a detailed survey of faulting at joints, the location and number of cracks in each slab and subbase density determinations.

<u>Pavement Settlement and Faulting at Joints</u>: Certain sections of project 82-96,C1 lying between Wayne and Merriman Roads, which exhibited excess faulting along the center joint, were selected for study. The extent to which pavement settling had occurred in these sections may be observed in Figure 3. It may be observed that settling up to approximately 3/4 inch has taken place in certain instances. Subsequent surveys have revealed settling of this type at other locations on the two Expressway systems and this type of faulting has also been observed on other concrete pavement projects not associated with this investigation where traffic is concentrated primarily in one lane.

On the same project, the degree of faulting of slabs at the transverse joints and cracks were also determined. It may be noted in Table II that on an average 83 percent of all joints in the traffic lane were faulted from 1/16 to 3/8 inch; whereas, only 27 percent of the joints observed in the passing lane were faulted to the same degree.

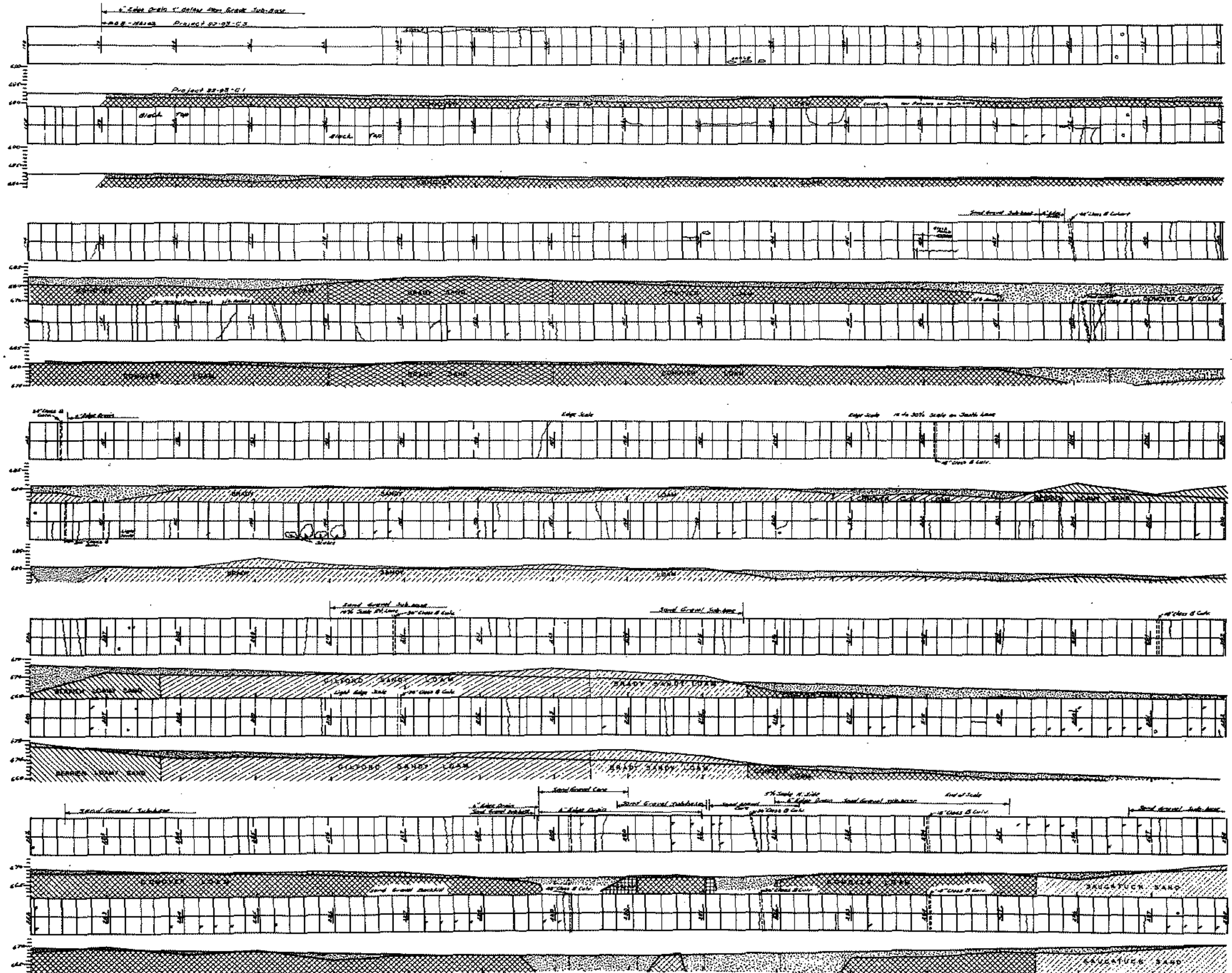

DETROIT INDUSTRIAL EXPRESSWAY
SETTLEMENT AT LONGITUDINAL JOINT
CONSTRUCTION PROJECT 82-96-C1
BETWEEN WAYNE ROAD AND MERRIMAN ROAD
DISTANCE IN INCHES
STATION
119 120 121 122 123 124 125 126 127 128
0.5
0.0
0.5
NORTH ROADWAY
153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172
NORTH ROADWA
SOUTH ROADW
260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278
NORTH ROADWAY
260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277
SOUTH ROADWAY
FIGURE 3

It was discovered from construction records that the subbase material used in the badly settled section between Wayne Road and Merriman Road was in general finer than the subbase materials used on other projects of the two Expressways. The material was taken from under water at the borrow pit, and dumped in piles on the project and allowed to drain. When sufficiently dry it was spread with a bulldozer. Since this material lacked mechanical stability and consequently would not support vehicles, it received very little subsequent compaction due to trucking operations.

In addition, the subbase on this project was constructed as a sand core section. The sand fill material was confined laterally by shoulder embankments constructed with native soil, through which sand bleeders were provided at definite intervals for drainage.

The water table beneath the pavement varied widely with the season. During the initial investigation in November and December there was free water in the lower foot of the sand core material, or one foot below the pavement slab, as compared to no observed free water in the sand core material when the same locations were investigated in July, 1946. This probably could be accounted for by the fact that there is poor subgrade drainage through the impervious clay under the sand and poor lateral drainage out of the core by way of the prepared sand bleeders.

<u>Cracking of Pavement Slabs</u>: All cracks appearing in the slabs on the five representative projects mentioned above have been carefully recorded and plotted. One half of each project has been presented in Figures 4, 5 and 6, respectively, for comparative study. The graphic presentation serves to illustrate the typical crack patterns found on all other projects located on the Willow Run and Detroit Industrial Expressway systems.



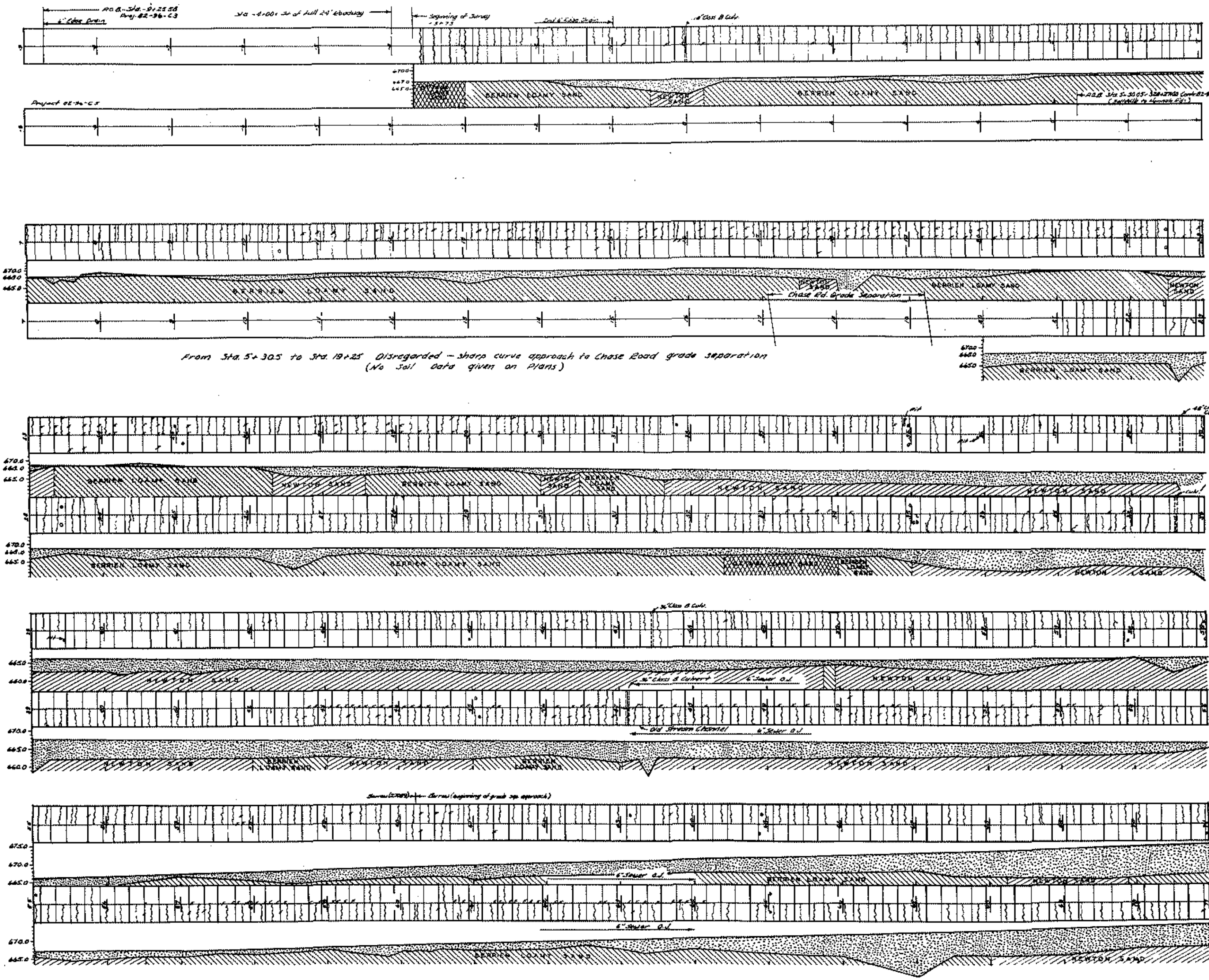
CONDITION SURVEY, NOV. 1946.

WILLOW RUN *and* DETROIT INDUSTRIAL EXPRESSWAYS

PROJECTS F82-93, C3 AND D.P.W. 82-93, C1 – BELLEVILLE TO HANNAN ROADS

GRAVEL AGGREGATE

FIGURE 4



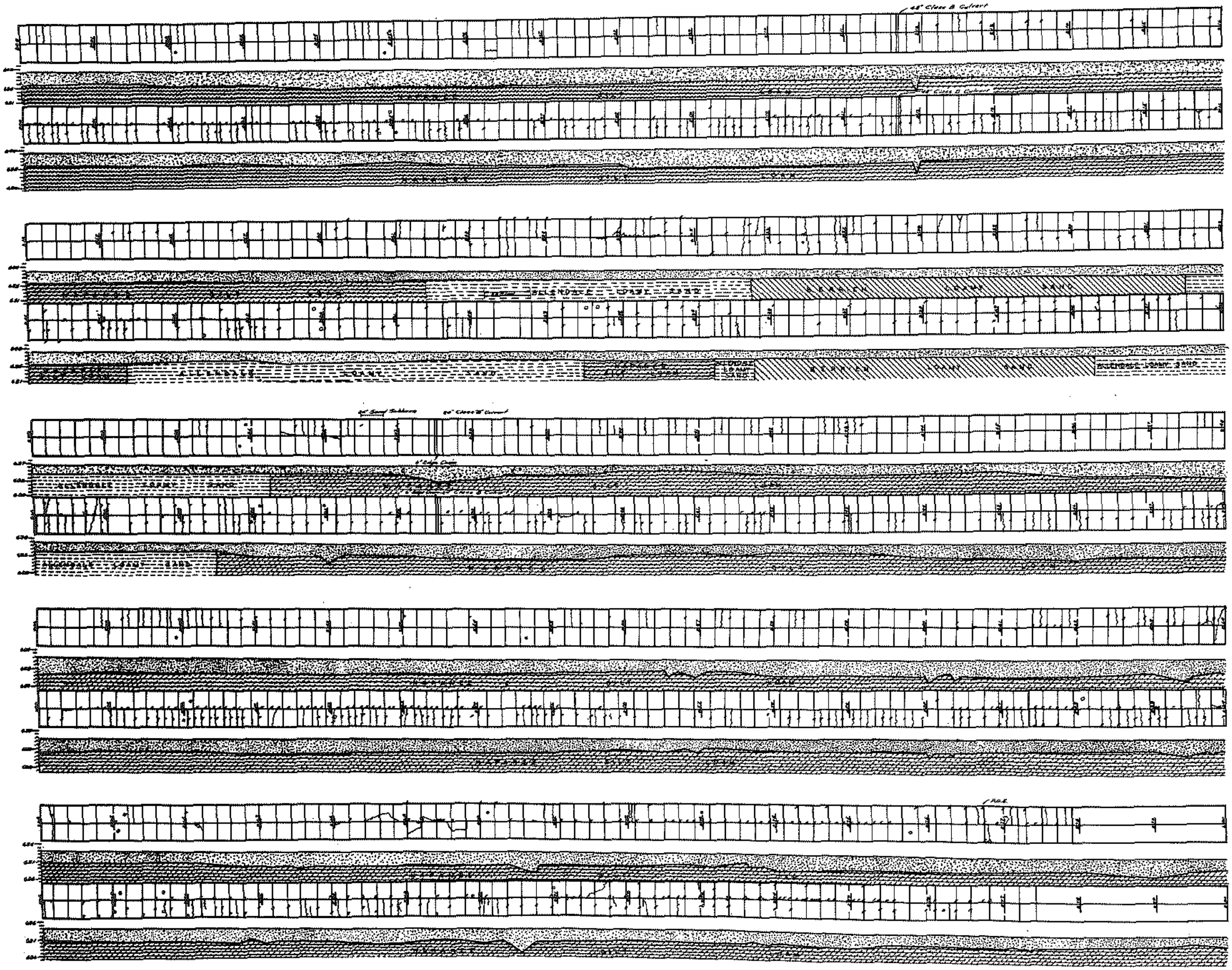
CONDITION SURVEY, NOV. 1946.

WILLOW RUN *and* DETROIT INDUSTRIAL EXPRESSWAYS

PROJECTS F82-93, C3 AND D.P.W. 82-93, C5 - HANNAN TO WAYNE ROAD

SLAG AGGREGATE

FIGURE 5



CONDITION SURVEY, NOV. 1946.

WILLOW RUN and DETROIT INDUSTRIAL EXPRESSWAYS

PROJECT F82-96 C1 - WAYNE TO MIDDLE BELT ROAD

LIMESTONE AGGREGATE

FIGURE 6

With reference to Table I the relative cracking of the slabs in seven adjacent projects constructed with different aggregates is quite pronounced as may be seen from the extracted data presented below:

Project	Slab Thickness	Passing Lane	Traffic Lane	Concrete
82-93,C3) 82-93,C1)	9 inches 9 inches	4.0%	7.2%	Gravel
82-96,C1)	9 inches	2.5%	34.1%	Limestone
82-96,C3) 82-96,C5)	9 inches 9 inches	7.3%	91.2%	Slag
82-95,C1) 82-95,C2)	10 inches	7.1%	10.8%	Gravel

Attention is called also to the unusually large number of cracks appearing in the traffic lanes as compared to adjacent passing lanes, and also to the excessive cracking in the slag projects in comparison with the projects constructed with limestone or gravel aggregates.

The subbase and subgrade materials are also shown in Figures 4, 5 and 6 for comparative study in relation to the cracking phenomena. From the data shown, there seems to be no apparent correlation between degree of cracking and subbase thickness.

As a matter of interest, projects 82-95,C1 and C2 were included in the crack study to show that even 10 inch slabs on the natural subgrade were not of sufficient thickness to completely resist cracking.

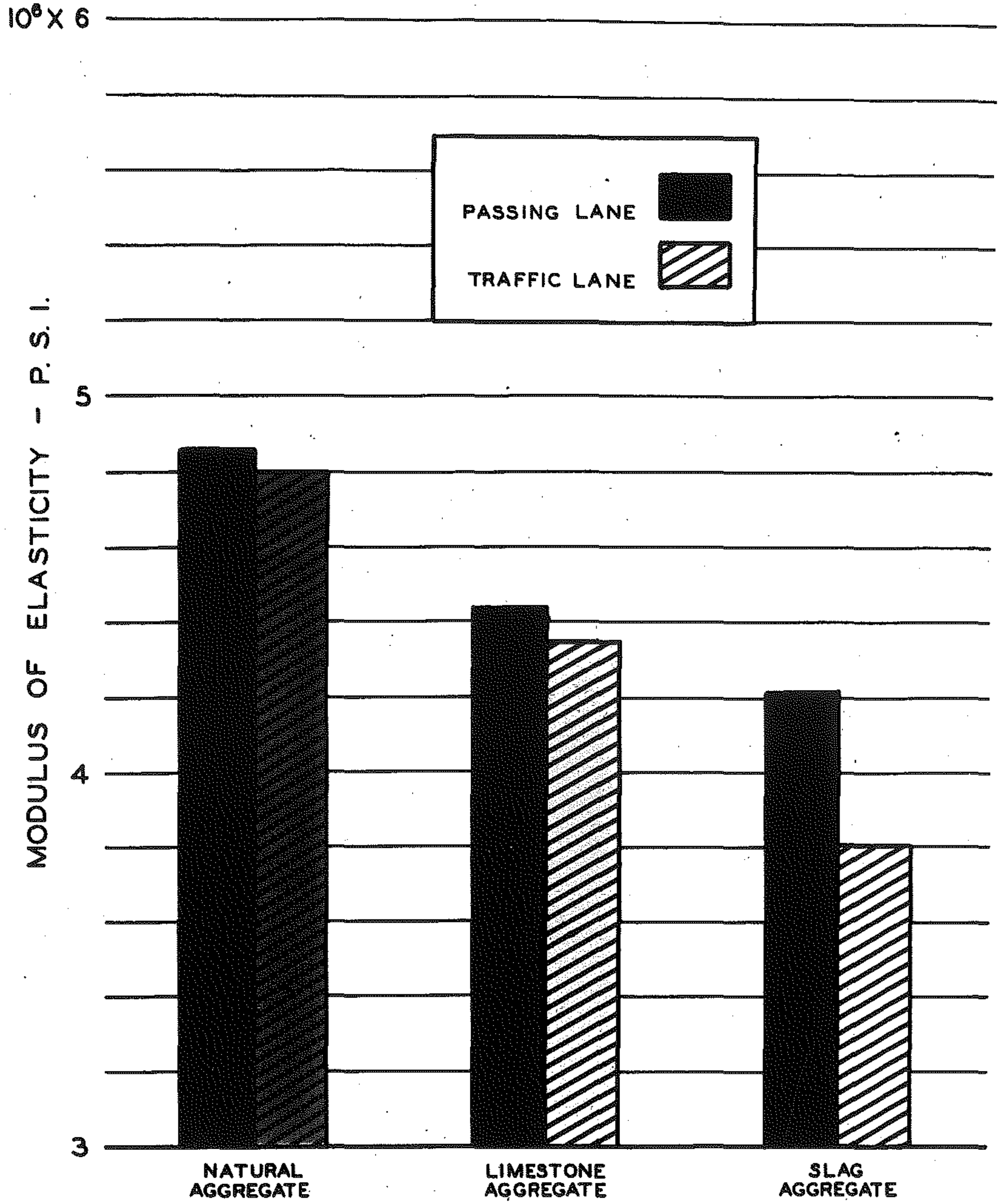
Five projects with 9 inch slabs were also cored to determine the physical characteristics of the concrete.

Concrete Core Study: Twenty cores were cut from each of the natural aggregate projects 82-93,C3 (north roadway) and 82-93,C1 (south roadway), twenty cores from each of the slag projects 82-96,C3 (north roadway) and 82-93,C5 (south roadway) and forty cores from limestone project 82-96,C1 (north and south roadway). These cores, totaling 100, were capped according to A.S.T.M., Designation C42-44, and the modulus of elasticity for each core was obtained at 500 pounds per square inch pressure. It was thought that any relative characteristic weakness of the different concretes associated with the cracking phenomena might be reflected in the modulus values. The average modulus of elasticity at 500 p.s.i. is shown in Table III and graphically in Figure 7.

The graphs in Figure 7 indicate a correlation between degree of cracking and modulus of the concrete. The natural aggregate concrete with the highest modulus had the greatest resistance to cracking, whereas, the slag concrete has the lowest modulus and has cracked the most. The modulus values for limestone aggregate concrete fall in between the two other types of concrete. Furthermore, in all cases the average modulus of the concrete in the traffic lane is slightly lower than that in the passing lane. This might indicate a natural inherent weakening of the concrete due to fatigue under traffic.

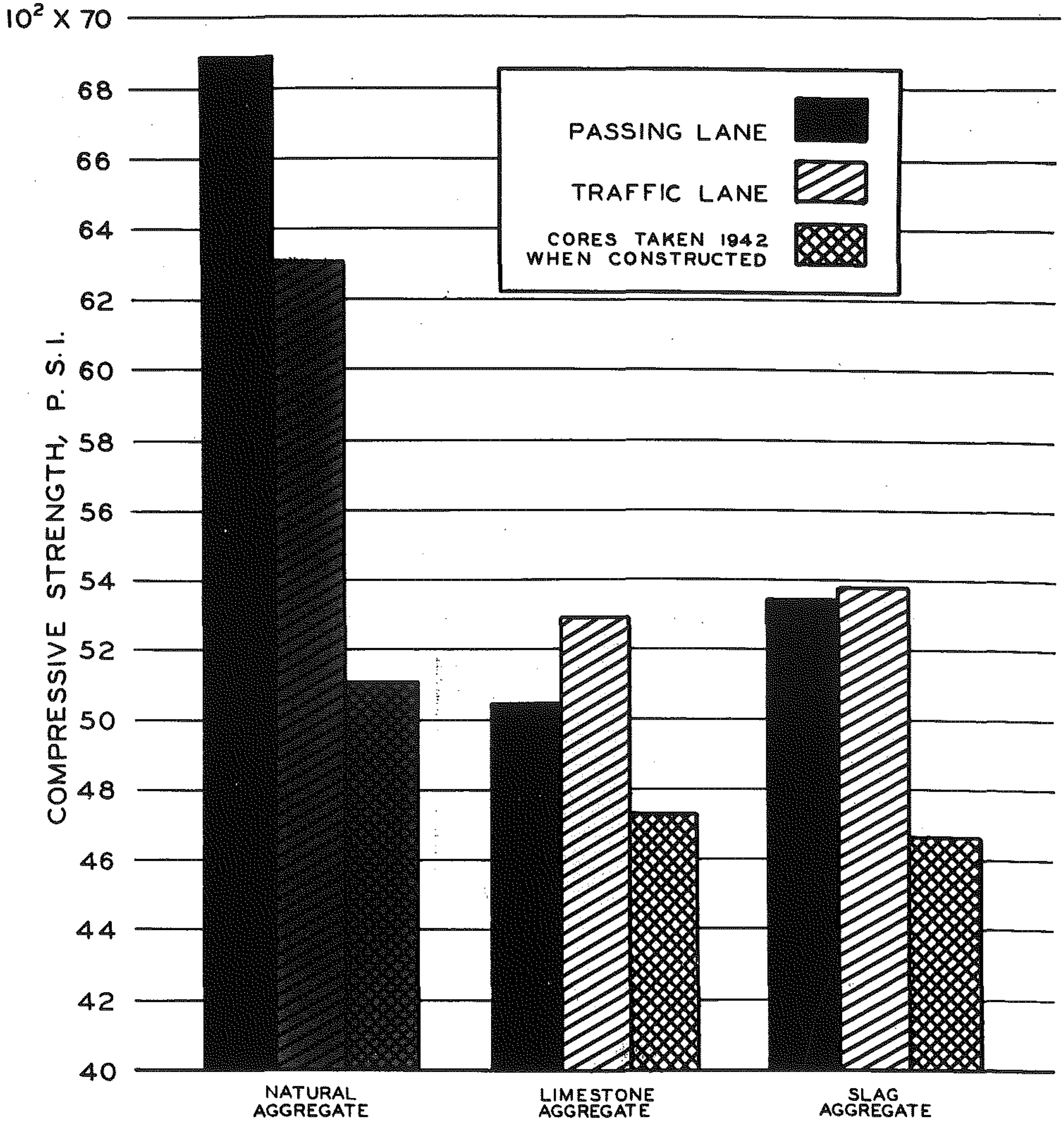
After determination of modulus of elasticity, the cores were broken to obtain their compressive strength. The compressive strength data are also summarized in Table III. The crushing strength of cores taken from the same project shortly after construction in 1942 are presented in Table IV for comparative study. The average core strengths are presented graphically in Figure 8.

The average strengths of all three concretes were above 5,000 pounds which would indicate good concrete in all cases. However, the gravel aggregate concrete had the highest value of 6598 p.s.i., whereas the limestone aggregate and slag aggregate concrete were approximately the same at 5173 p.s.i. and 5365 p.s.i., respectively. The average strength of the concrete



AVERAGE MODULUS *of* ELASTICITY *in* RELATION *to* TYPE *of* AGGREGATE

FIGURE 7



AVERAGE of CORE STRENGTHS in RELATION to TYPE of AGGREGATE

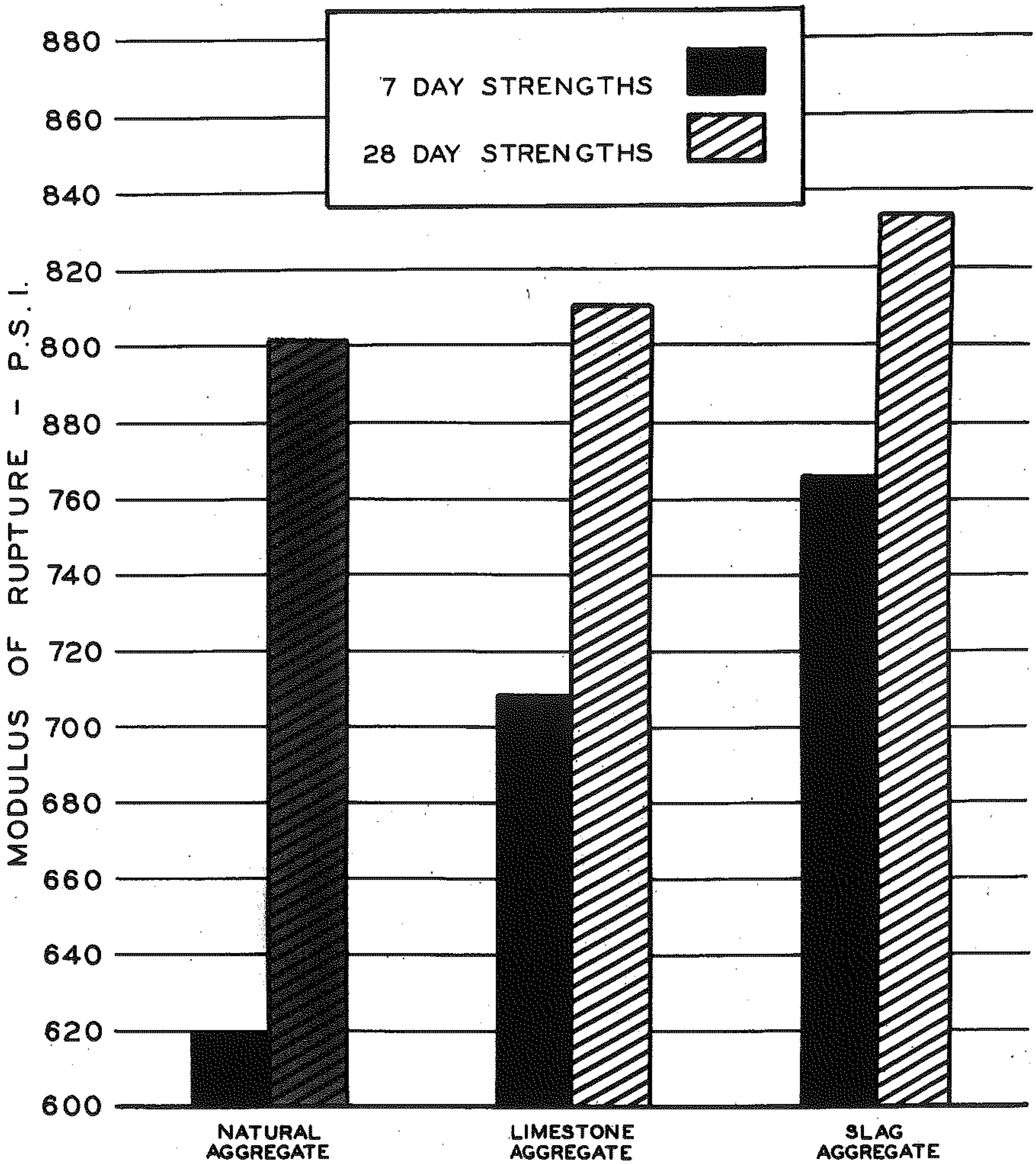
FIGURE 8.

in adjacent lanes was very close to these values. All concretes show an increase in compressive strength with age. The gravel aggregate possessed the greatest change in this respect.

Flexural Strength of Concrete: As a matter of interest flexural strength data at time of construction was extracted from the files and tabulated in Table V. Table V contains both the 7 and 28 day beam strengths together with the slump values. The value for each strength reported is the average of two beams with two breaks from each beam; in other words, the average of 4 breaks for each strength reported. The slump values range between 1-1/2 and 2-1/4 inches. The average rupture strengths for all beams of each type of concrete at 28 days are: slag, 834 p.s.i.; limestone, 811 p.s.i.; and natural aggregate, 802. See Figure 9 for graph of rupture values. This is exactly in reverse order to what might be expected from the cracking performance of each type of concrete. With the exception of the gravel concrete, the flexural strength of all beams, even at 7 days, was well above the minimum allowable by Department specifications. The strength of the slag beams was higher than the other two types of concrete at both the 7 and 28 day tests; but the increase between 7 and 28 days was less than in either the limestone or natural aggregate beams. This may indicate that slag concrete attains a high strength at an early age, but the rate of gain diminishes as the concrete ages.

The flexural strength of the concrete at time of survey has not been obtained. Such a study would necessitate removal of sections of the pavement from which suitable modulus of rupture beams would be cut.

Subbase Density Studies: In order to determine the relative density of the soil under the passing and traffic lanes, undisturbed soil samples were taken through the pavement core holes immediately after the core was removed.



AVERAGE MODULUS *of* RUPTURE *in* RELATION *to* TYPE *of* AGGREGATE

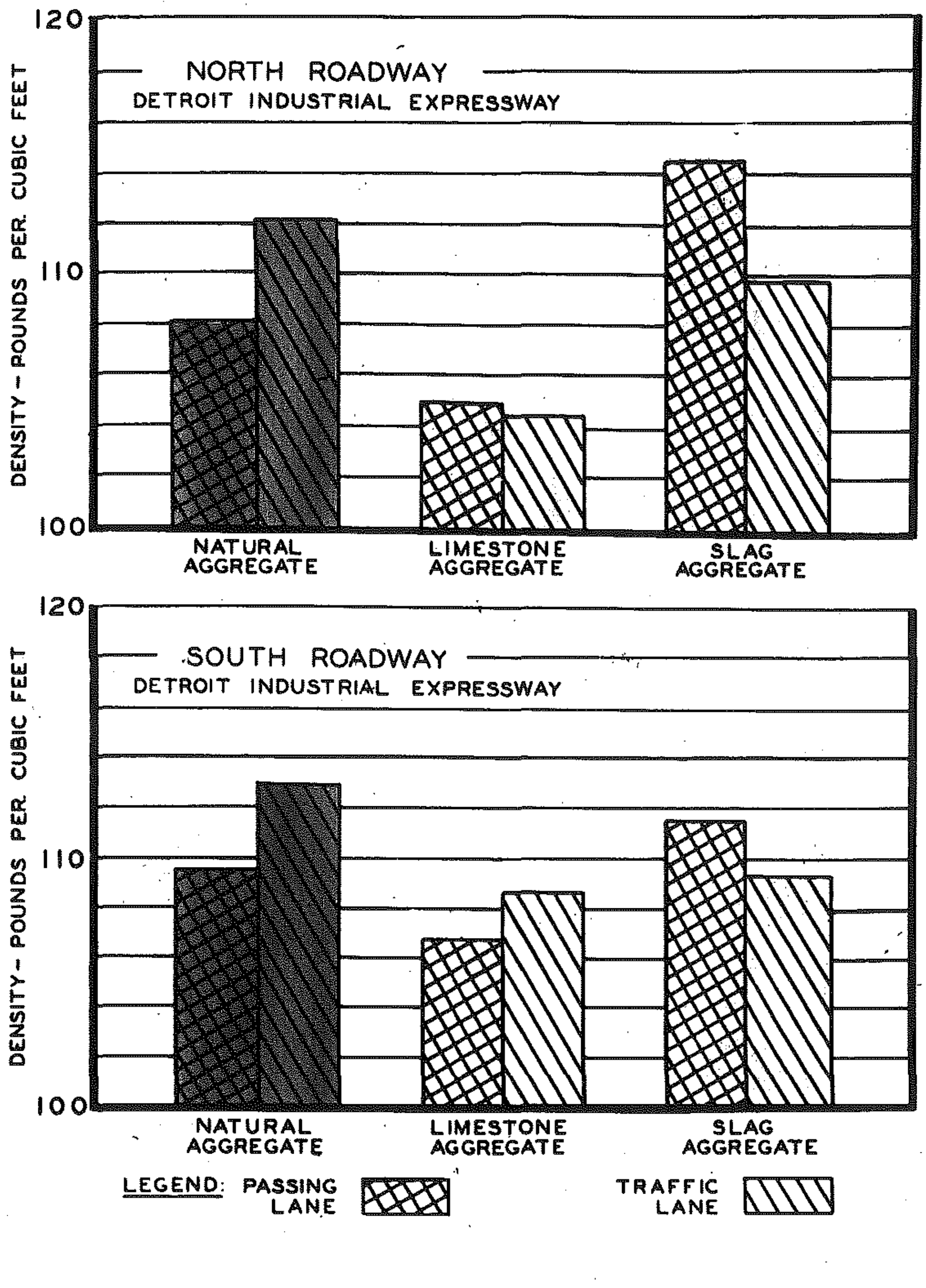
FIGURE 9.

Before taking the soil sample the surface of the subbase was skimmed off to a depth of one to two inches to remove soil containing excess water left in the hole from the core cutting process.

All density samples were taken by a core barrel apparatus similar to the clay soil sampler in current use by the Department and having cylindrical liners 4 inches long and approximately 3-1/4 inches inside diameter. The apparatus, having a tapered cutting edge and straight inside face, was driven into the soil, the liners were removed when full and their ends trimmed by a trowel. The soil was next pushed out of the liner into a tin can, sealed and brought to the laboratory for moisture and density determination.

Although this method produced apparently satisfactory results in fine granular soils it is believed that in coarse granular soils there would be too much disturbance of soil along the cutting edge of the core barrel which in turn would tend to influence the density results.

The results from the field density studies are summarized in Table VI. Average density values in relation to traffic lanes are presented graphically in Figure 10. It may be noted from the data in Table VI that the results are erratic. This may be a result of the test procedure which is not considered altogether satisfactory. A comparison of individual density values shows, however, that in certain cases the density of the subbase material under the traffic lane was as much as 12 pounds higher than that of the subbase under the corresponding passing lane. It also may be noted that in certain instances higher densities were encountered under the passing lane. For some unexplainable reason the average density of the subbase under the traffic lane on the slag projects studied was higher than that of the subbase under



AVERAGE DENSITY of SUBBASE in RELATION to TRAFFIC LANE and AGGREGATE PROJECTS

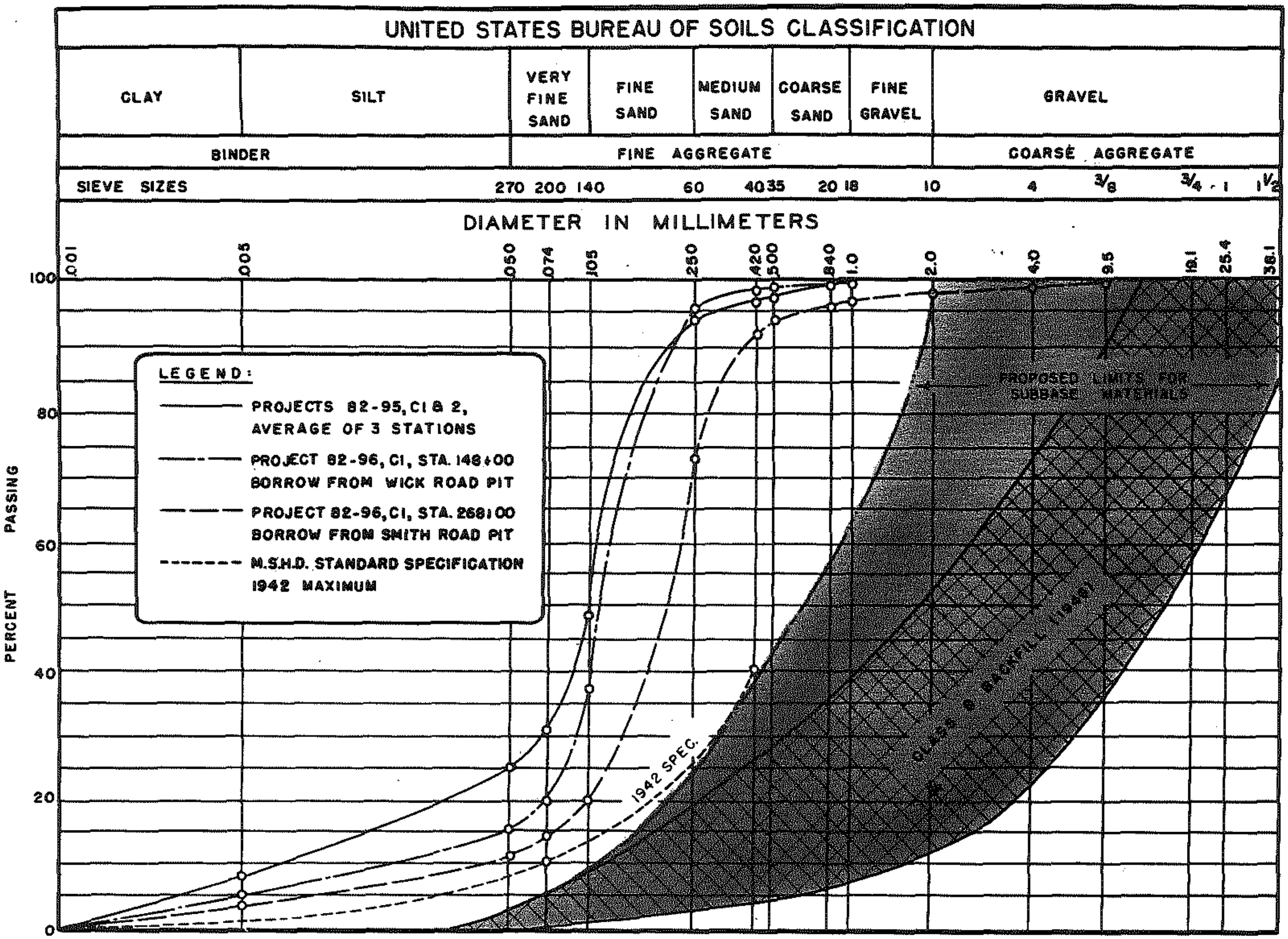
FIGURE 10

the passing lane. With the exception of the slag projects the data indicate in general a slight increase in density under the traffic lane which is logical to expect under the circumstances. This is especially true at those locations where abnormal settlement of the traffic lane has occurred.

An additional study was made in the laboratory to compare the densities of the soils in place with standard Proctor densities at optimum moisture content. The soil taken from the core holes was combined into representative samples and subjected to the Proctor density procedure. The results of this study are shown in Table VII. It may be observed from the data in Table VII that the subbase soils were for the most part well under their maximum possible density. This fact would indicate that the subbase was not fully consolidated at time of construction.

Physical Characteristics of Subbase Material: Representative subbase soil samples were subjected to further laboratory studies in order to determine their physical properties. The results of these tests are presented in Table VIII. The soils have been divided according to their location in the project and source of borrow. To facilitate a comparison of grading characteristics the results of screen analyses are presented graphically in Figure 11. Also on the graph in Figure 11 there are shown the specification limits for desirable backfill material in accordance with 1942 and 1946 specifications and also proposed limits for subbase materials. These latter limits are based on experience and laboratory data and recommended by the Department's Soil Engineers.

It is understood that the subbase materials used throughout the construction of the Expressways, where subbase was needed, was of the same general type. This being true it may be readily observed in Figure 11 that they were



MECHANICAL ANALYSIS of SUB-BASE SOILS

WILLOW RUN and DETROIT INDUSTRIAL EXPRESSWAYS

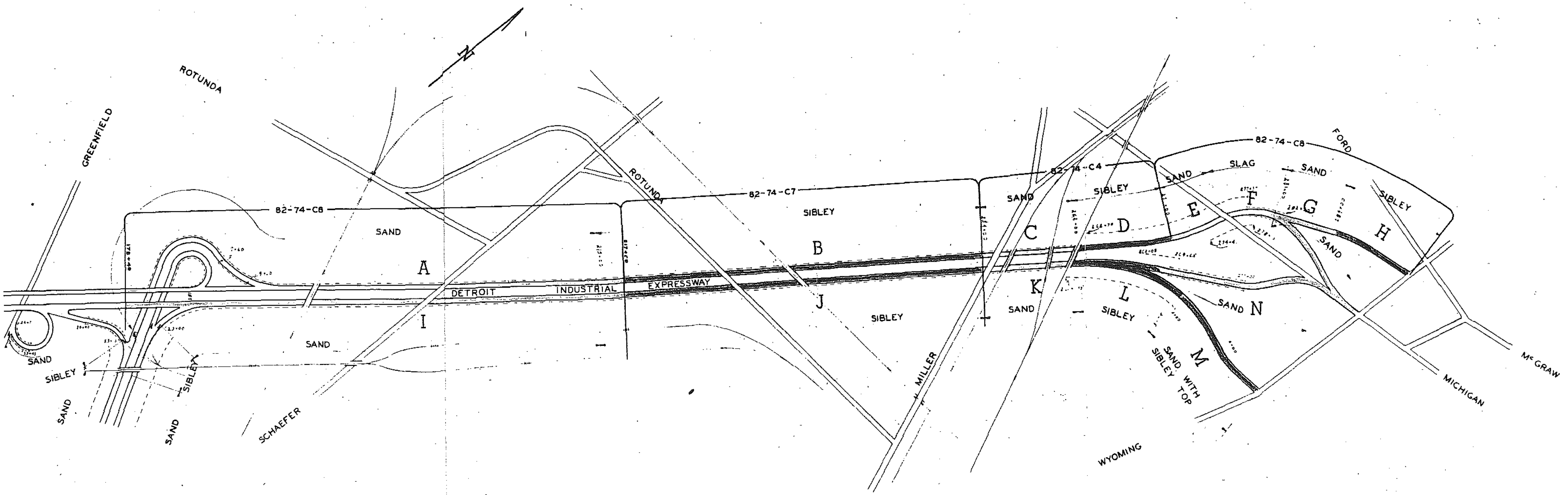
FIGURE II.

not what could be classed as ideal for subbase purposes.

Subbase Construction with Sibley Stone.

Waste limestone screenings from Sibley, Michigan were used as subbase material throughout project 82-74,C7 and on sections of projects 82-74,C8 and 82-74,C4. See Figure 12 for exact locations. Under normal compaction effort by bulldozers and traffic it is understood that this subbase material became very hard and stable.

As part of the general condition survey a special study has been made of the Sibley limestone subbase sections to establish their location and to determine the extent of slab cracking as compared to other types of subbase construction. Comparative crack data are presented in Table IX. The data in Table IX indicate in general that the cracking is slightly more severe on the limestone subbase sections. However, the relative degree of cracking is not highly significant in view of the limited amount of limestone subbase involved.



DETROIT INDUSTRIAL EXPRESSWAY

PROJECTS USING SIBLEY LIMESTONE SCREENINGS FOR SUB-BASE CONSTRUCTION

1946

FIGURE 12

GENERAL CONSTRUCTION AND TRAFFIC CONDITIONS

Because of the prevailing wartime conditions under which both Expressways were constructed, many undesirable practices were tolerated in order to complete the various projects on time. From the standpoint of this investigation it is believed desirable to recall the more important factors because unquestionably they are to a large extent responsible for the present physical condition of the pavements on the Willow Run and Detroit Industrial Expressways.

Foundation and Pavement Construction Practice

In general, with the exception of the section between Wayne and Merriman Roads, the materials used in subbase construction on the two Expressways were considered satisfactory for subbase purposes. No extensive subbase construction was required on the projects between the Huron River and Hannan Road except in fills and undesirable subgrade soil areas. The existing soil on these projects was in general considered suitable for subbase purposes without alterations.

The method of consolidation employed throughout the work was in keeping with the types of subbase materials used and consistent with the emergency wartime construction conditions. Consolidation of the subbase consisted in general of placing the material on the prepared subgrade by end dumping, spreading by bulldozer and subsequently receiving some subsequent consolidation by truck traffic. Such a procedure does not insure adequate or uniform results. It is understood that the design and consolidation of the subbase between Southfield Road and Greenfield Road is better than that on the balance of the Expressway system.

As a wartime measure to conserve steel, the pavement was constructed without mesh reinforcement and without load transfer devices at transverse joints or even tie bars at the longitudinal joint. Also it was necessary to continue construction during the winter months at which time the concrete was laid in many instances under very unfavorable circumstances. Furthermore, due to the extreme haste for completion of the job many construction irregularities were permitted which under normal times would not have been tolerated.

In addition to all of these factors, the new pavement slabs were subjected to unusually heavy traffic immediately after the jobs were opened resulting from the many construction activities taking place on the various highway projects as well as at the Willow Run Bomber Plant.

Traffic Conditions

Traffic data for the years 1944, 1945 and 1946 have been supplied by the Planning and Traffic Division. These data are presented in Table X. The data show that traffic has more than doubled since 1944. However, the average percent of commercial to passenger traffic has remained fairly constant for the three year period. The average commercial traffic for the three year period is approximately 21.3 percent. Also the amount of traffic on each roadway is approximately the same. The average daily traffic volume per roadway for the three year period is 3694 vehicles. The approximate average daily commercial traffic volume for the three year period would be 21.3 percent of 3694 vehicles or 787 vehicles. However, in 1946 the average daily commercial traffic had increased 20.8 percent of 4875 vehicles or 1014 vehicles. From recent classification surveys the ratio of axles to vehicles has increased to approximately 2.8. Thus 1014 x 2.8 gives a total 2839 critical axles per day per lane.

ANALYSIS OF FAILURES

The condition surveys previously discussed have disclosed four outstanding types of failures which warrant careful consideration in view of future construction. They may be described as: (1) differential settling of pavement in adjacent traffic lanes; (2) faulting at transverse joints and cracks; (3) general excessive cracking of slabs in traffic lane as compared to passing lane in the case of dual lane construction, and (4) different structural performance of pavement slabs in relation to type of aggregate employed in making the concrete. The probable causes of these four types of failures will be discussed separately in the light of the factual data presented previously in the report.

Differential Settlement of Pavement Lanes

This phenomenon, which has occurred to an alarming degree between Wayne and Merriman Roads and sporadically through both Expressways, is definitely caused by progressive consolidation and subsequent settling of the subbase under concentrated traffic in the outside lane. It is augmented, of course, by questionable foundation construction practices in conjunction with the use of questionable subbase soil materials. Also faulting action at the longitudinal joint was accelerated because no tie bars were employed to hold the adjacent slabs together.

Faulting at Joints and Cracks

Faulting at joints and cracks is obviously due to lack of subgrade support at such locations augmented by the lack of load transfer at joints and no reinforcement throughout the slab to hold the adjacent edges of cracks together when fracture occurs.

Furthermore, it is apparent that the length of a 20 foot unrestrained pavement slab seems to be critical with respect to vertical displacement of the slab ends under modern truck traffic. This movement is manifested by a rocking action of the slabs under the influence of the repeated axle loads. Rocking of the slabs ultimately results in permanent consolidation of the subbase at joints more than at the center. When a crack forms in the center of the slab, permanent faulting of the slab ends will take place. Subsequantly, the slab sections fault at the cracks.

The use of 120 foot expansion joint spacing has aggravated the condition because the individual slabs have had sufficient space for horizontal movement to destroy what little load transfer possibilities might have existed at transverse joints and cracks had the slabs been held more or less in intimate contact by horizontal restraint.

Excessive Cracking of Slabs in the Traffic Lane

It may be stated that the general abnormal cracking which has developed in the traffic lanes of both roadways of the two Expressways can be attributed largely to the fact that the pavement slab is of inadequate thickness for the type of construction and traffic conditions.

With the exception of projects 82-95,C1 and C2, located between the Wayne County Line and Belleville Road the pavement on both Expressways is of nine inch uniform thickness with expansion joints at 120 foot spacing and intermediate contraction joints at 20 to 30 foot spacing. The slabs are unreinforced and no load transfer is provided at the transverse joints. The adjacent lanes are not doweled at the longitudinal joint. Furthermore, the granular subbase material was not uniformly consolidated to any specified density. Projects 82-96,C1 and C2 have 10 inch uniform slabs. The subbase materials on these projects were of such a nature that no subbase cushion was necessary.

From the best available data concerning truck traffic on the Expressways it has been estimated that the outer lanes will receive approximately 2839 critical axle loads per day. With a traffic load of this character the pavement comes under the design of Class I Highway. See Table IV, 1945, report on "The Design of Concrete Pavements for Postwar Construction". In accordance with Table IV of the report just mentioned it is evident that a 9-1/2 inch to 10 inch slab would be the minimum required for the Expressways provided subgrade conditions were perfect.

At the request of the Design section of the Road Division in June 1943, recommendations for slab thickness were prepared and submitted by the Research Laboratory for Section 3 of the Detroit Industrial Expressway. The calculated values for slab thickness under prevailing conditions on the projects indicated that 12-1/2 inches would be necessary for the pavement to withstand traffic without cracking. (See Departmental Report "Design Recommendations Section 3 Industrial Express Highway" of June 25, 1943). Further, it was stated in that report that "on the basis of what is known at present on the endurance limit of concrete under certain traffic conditions it may be expected that for a slab of 10 inch thickness and 20 foot slab lengths, cracks will form at the end of approximately three years." These latter dimensions were proposed by the Road Division.

The apparent discrepancy in slab thickness as set forth in the two reports is due to the fact that in the first case slab thickness is based on a crack expectancy of only 20 years, whereas in the second case infinite crack expectancy is considered.

It was previously mentioned that the pavement slabs on projects 82-95, C1 and C2 are 10 inches thick. It may be observed from Table I (this report) that the slabs in these two projects have cracked on the average of 7.0 percent in the passing lane and 10.8 percent in the traffic lane. This would indicate that even the 10 inch slab thickness would be structurally inadequate for a normal life expectancy (20 years) under the conditions to which they have been imposed.

Theoretical Discussion of Probable Causes of Cracking

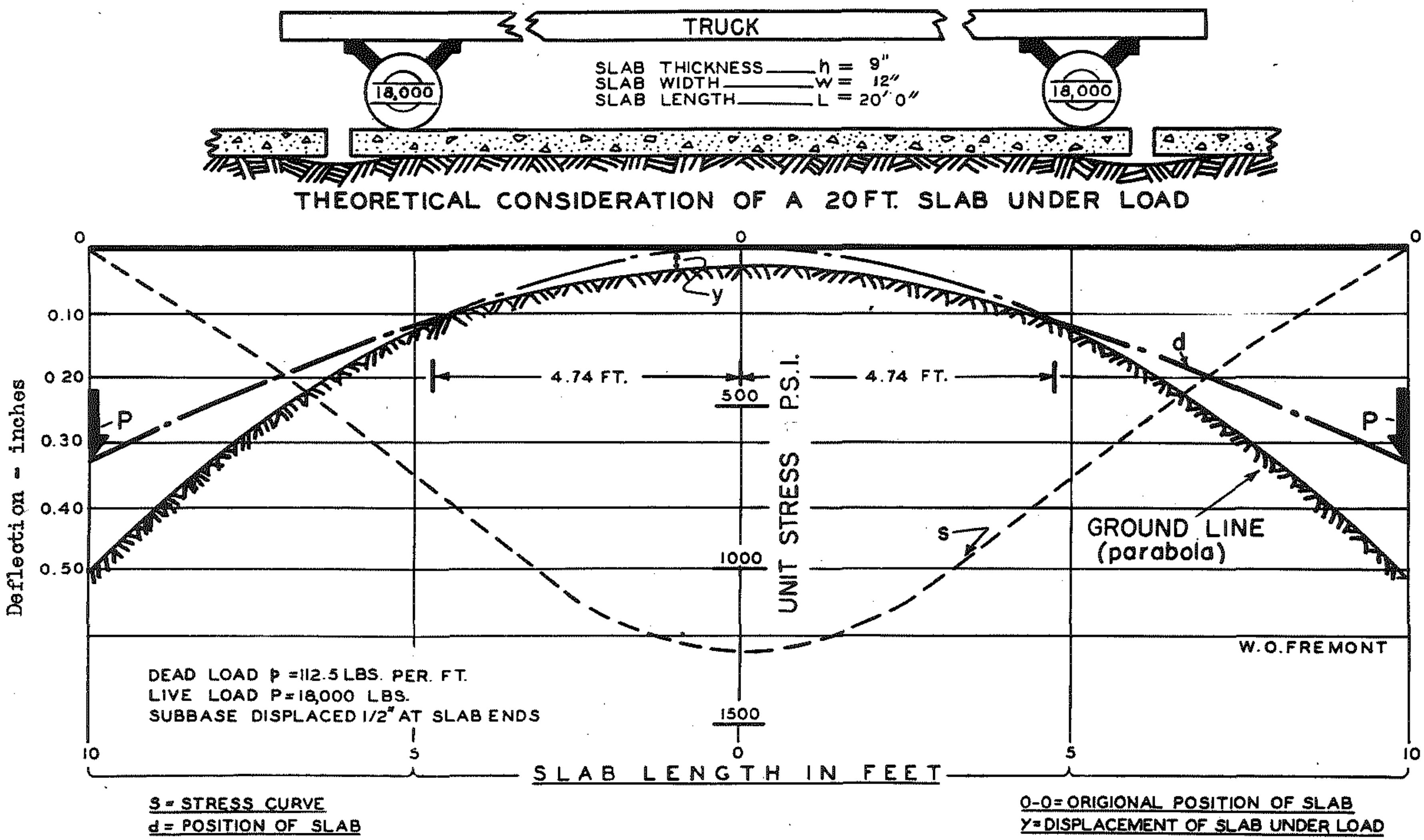
From visual inspection on the Expressways it may be seen in many cases, when the wheels of a heavy truck pass over an expansion or contraction joint or crack, that the ends of the abutting slabs deflect vertically as much as 1/4 inch or even more in some cases. In view of this, it is reasonable to assume that the subgrade under the joints or cracks has been compacted to a greater degree than that under the middle of the slab. This would have the effect of producing a subbase having a convex surface under each slab, while the slab itself remained in essentially a horizontal plane. It is also reasonable to assume that when this condition of subgrade convexity exists, the subgrade support varies from zero at the slab ends to a maximum at the center of the slab which theoretically becomes, when loaded at each end, a simply supported beam having a maximum bending moment at the center of the span. Thus, for the same condition of span and load, the beam having the least resistance to bending will fail first. This is all predicated on the assumption that there is no load transfer between adjoining slabs. For the pavements under study there will be no load transfer at expansion joints. The load transfer contributed by the aggregate interlock at contraction joints and cracks is fully destroyed only after the contraction of the concrete produces a wide joint or when the aggregate at the joint surfaces has been worn by the abrasion of repeated vertical movement of the end of one slab with respect to the adjoining slab. This leads to the theory that the convexity of subgrade surface mentioned above is not produced especially at cracks until the aggregate interlock is destroyed by the abrasive action of the slab ends. In view of this it may be expected that the aggregate having the least resistance to abrasion, which is an inherent property of slag, will produce the condition of no interlock first. Consequently the subsequent concentration of load at the slab ends and greater compaction of the subgrade in the vicinity of the joints, results in a convex subgrade surface.

When the slabs are rocking due to the convexity of the subgrade, the twenty foot unbroken slabs will be subjected to maximum stress conditions in the center portion when two axles of the same vehicle bear on the slab ends simultaneously. This condition must take place a great many times a day because the normal single axle spacing on most trucks varies between 10 and 22 feet. Figure 13 has been developed to show theoretically how the 20 foot slabs may become highly stressed at the center due to the occurrence of axle loads simultaneously at each end. It would appear from this analysis that short slabs would be highly undesirable in concrete pavements, especially when expansion joints are employed at short intervals.

It is reasonable to believe that these two factors just mentioned may have had considerable influence in respect to the degree of cracking which has developed on the various projects of the two Expressways.

<u>Influence of Aggregate Type on Slab Cracking</u>

The investigation so far has not provided sufficient information to warrant definite conclusions as to why the pavement in the slag aggregate projects is cracking at a more rapid rate than that in the projects constructed with either limestone or gravel aggregates.



POSSIBLE BEHAVIOR of DISCONNECTED SHORT SLABS UNDER the INFLUENCE of TRUCK TRAFFIC

FIGURE 13

The slag aggregate, which came from the Great Lakes Steel Corporation in Detroit, apparently meets the Department's specifications for both physical and chemical properties. The chemical composition of the slag evidently can vary but little at the blast furnace. However, the subsequent manufacture of the slag aggregate after it leaves the furnace is not entirely satisfactory because it is cooled by the open pit method which is not generally considered by authorities to be the best method especially when the aggregate is intended for use in concrete.

Physical properties of slag produced by the Great Lakes Steel Corporation as determined by Testing Laboratory[(1)] are given in Table XI.

Chemical analysis of the slag from the Great Lakes Steel Corporation is also presented in Table XI. From a chemical standpoint, the slag is apparently satisfactory. According to Knight[(2)] slags tend to disintegrate when the lime content exceeds a certain ratio (1-3) with respect to the silica, owing to the formation and subsequent inversion of calcium orthosilicate. Knight further states that an excess of 2 percent of sulphur in slag is dangerous and slag containing 3.35 percent sulphur has been known to disintegrate in 20 minutes.

Physical tests on cores and flexural beams representing slag concrete from the various projects on the Willow Run and Detroit Industrial Expressways indicate normal strength values in all cases; in fact, higher values in some cases. The test values also indicate that there is no apparent decrease in compressive strength with age. The flexural strengths of fresh slag concrete

(1) From Departmental Report "Blast Furnace Slag" by Testing Laboratory, Ann Arbor, December 1945.

(2) Road Aggregates, Bernard H. Knight - 1935.

increase normally between the 7 day and 28 day periods. The data in Table XII which was obtained from a report, titled, "Blast Furnace Slag as Concrete Aggregate" by George A. Smith [3] indicates a slight gain in flexural strength over a period of 5 years.

Further information on relative strength characteristics of gravel, limestone and slag aggregates are given in Table XIII which is based on work by the Testing Laboratory of the Testing and Research Division in 1933[4]. Relative physical properties are also included in Table XIII. These data also indicate that concrete made with slag aggregates is comparable in strength to that made from other aggregates under consideration.

Additional strength test data of concrete specimens made from slag aggregate furnished by the Great Lakes Steel Corporation are given in Table XIV. A comparison of strength values is shown for regular concrete and concrete made with air-entraining cement. Although the strength values are within the normal range for pavement concrete, there is in this case a 12 percent drop in strength when air-entraining cement is used. This is of no significant importance to the problem under consideration since the same phenomena will occur in the case of concrete manufactured with gravel aggregates and air-entraining cement.

(3) Blast Furnace Slag as Concrete Aggregate, by George A. Smith Technical Research Report No. 127, February 29, 1936; Resettlement Administration, Division of Suburban Resettlement

(4) Comparative Strengths of Pavement Concretes Using Slag, Gravel and Crushed Stone Coarse Aggregates - Departmental Report Testing Laboratory, September 30, 1933.

TABLE XIV

STRENGTH PROPERTIES OF AIR-ENTRAINED CONCRETE MADE WITH
SLAG FROM GREAT LAKES STEEL CORPORATION
Testing Laboratory, 1945

	GRADE A CONCRETE Cylinders		Beams	
	7 day	28 day	7 day	28 day
Regular Cement	4416	5195	659	753
Air Entraining Cement V.R.	3745	4548	595	662
Percent Difference	15.2	12.4	12.1	12.1

The fact that the slag concrete is apparently sound even at the crack edges has given rise to the belief that the concrete, due to the inherent physical properties of the slag particles, namely brittleness and softness, may fail in flexure by fatigue. The sequence in crack frequency of the three aggregate type concretes varies with their respective relative abrasion resistance. On account of its brittleness the slag aggregate may not be able to withstand the induced stresses set up within the slag particles by moving vehicles.

Another factor which might be associated with the unusual cracking characteristics of slag concrete slabs is the relatively low thermal conductivity and high moisture absorption of slag aggregates. It is logical to assume that these two properties under certain conditions may be instrumental in causing high localized tensile stresses to exist in the slab. Such stresses when combined with high load stresses will no doubt cause cracking of the slabs at early ages.

At the present time the suitability of slag as an aggregate for concrete pavements has been based primarily on laboratory strength tests. From field experiences it is quite evident that such tests do not furnish the necessary answers as to why slag concrete has a higher crack factor than that of gravel concrete. It is believed that studies involving the warping and fatigue properties of slag concrete are desirable and necessary in order to attain more complete answers on the problem.

In the event that slag aggregate will still be permitted for pavement slabs, it is suggested that independent laboratory studies be made to determine the effect of repeated loadings on the flexural strength of slag concrete. Furthermore, it is believed desirable to prepare and break flexure specimens of slag concrete taken from the roadway to determine if the flexural strength has decreased with age. Volume changes due to variations in temperature and moisture should also be considered.

CONCLUSIONS AND RECOMMENDATIONS

It is believed that most of the apparent structural weaknesses of the concrete pavement in the Willow Run and Detroit Industrial Expressway systems have been overcome to a large extent by the Department's current concrete pavement design standards, with perhaps three exceptions, provided strict adherence to specification requirements is maintained in the future. The exceptions are:

1. The Foundation: In view of modern and anticipated greater highway loadings it is obvious that more consideration must be given to the acquisition of suitable subbase materials and to their proper consolidation in the roadway. To this end it is recommended that all subbase materials be selected in accordance with the gradation limitation set forth in Figure 11 of this report and that the material shall be uniformly consolidated in place for the entire width of the constructed embankment to a specified density based on Laboratory density tests. Furthermore, the consolidation of the subbase and subgrade should be continuous throughout the entire length of the project irrespective of cut or fill sections.

2. Aggregates: Aggregates are definitely associated with the ultimate serviceability of the concrete in which they are used. This being true greater emphasis should be placed by the Department on the selection of aggregates to be used as future highway construction projects. In view of the performance record of the slag projects on the Willow Run and Detroit Industrial Expressway systems and on account of the difficulties encountered in obtaining uniform quality material and in controlling slag concrete mixtures in order to realize a continuous uniform concrete product, it is recommended that slag, as an

aggregate for concrete pavement slabs, should not be considered on future construction projects or at least until such time that more definite information can be obtained on the behavior of slag concrete in pavement.

3. Slab Thickness: Present pavement design standards set forth in the Departmental report "The Design of Concrete Pavements for Postwar Construction" (1945) have been based primarily on the original Westergaard analysis in conjunction with Michigan 1936 traffic conditions revised in accordance to traffic counts made in 1942 and 1943. On the basis of recent traffic loadometer studies now in progress it is known that the wheel load factor and wheel load frequency values which govern slab thickness have increased considerably since 1943 and will continue to do so in the future. Furthermore, data from recent field experiments indicate that slab thickness as determined by the Westergaard equations may be too low, and it is therefore quite apparent that slab thickness values for future construction will have to be revised upward accordingly. It may be expected that on those trucklines carrying large volumes of heavy truck traffic, such as would be experienced on Class 1 and Class 2 highways, that slab thickness may have to be increased by as much as 10 percent. This fact should not be overlooked especially in the future design of divided lane expressways or widening strips where one pavement lane in many cases will carry practically all of the commercial traffic in one direction. Studies are now in progress directed towards the determination of slab thickness with these considerations in mind.

APPENDIX

Tables I to XIII

TABLE NO. I

SUMMARY OF SLAB CRACK DATA
Willow Run and Detroit Industrial Expressways

Project Number	Stations P.O.B.	Stations P.O.E.	Length of Project in feet	Number of Slabs in Each Lane	Number Cracked Slabs * Passing Lane	Number Cracked Slabs * Traffic Lane	Percent of Cracked Slabs Passing Lane	Percent of Cracked Slabs Traffic Lane	Construction Date
21.87 MILES OF SLAG COARSE AGGREGATE CONCRETE PAVEMENT									
SOUTH ROADWAY									
82-96-C5	21+10	120+00	9890	495	47	433	9.5	87.4	Sept., Oct. '42
82-96-C6	286+54	350+00	6196	310	57	255	18.4	82.3	Nov. '42
82-96-C7	350+00	391+00	3840	192	73	177	38.0	92.2	Sept. '42
82-96-C8	391+00	438+90	4640	232	15	165	6.5	71.1	June '42
82-73-C1	593+05	638+67	4562	228	59	186	25.9	82.5	Aug., Oct. '43
82-73-C2	638+67	90+00	4736	237	88	220	37.2	93.0	Aug., Sept. '43
82-73-C5	147+00	173+10	2610	131	14	81	10.8	61.7	June, '43
82-74-C6	178+38	217+90	3952	198	5	56	2.4	28.4	July, Aug., Sept. '44
82-74-C7	217+90	230+10	1220	61	39	53	64.0	86.8	Aug., Sept. '44
82-74-C7	237+50	254+00	1650	83	21	62	25.3	74.7	Aug., Sept., Nov. '44
82-74-C4	254+00	282+00	2800	140	33	91	23.6	65.0	Sept., Nov. '44
81-7-C8	76+40	176+30	9990	500	77	466	15.4	93.2	June, July, Aug. '43
NORTH ROADWAY									
82-96-C3	-4+27	120+00	12427	621	45	566	7.3	91.2	Sept., Oct. '42
82-96-C6	306+65	332+55	2590	130	27	100	20.8	76.9	Nov., Dec. '42
92-96-C6	336+20	337+80	160	8	2	8	25.0	100.0	Replaced-No record of pour
82-96-C7	348+00	389+00	3950	198	58	173	29.3	87.4	Sept. '42
82-96-C9	389+00	459+00	6850	343	141	287	41.1	83.7	Nov., Dec. '42
82-73-C1	583+64	636+98	5334	267	6	227	2.4	84.9	Aug., Oct. '43
82-73-C2	636+98	90+00	4692	235	87	218	37.2	93.0	Aug., Sept., Nov. '43
82-73-C5	146+54	173+10	2656	133	12	78	8.7	58.6	Oct., Nov. '43
82-74-C6	178+40	217+90	3950	198	68	198	34.3	100.0	July, Sept. '44
82-74-C7	217+90	229+50	1160	58	3	50	5.2	86.2	Aug., Sept., Nov. '44
82-74-C4	254+00	271+00	1700	85	14	45	16.5	52.9	Nov. '44
82-74-C7	237+00	254+00	1700	85	9	85	10.6	100.0	Aug., Nov. '44
82-74-C8	271+00	293+45	2245	112	35	41	31.2	36.6	Oct., Nov., Dec. '44
81-7-C8	76+40	176+30	9990	500	70	430	14.0	86.0	July, Aug. '43
Totals, both roadways			115,490	5780	1105	4751	19.1	82.2	
10.7 MILES OF LIMESTONE COARSE AGGREGATE CONCRETE PAVEMENT									
SOUTH ROADWAY									
82-96-C1	120+00	276+80	15680	784	14	249	1.8	31.8	June, July '42
82-94-C1	465+50	514+15	4865	243	3	59	1.2	24.3	Sept., Dec. '42
82-94-C2	520+25	545+00	2475	124	18	55	14.5	44.4	Sept., Nov., May '42-'43
82-94-C3	545+00	584+70	3970	199	23	55	11.7	27.5	Nov., Dec., May '42-'43
82-96-C8	438+90	455+40	1650	83	20	47	24.1	56.6	Dec., Jan. '42-'43
NORTH ROADWAY									
82-96-C1	120+00	276+80	15680	784	25	285	3.2	36.4	July, Aug. '42
82-94-C1	459+00	519+11	6011	301	13	155	4.4	51.6	Sept., Dec. '42
82-94-C2	519+11	545+00	2300	115	2	42	2.0	36.7	Oct. '42
82-94-C3	545+00	583+64	3864	193	21	74	11.1	38.2	Oct. '42
Totals, both roadways			56,495	2826	139	1021	4.9	36.1	
24.0 MILES OF GRAVEL COARSE AGGREGATE CONCRETE PAVEMENT									
SOUTH ROADWAY									
81-47-C1	94+80	21+87	7293	365	20	36	5.5	9.9	Nov., Dec. '41
81-50-C3	21+87	0+25	2162	108	0	2	0.0	1.9	June, '42
81-50-C2	35+76	0+00	3576	179	4	10	2.2	5.6	May, June '42
82-95-C2	0+00	158+24	15824	791	18	50	2.3	6.3	Apr., May '42
82-93-C1	158+24	324+05	16581	829	32	52	3.9	6.3	Nov., Dec., Apr. May'41-'42
82-73-C3	90+00	138+95	4895	245	0	1	0.0	0.5	Sept., Oct. '43
82-74-C7	230+10	237+50	740	37	21	28	56.8	75.7	Nov., Feb. '44-'45
81-7-C7	176+30	260+00	8370	419	71	189	16.9	45.2	June, July '43
82-96-C6	276+80	286+54	824	41	1	23	2.4	56.1	Dec. '42
NORTH ROADWAY									
81-47-C2	95+00	26+22	6878	334	4	15	1.1	4.4	June, July '42
91-50-C3	26+22	-4+91	3113	156	10	22	6.4	14.1	June, '42
81-50-C1	29+90	0+00	2990	150	7	8	4.7	5.3	'41 - Wayne County
82-95-C1	0+00	155+74	15574	779	92	120	11.8	15.4	'41 - Wayne County
82-93-C3	159+02	312+81	15379	769	32	62	4.2	8.1	May, June '42
82-96-C8	276+80	306+65	2985	149	8	77	5.1	51.6	Dec. '42
82-96-C8	332+55	336+20	365	18	2	5	11.1	28.0	Jan. '43
82-96-C6	337+80	348+00	1020	51	7	41	14.3	81.0	Jan. '43
82-73-C3	90+00	138+30	4830	242	0	0	0.0	0.0	Oct. '43
82-74-C7	229+50	237+00	750	38	18	26	47.4	68.4	Nov., Feb. '44
81-7-C7	176+30	302+40	12610	631	46	145	7.3	23.0	May, June, July, Oct. '43
Totals, both roadways			126,759	6331	393	912	6.2	14.4	

TABLE NO. II

SUMMARY OF JOINT FAULTING DATA
Willow Run and Detroit Industrial Expressways

Project	Roadway	Station	Traffic Lane: Percentage of Joints Faulted	Traffic Lane: Joints Faulted 1/16" to 1/8" Percent	Traffic Lane: Joints Faulted 1/8" to 1/4" Percent	Traffic Lane: Joints Faulted 1/4" to 3/8" Percent	Passing Lane: Percentage of Joints Faulted	Passing Lane: Joints Faulted 1/16" to 1/8" Percent	Passing Lane: Joints Faulted 1/8" to 1/4" Percent	Passing Lane: Joints Faulted 1/4" to 3/8" Percent
82-96,C3	North	119+38 to 128+22	94	55	33	6	27	27	0	0
82-96,C1	North	153+00 to 173+00	86	51	33	2	35	35	0	0
82-96,C1	South	153+00 to 173+00	86	48	37	1	45	41	4	0
82-96,C1	North	260+00 to 278+00	78	62	14	2	38	36	2	0
82-96,C1	South	260+00 to 278+00	73	60	12	1	38	36	2	0
		Average	83	55	26	2	37	35	2	0

TABLE NO. III

SUMMARY OF CORE STRENGTH AND MODULUS OF ELASTICITY DATA
Willow Run and Detroit Industrial Expressways

Cores taken and tested September, 1946

SLAG

Station	Compressive Strength p.s.i. Passing Lane	Compressive Strength p.s.i. Traffic Lane	Young's Modulus * 10^6 p.s.i. Passing Lane	Young's Modulus * 10^6 p.s.i. Traffic Lane
NORTH ROADWAY Project 82-96, C3				
25+00	5791	5600	3.93	3.53
35+00	5165	5772	3.98	3.54
45+00	5459	4754	4.07	3.50
55+00	5935	6210	4.28	4.20
65+00	5420	5971	4.27	4.17
75+00	5602	7151	4.22	4.03
84+60	6047	6142	4.15	3.41
95+00	5054	4193	4.39	3.66
105+00	4071	5869	4.24	4.27
113+40	----	----	3.40	3.36
Average	5394	5740	4.09	3.77
SOUTH ROADWAY Project 82-96, C5				
25+00	6528	4947	4.15	3.36
35+00	5690	5750	3.51	4.47
45+00	4987	3739	5.50	3.97
55+00	4154	4342	4.48	3.52
65+00	4651	5495	5.14	3.71
75+00	5699	5758	3.88	4.34
83+00	4615	4836	3.52	4.13
95+00	6061	4740	4.76	3.52
105+00	5225	5411	4.22	4.14
112+65	5484	5568	4.17	3.46
Average	5309	5059	4.33	3.86
Average, 2 Projects	5349	5381	4.21	3.81

LIMESTONE

Station	Compressive Strength p.s.i. Passing Lane	Compressive Strength p.s.i. Traffic Lane	Young's Modulus * 10^6 p.s.i. Passing Lane	Young's Modulus * 10^6 p.s.i. Traffic Lane
NORTH ROADWAY Project 82-96, C1				
130+00	6088	5879	4.50	4.06
145+00	4251	4212	4.04	3.77
160+00	5796	5628	4.36	4.42
175+00	----	----	4.65	4.91
190+00	5317	5684	4.69	4.57
205+00	3698	5414	4.69	3.86
220+00	4484	3605	3.53	3.54
235+00	4853	3865	4.33	3.87
250+00	5500	5640	5.16	4.65
265+00	5006	4140	4.22	4.58
Average	4999	4896	4.42	4.22
SOUTH ROADWAY Project 82-96, C1				
265+00	4801	5955	3.95	4.31
250+00	5062	5351	5.03	4.50
235+00	4900	4565	4.87	4.30
220+00	5740	4681	3.80	3.94
205+00	3996	6950	5.20	4.34
190+00	4226	4891	3.93	4.33
175+00	3743	4911	4.13	5.07
160+00	6252	7061	4.91	4.67
145+00	5843	5194	4.10	4.15
130+00	6367	7032	4.71	5.07
Average	5093	5659	4.46	4.47
Average, 2 Projects	5049	5298	4.44	4.35

GRAVEL

Station	Compressive Strength p.s.i. Passing Lane	Compressive Strength p.s.i. Traffic Lane	Young's Modulus * 10^6 p.s.i. Passing Lane	Young's Modulus * 10^6 p.s.i. Traffic Lane
NORTH ROADWAY Project 82-93, C3				
----- **	6132	6570	4.74	5.38
-----	6351	4927	4.50	4.97
-----	7602	6402	5.45	4.93
-----	7169	5461	4.82	4.57
-----	7419	5564	4.76	5.03
Average	6935	5785	4.85	4.98
SOUTH ROADWAY Project 82-93, C1				
----- **	6785	7248	5.24	5.76
-----	6246	5940	5.16	4.85
-----	6767	7419	4.97	4.51
-----	----	----	4.71	4.48
-----	7494	7271	4.25	3.51
Average	6823	6969	4.87	4.62
Average, 2 Projects	6885	6311	4.86	4.80

* Secant modulus, 500 p.s.i.

** No stencils on pavement; cores spaced at .625 mi. intervals

TABLE NO. IV

SUMMARY OF CONSTRUCTION CORE STRENGTH DATA
Willow Run and Detroit Industrial Expressways

SLAG

Station	Compressive Strength, p.s.i.	Date Reported
NORTH ROADWAY Project 82-96, C3 Poured Sept., Oct., 1942		
1+12	4930	3-22-44
10+41	4410	3-22-44
19+85	2415	3-22-44
30+86	4830	3-22-44
42+08	4045	3-22-44
53+95	5070	3-22-44
63+11	4770	3-22-44
70+97	4645	3-22-44
112+52	4355	3-22-44
119+20	6900	3-22-44
Average	4637	
SOUTH ROADWAY Project 82-96, C5 Poured Sept., Oct., 1942		
6+25	5000	3-13-44
7+52	5175	3-13-44
7+72	4430	3-13-44
12+65	5055	3-13-44
26+94	5050	3-13-44
35+00	3825	3-13-44
43+87	4280	3-13-44
55+45	4635	3-13-44
67+01	3905	3-13-44
105+76	4660	3-13-44
117+95	4270	3-13-44
324+99	4660	3-13-44
325+13	5070	3-13-44
325+61	4745	3-13-44
326+62	4830	3-13-44
327+77	5260	3-13-44
328+28	4785	3-13-44
Average	4684	
Average, 2 Projects	4661	

LIMESTONE

Station	Compressive Strength, p.s.i.	Date Reported
NORTH ROADWAY Project 82-96, C1 Poured July, Aug., 1942		
126+92	4535	2-1-44
133+91	5120	2-1-44
146+01	4715	2-1-44
154+45	4725	2-1-44
169+09	4305	2-1-44
177+92	5515	2-1-44
189+75	5855	2-1-44
195+10	5235	2-1-44
202+11	3960	2-1-44
214+70	4895	2-1-44
226+44	4275	2-1-44
236+07	4490	2-1-44
247+02	4435	2-1-44
254+75	4890	2-1-44
265+91	5310	2-1-44
270+16	5140	2-1-44
273+08	4805	2-1-44
275+82	4720	2-1-44
Average	4829	
SOUTH ROADWAY Project 82-96, C1 Poured June, July, 1942		
128+15	6330	2-1-44
135+07	5335	2-1-44
144+54	3980	2-1-44
155+50	4770	2-1-44
164+50	4720	2-1-44
176+42	5490	2-1-44
187+65	6400	2-1-44
197+03	4760	2-1-44
205+07	5270	2-1-44
213+50	4680	2-1-44
223+59	4965	2-1-44
235+96	3885	2-1-44
246+05	4780	2-1-44
252+03	4220	2-1-44
262+02	4090	2-1-44
271+09	4160	2-1-44
273+02	5710	2-1-44
276+30	4050	2-1-44
Average	4642	
Average, 2 Projects	4736	

GRAVEL

Station	Compressive Strength, p.s.i.	Date Reported
NORTH ROADWAY Project 82-93, C3 Poured May, June, 1942		
322+50	6340	6-8-42
312+50	5700	6-9-42
302+00	4940	6-30-42
292+00	3980	6-30-42
282+00	5090	6-30-42
271+00	5610	6-30-42
252+00	5660	6-30-42
242+00	5380	6-30-42
232+00	5090	6-30-42
222+00	6020	7-3-42
212+00	4300	7-4-42
202+00	5300	7-7-42
192+00	5040	7-8-42
182+00	4850	7-9-42
172+00	5140	7-14-42
162+00	4280	7-15-42
Average	5170	
SOUTH ROADWAY Project 82-93, C1 Poured Nov., Dec., 1941; Apr., May, 1942		
160+15	5930	1-12-42
170+10	3260	1-12-42
180+00	5660	1-12-42
190+00	4320	1-13-42
200+00	5000	1-13-42
210+00	3920	1-13-42
220+00	4790	1-15-42
242+00	5700	6-5-42
252+00	4720	6-4-42
262+00	6280	6-3-42
272+00	5510	6-1-42
282+00	4840	5-29-42
292+00	6070	5-28-42
302+00	4940	5-26-42
313+00	4910	5-26-42
322+00	5080	5-26-42
Average	5060	
Average, 2 Projects	5115	

TABLE NO. V

SUMMARY OF FLEXURAL STRENGTH DATA
Willow Run and Detroit Industrial Expressways

SLAG

Station	Date Poured	Slump, Inches	Flexural Strength; p.s.i. 7 days	Flexural Strength; p.s.i. 28 days
NORTH ROADWAY Project 82-96, C3				
4+50	9-9-42	1-1/2	604	664
23+00	9-11-42	2	640	720
49+70	9-16-42	2	903	907
57+50	9-18-42	1-1/2	907	895
75+80	9-21-42	2-1/4	867	909
105+00	10-19-42	2	635	---
90+10	10-21-42	2-1/4	856	---
Average		2	773	819
SOUTH ROADWAY Project 82-96, C5				
111+30	9-23-42	1-3/4	867	841
93+10	9-25-42	2	806	816
63+70	9-30-42	2-1/4	691	858
50+20	10-2-42	2	683	845
20+30	10-7-42	2-1/4	760	886
Average		2	761	849
Average, 2 Projects		2	767	834

LIMESTONE

Station	Date Poured	Slump, Inches	Flexural Strength; p.s.i. 7 days	Flexural Strength; p.s.i. 28 days
NORTH ROADWAY Project 82-96, C1				
274+80	8-26-42	2	809	860
259+35	8-24-42	2	773	773
241+75	8-21-42	2	715	738
223+10	8-19-42	2	628	852
202+90	8-17-42	2	661	785
190+10	8-14-42	2	622	862
176+20	8-10-42	2	707	896
157+50	8-5-42	1-3/4	630	875
139+00	7-30-42	2	637	865
121+00	7-27-42	1-1/2	720	696
Average		2	690	820
SOUTH ROADWAY Project 82-96, C1				
269+25	7-21-42	2	777	728
250+50	7-17-42	1-1/2	727	748
232+00	7-14-42	1-3/4	650	787
214+40	7-11-42	1-1/2	651	875
198+50	7-8-42	2	641	723
183+50	7-3-42	2	764	900
163+80	7-1-42	2	615	746
148+30	6-29-42	1-1/2	697	750
136+75	6-25-42	2	843	896
120+65	6-23-42	2	909	862
Average		1-3/4	727	802
Average, 2 Projects		1-7/8	709	811

GRAVEL

Station	Date Poured	Slump, Inches	Flexural Strength; p.s.i. 7 days	Flexural Strength; p.s.i. 28 days
NORTH ROADWAY Project 82-93, C3				
323+00	5-11-42	1-1/2	688	745
304+50	5-13-42	1-1/2	691	774
287+15	5-15-42	1-1/2	673	867
276+10	5-20-42	1-1/2	578	879
268+50	5-25-42	1-1/2	535	795
251+25	5-27-42	1-1/2	619	783
235+20	5-29-42	1-1/2	605	775
220+90	6-5-42	1-1/2	611	872
204+55	6-8-42	1-1/2	677	904
193+00	6-10-42	1-1/2	662	905
179+00	6-15-42	1-1/2	671	905
165+00	6-17-42	1-1/2	738	909
Average		1-1/2	646	843
SOUTH ROADWAY Project 82-93, C1				
167+70	11-28-41	2	637	554
179+40	11-30-41	2	662	786
189+90	12-2-41	2	534	773
199+00	12-4-41	2	458	773
212+60	12-7-41	1-1/2	467	721
226+30	12-9-41	1-1/2	539	732
232+30	12-12-41	1-3/4	661	816
239+40	12-14-41	2	652	760
321+00	4-23-42	1-1/2	674	904
312+80	4-27-42	1-1/2	653	703
299+50	4-29-42	1-1/2	525	760
286+00	5-1-42	1-1/2	516	736
269+00	5-5-42	1-1/2	643	759
252+70	5-7-42	1-1/2	623	803
158+25	6-4-42	1-3/4	633	834
Average		1-3/4	592	761
Average, 2 Projects		1-5/8	619	802

TABLE NO. VI

SUMMARY OF SUBBASE DENSITY AND MOISTURE DATA
Willow Run and Detroit Industrial Expressways

SLAG

Station	Dry Density p.c.f. Passing Lane	Dry Density p.c.f. Traffic Lane	Moisture Per Cent Passing Lane	Moisture Per Cent Traffic Lane
	NORTH ROADWAY Project 82-96, C3			
25+00	B 99.2*	97.0	7.1	8.0
	A 97.9	---	9.4	---
35+00	113.2	113.7	8.2	6.4
45+00	112.0	108.6	7.6	6.4
55+00	107.2	106.1	4.3	5.2
65+00	119.1	112.3	5.2	4.3
75+00	108.5	99.1	5.1	3.3
84+60	110.6	110.8	5.1	6.6
95+00	124.0	114.3	5.7	6.8
105+00	115.1	113.5	5.2	9.8
113+40	124.8	122.5	6.4	9.2
Average	111.9	109.8	6.3	6.6
	SOUTH ROADWAY Project 82-96, C5			
25+00	108.0	106.3	9.6	6.7
35+00	109.2	104.7	6.4	5.9
45+00	105.2	110.6	6.4	7.8
55+00	108.7	107.4	12.8	10.2
65+00	107.1	109.3	4.9	6.5
75+00	108.5	107.5	4.2	5.4
83+90	110.0	109.9	3.6	4.8
95+00	110.8	107.1	4.0	4.3
105+00	121.4	117.3	10.1	6.0
112+65	126.9	115.1	9.4	9.0
Average	111.6	109.5	7.1	6.7
Average, 2 Projects	111.8	109.7	6.7	6.7

LIMESTONE

Station	Dry Density p.c.f. Passing Lane	Dry Density p.c.f. Traffic Lane	Moisture Per Cent Passing Lane	Moisture Per Cent Traffic Lane
	NORTH ROADWAY Project 82-96, C1			
130+00	95.8	105.2	7.8	9.9
145+00	97.5	104.0	15.0	13.1
160+00	103.3	100.1	17.2	4.2
175+00	103.8	100.3	11.7	11.5
190+00	100.9	109.3	12.6	9.0
205+00	101.5	103.6	10.4	10.0
220+00	109.5	102.9	6.4	7.6
235+00	122.5	103.2	9.1	8.8
250+00	104.7	105.9	6.6	6.9
265+00	110.5	109.0	13.4	7.3
Average	105.0	104.4	11.0	8.8
	SOUTH ROADWAY Project 82-96, C1			
130+00	113.6	112.7	11.6	12.8
145+00	114.1	110.8	13.0	12.9
160+00	115.3	113.9	8.8	8.1
175+00	102.9	102.9	9.1	11.3
190+00	105.2	114.8	10.3	10.7
205+00	100.1	103.0	6.0	10.1
220+00	108.7	107.2	8.7	9.1
235+00	100.0	105.2	7.5	5.4
250+00	102.3	108.7	10.3	13.1
265+00	103.2	106.9	10.1	10.0
Average	106.5	108.6	9.5	10.4
Average, 2 Projects	105.8	106.5	10.3	9.6

GRAVEL

Station	Dry Density p.c.f. Passing Lane	Dry Density p.c.f. Traffic Lane	Moisture Per Cent Passing Lane	Moisture Per Cent Traffic Lane
	NORTH ROADWAY Project 82-93, C3			
--- **	---	119.4	8.6	4.1
---	110.8	113.7	10.1	9.4
---	115.7	111.9	8.0	8.8
---	101.2	105.8	6.2	7.7
---	104.1	104.4	4.4	3.1
	Project 82-95, C1			
21+00	103.0	115.0	4.7	7.8
133+00	114.2	115.0	12.6	13.1
Average, 2 Projects	108.2	112.2	7.8	7.7
	SOUTH ROADWAY Project 82-93, C1			
--- **	102.9	105.8	3.3	4.8
---	105.5	117.7	10.2	9.1
---	106.6	110.7	9.1	7.9
---	117.1	126.3	6.7	6.5
---	121.7	112.5	9.7	9.9
	Project 82-95, C2			
17+00	100.0	100.1	13.0	8.7
84+00	112.0	119.1	8.7	10.0
Average, 2 Projects	109.4	113.2	8.7	8.1
Average, 4 Projects	108.8	112.7	8.25	7.9

* Two samples from same core hole; B at 1 to 4 in. and A at 8 to 12 in. depth below pavement

** No stencils on pavement; core holes spaced at .625 mi. intervals

TABLE NO. VII

DENSITIES OF FIELD AND PROCTOR COMPACTED SUBBASE SOILS
Willow Run and Detroit Industrial Expressways

			Subbase		Dry Densities, p.c.f.		
Soil No.	Project	Station	Type	Source of Material	Field Density	Equivalent Proctor Density**	Maximum Proctor Density
16-17	82-96,C3	75+00, 84+60	Constructed	- - - -	107.3	109.4	111.8
18-19	North Roadway	95+00, 105+00	Constructed	- - - -	116.7	120.8	125.4
20		113+40	Constructed	- - - -	123.7	123.1	124.4
21	82-96,C1	130+00	Constructed	Wick Road Pit	100.5	124.0	124.4
22-23	North Roadway	145+00, 160+00	Constructed	Wick Road Pit	101.2	102.1	105.0
24-25		175+00, 190+00	Constructed	Wick Road Pit	103.6	110.1	111.4
27-28		220+00, 235+00	Constructed	Wick and Smith Pits	109.5	113.5	114.8
29-30		250+00, 265+00	Constructed	Smith Road Pit	107.5	109.6	112.9
31-32	82-96,C1	250+00, 265+00	Constructed	Smith Road Pit	105.3	106.1	106.8
33-34	South Roadway	220+00, 235+00	Constructed	Smith Road Pit	105.3	108.4	109.4
35-36		190+00, 205+00	Constructed	Smith Road Pit	105.8	109.0	109.7
37-38		160+00, 175+00	Constructed	Smith Road Pit	108.8	116.3	117.9
39-40		130+00, 145+00	Constructed	Smith Road Pit	112.8	118.3	118.5
41-42	82-93,C1	- - - - *	Natural***	- - - -	108.0	110.5	114.9
43-44	South Roadway	- - - -	Natural	- - - -	115.2	123.9	124.9
45		- - - -	Natural	- - - -	117.1	129.0	129.5
46	82-93,C3	- - - - *	Natural***	- - - -	105.0	124.4	129.5
47-48	North Roadway	- - - -	Natural	- - - -	113.0	123.5	124.2
49-50		- - - -	Natural	- - - -	103.9	101.9	107.3

* No stencils on pavement; samples spaced .625 miles apart.

** Density obtained by Proctor compaction of the soil at the same moisture content as that of the field sample.

*** Granular subbase employed for short distances at designated locations.

TABLE VIII

SUMMARY OF SUBBASE SOIL TESTS
Willow Run and Detroit Industrial Expressways

	U. S. Bureau of Soils Classification	Sieve Opening Inches	Sieve Opening mm.	Wayne County Line to Belleville Road						Wayne to Merriman Road							
				Natural Soil Subbase						From Wick Pit		From Smith Pit					
				82-95,C1 N. Roadway Sta. 22+00		82-95,C2 S. Roadway Sta. 84+00		82-95,C1 N. Roadway Sta. 133+00		82-96,C1 N. Roadway Sta. 149+00		82-95,C1 S. Roadway Sta. 268+00		Smith Road Pit		Wick Road Pit	
				Cumulative Percent Passing	Percent Retained	Cumulative Percent Passing	Percent Retained	Cumulative Percent Passing	Percent Retained	Cumulative Percent Passing	Percent Retained	Cumulative Percent Passing	Percent Retained	Cumulative Percent Passing	Percent Retained	Cumulative Percent Passing	Percent Retained
Sieve Analysis	Gravel	3/4	19.10														
		1/2	12.70														
		3/8	9.52	100				100									
		No. 4	4.76	99		100		99									
		No. 10	2.00	98	2	99	1	96	4								
	Fine Gravel	No. 18	1.00	97	1	98	1	95	1	100		100					
	Coarse Sand	No. 20	0.84	97		98		94		99		99		100		100	
		No. 35	0.50	93	4	94	4	92	3	99	1	98	2	96	4	98	2
	Medium Sand	No. 40	0.42	92		92		91		98		97		94		97	
		No. 60	0.25	70	23	70	24	78	14	96	3	94	4	80	16	64	34
	Fine Sand	No. 140	0.105	12	58	18	52	29	49	37	59	48	46	26	54	13	51
	Very Fine Sand	No. 200	0.074	7		13		22		20		31		18		10	
		No. 270	0.053	6	6	9	9	17	12	15	22	25	23	4	22	8	5
Hydrometer	Silt		0.005	1	5	3	6	5	12	5	10	8	17	1	3	2	6
	Clay		0.001		1		3		5		5		8		1		2
	Colloids		- - -														
Soil Constants	Liquid Limit			19		19		18		20		19		19		20	
	Plasticity Index			N.P.		N.P.		1		N.P.		N.P.		N.P.		N.P.	
	Specific Gravity			2.62		2.60		2.61		2.63		2.60		2.60		2.65	
	Shrinkage Limit, percent			No Shrinkage		No Shrinkage		No Shrinkage		No Shrinkage		No Shrinkage		No Shrinkage		No Shrinkage	
	Loss on Ignition, percent			0.93		1.75		3.39		7.93		8.67		0.68		4.52	
	Organic Content, percent			0.60		1.31		2.95		1.53		2.77		0.55		2.42	
	Field Moisture Equivalent, percent			22		19		18		21		20		22		21	
	Capillary Rise, Inches			30-1/2		32-3/4		31		32		26		25-1/4		18-1/2	
	Coefficient of Permeability, cu. ft. per sq. ft. per hr.			0.037		0.016		0.015		0.016		0.17		0.06		0.016	
	Voids, percent*			32.8		32.7		31.9		33.9		35.0		34.3		37.8	

* Voids computed on basis of maximum compaction in dry state

TABLE NO. IX

EFFECT OF SUBBASE TYPE ON SLAB CRACKING
Detroit Industrial Expressway

Project	Station to Station	Section Designation	Total All Slabs	Cracked Slabs Passing Lane	Cracked Slabs Traffic Lane	Percentage Cracked Passing Lane	Percentage Cracked Traffic Lane	Type of Subbase
			NORTH ROADWAY					
S-82-74,C6	178+40 to 217+90	A	186	46	155	24.73	83.33	Sand
82-74,C7	217+90 to 254+00	B	170	37	148	21.76	87.05	Sibley
82-74,C4	254+00 to 262+00	C	37	7	21	18.91	56.75	Sand
82-74,C4	262+00 to 271+00	D	45	7	33	15.55	73.33	Sibley
82-74,C8	271+00 to 277+00	E	19	10	12	52.63	63.15	Sand
82-74,C8	277+00 to 281+00	F	27	10	7	37.03	25.92	Slag
82-74,C8	281+00 to 289+00	G	38	9	12	23.68	31.57	Sand
82-74,C8	289+00 to Wyoming	H	29	5	6	17.24	20.68	Sibley
			SOUTH ROADWAY					
82-74,C6	178+40 to 217+90	I	188	75	149	39.89	79.25	Sand
82-74,C7	217+90 to 254+00	J	167	87	149	52.09	89.22	Sibley
82-74,C4	254+00 to 262+00	K	38	9	21	23.68	55.26	Sand
82-74,C4	262+00 to 3+75	L	25	2	4	8.00	16.0	Sibley
82-74,C4	3+75 to Wyoming	M	65	9	16	13.84	24.61	Sand with Sibley Top
82-74,C4	264+60 to Michigan	N	88	16	62	18.18	70.45	Sand
82-74,C6		A-I	374	121	304	32.3	81.3	Sand
82-77,C7		B-5	337	124	297	36.8	88.0	Sibley

TABLE X

TRAFFIC DATA

Detroit Industrial Expressway

at Jim Daly Road

1. 24-Hour Average Daily Traffic Volumes:

Year	Westbound	Eastbound
1944	2292	2313
1945	3094	3010
1946	4792	4875

2. Vehicle Classification Data*:

		Passenger Cars		Single Trucks		Trailer Combs.		Busses		Total		Commercial
		No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.	Pct.
1944	WB	5619	79.8	742	10.6	668	9.5	8	0.1	7037	100.0	20.2
	EB	5500	77.9	797	11.3	753	10.7	10	0.1	7060	100.0	22.1
1945	WB	5940	81.4	675	9.3	657	9.0	23	0.3	7295	100.0	18.6
	EB	5628	77.9	842	11.6	723	10.0	33	0.5	7226	100.0	25.1
1946	WB	2463	80.9	298	9.8	258	8.5	25	0.8	3044	100.0	19.1
	EB	2381	77.5	340	11.1	331	10.8	19	0.6	3071	100.0	22.5

* Number of vehicles in the above table are the accumulation of a series of counts varying in length from 1 to 24 hours, all made on weekdays. They do not represent 24 hour volumes.

TABLE XI

PHYSICAL AND CHEMICAL PROPERTIES OF SLAG PRODUCED BY THE GREAT LAKES STEEL CORPORATION

PHYSICAL PROPERTIES OF SLAG (1)

Location	Pit A	Pit B	Pit C	Grand Average
Weight per cu. ft., lbs.	73.3	74.0	72.2	73.2
Absorption, percent	2.84	3.38	3.02	3.08
Specific gravity	2.29	2.27	2.31	2.29

CHEMICAL PROPERTIES OF SLAG (2)

Sample	Great Lakes Steel Corp. Sample No.			Average Range for United States (3)
	1	2	3	
Iron Oxide	0.23	0.22	0.22	0.1 to 0.7
Silica	34.97	36.82	35.44	32 to 38
Alumina	13.49	12.57	12.96	10 to 14
Lime	42.51	43.62	42.69	38 to 45
Manganese	0.79	0.90	0.72	0.2 to 1.5
Magnesia	7.12	5.10	7.26	4 to 9
Sulphur	1.53	1.21	1.23	1 to 2
Lime/Silica Ratio	1.23	1.19	1.21	1 to 3

(1) From Report "Blast Furnace Slag" - Testing Laboratory Report December, 1945.

(2) From Chemical Analysis by Great Lakes Steel Corporation.

(3) The Commercialization of Blast Furnace Slag by Fred Hubbard, Iron & Steel Engineer, June, 1943.

TABLE XII

RESULTS OF TESTS OF SLAG, GRAVEL AND STONE AGGREGATES*

Test	Results of tests of								
	Slag			Gravel			Stone		
	Min.	Max.	Ave.	Min.	Max.	Ave.	Min.	Max.	Ave.
Compressive strength at 28 days – p.s.i.	4550	5420	5070	4250	4790	4590	4620	5160	5040
Compressive strength at 3 mo. – p.s.i.	5230	6610	5880	4960	5850	5400	5630	6080	6020
Compressive strength at 1 yr. – p.s.i.	6010	7260	6460	5230	6280	5800	5720	7420	6700
Compressive strength at 5 yrs. – p.s.i.	5700	7290	6770	5590	6740	6160	6410	7830	6910
Modulus of Rupture at 28 days – p.s.i.	635	840	720	605	785	710	680	890	771
Modulus of Rupture at 3 mo. – p.s.i.	655	820	745	665	965	791	715	960	837
Modulus of Rupture at 1 yr. – p.s.i.	785	910	840	725	965	822	810	1040	917
Modulus of Rupture at 5 yrs. – p.s.i.	850	1035	905	790	985	893	825	1045	939
Depth of wear at 28 days – inches	.051	.130	.088	.054	.071	.064	.047	.068	.061
Depth of wear at 90 days – inches	.040	.073	.056	.034	.062	.047	.048	.061	.055
Absorption of concrete at 28 days – %	4.32	7.83	5.88	4.14	5.40	4.84	4.67	6.96	5.78
Absorption of concrete at 3 mo. – %	4.48	6.56	5.59	3.89	6.14	5.17	4.74	7.23	5.44

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* Data summarized from results shown in a report to be published as a part of A.S.T.M. Committee C-9 on Concrete and Concrete Aggregates

TABLE XIII
RESULTS OF TESTS OF GRAVEL, LIMESTONE AND SLAG AGGREGATES
LABORATORY STUDIES AT ANN ARBOR, 1933

RELATIVE COMPRESSIVE STRENGTHS, P.S.I.

GRAVEL			LIMESTONE			SLAG		
Source	7 day	28 day	Source	7 day	28 day	Source	7 day	28 day
Killins	3973	5248	France Stone, Monroe	4023	5918	France Stone, Toledo	4108	5389
Oxford	4143	5534	Wallace, Bay Port	4098	5448	Detroit Slag & Dock Co.	4300	5815
Grand Rapids #4	4346	5552				Illinois Slag & Ballast Co.	4097	5619
Hersey	4196	5419				France Stone, Chicago	4283	5479
Average	4165	5438		4060	5683		4197	5575

RELATIVE MODULUS OF RUPTURE STRENGTHS, P.S.I.

GRAVEL	7 day	28 day	LIMESTONE	7 day	28 day	SLAG	7 day	28 day
Killins	578	691	France Stone, Monroe	547	724	France Stone, Toledo	544	656
Oxford	585	703	Wallace, Bay Port	575	688	Detroit Slag & Dock Co.	604	728
Grand Rapids #4	596	665				Illinois Slag & Ballast Co.	598	650
Hersey	576	669				France Stone, Chicago	581	596
Average	584	682		561	706		582	658

RELATIVE PHYSICAL PROPERTIES

	Percent Absorption	Percent Wear		Percent Absorption	Percent Wear		Percent Absorption	Percent Wear
Killins	1.32	6.38	France Stone, Monroe	1.97	24.60	France Stone, Toledo	2.52	10.16
Oxford	0.97	6.32	Wallace, Bay Port	0.62	14.02	Detroit Slag & Dock Co.	1.53	16.20
Grand Rapids #4	0.85	5.60				Illinois Slag & Ballast Co.	1.57	14,80
Hersey	0.85	6.40				France Stone, Chicago	1.08	26.30
Average	1.00	6.18		1.30	19.31		1.67	16.86