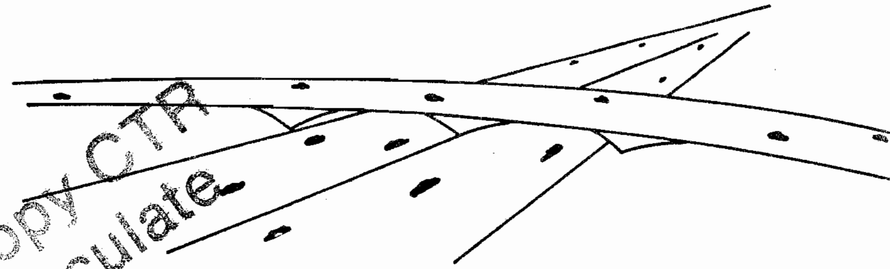

DEPARTMENTAL RESEARCH

Report Number 45-5F

PAVEMENT MATERIAL PROPERTIES AS RELATED TO SKID RESISTANCE

TEXAS HIGHWAY DEPARTMENT

PAVEMENT MATERIAL PROPERTIES AS RELATED TO SKID RESISTANCE

BY

Kenneth D. Hankins

Research Report 45-5F

Determining and Evaluating Skid Characteristics of Texas Highways

Research Study 1-8-63-45

Conducted By

Highway Design Division, Research Section

Texas Highway Department

In Cooperation With The

U. S. Department of Transportation

Federal Highway Administration

Bureau of Public Roads

August 1969

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Dr. Clyde Lee, Center for Highway Research, is thanked for his assistance and counsel during the texture study and Mr. Frank Scrivner is thanked for assistance in obtaining part of the data reported herein.

ABSTRACT

Pavement Materials Properties as Related to Skin Resistance
Project Number: HPR-1( ), 1-8-63-45
Investigator: Kenneth D. Hankins
Research Agency: Texas Highway Department
Sponsor: Texas Highway Department & Bureau of Public Roads
Date: June, 1970
Started: September, 1963
Status: Complete

Key Words: Skid Resistance, Pavement Type, Aggregate Type, Aggregate Grade, Aggregate Shape, Aggregate Hardness, Binder Content, Pavement Texture

Skid Resistance at 20 mph and 50 mph as obtained with a two wheeled skid test trailer was studied in relation to various pavement materials properties which include pavement type, aggregate type, aggregate shape, aggregate grade, aggregate hardness, pavement texture and asphalt or cement contents. It was found that the average initial friction was about the same for each pavement type, but P. C. concrete pavements generally revealed a smaller wear or polish rate. Aggregate type was found to be important for flexible pavement surfaces and the L. A. wear test results were found to be relatively unimportant for each pavement type studied. The importance of Binder Content, Aggregate grade and aggregate shape were found to depend on the pavement type. A statistical analysis using multiple regression techniques resulted in a poor correlation when materials property variables were related to friction.

SUMMARY

The report contained herein is the fifth and final report for this project. A skid test trailer has been developed along with suggested test methods and a description of several variables affecting the operation of a skid trailer. Recommended skid resistance guidelines have been suggested for District use. A detailed study of pavement surface texture has been performed and equipment developed to measure both macro and micro texture.

A study of materials properties which were believed to be related to skid resistance was performed and reported herein. Excellent relationships between materials properties and skid resistance were not found, however, trends indicated the following postulation:

I. For Portland Cement Concrete Pavements

Coarse Aggregate Type, Shape and L.A. Wear are unimportant but Cement Content is important in providing and maintaining friction.

II. For Surface Treatment Pavements

L.A. Wear and Asphalt Application Rates are unimportant, but Coarse Aggregate Type, Shape and Grade is important to the friction availability.

III. For Asphaltic Concretes

Coarse Aggregate Shape, Asphalt Content, and L.A. Wear are unimportant, but, Coarse Aggregate Type is important in providing and maintaining friction.

Further research is recommended to determine the influence construction practices on skid resistance. It has been recommended that research be performed toward developing polish tests for aggregate used in the pavement surface and presently there is a project being conducted in this area.

Implementation of this project is under way and consists of expanded use

of the equipment developed, along with the use of the suggested test procedures. Three additional test trailers have been fabricated and an information retrieval system designed for a skid resistance inventory.

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I. INTRODUCTION

The first concentrated studies of skid resistance of the pavement surface in Texas began in 1962 when attention was focused on a high-accident section of expressway in a south-central city in the state. This research study resulted from the attempts to find equipment to measure the friction level on this expressway and from a District survey of skid resistance during this period.

This study led to the development of a skid test trailer, an analysis of accidents and skid resistance, an analysis of pavement material properties, and an analysis of surface texture and friction. The analysis of accidents and skid resistance resulted in recommended guidelines for maintenance friction values.

Object

The object of this study was to determine and evaluate the skid characteristics of Texas Highway. The object of report is to document the total research study, but more particularly, to reveal the study and analysis of the pavement surface material properties as those properties are related to skid resistance.

II. INTERIM REPORTS

This report is the fifth and final report of this project. A short discussion of the four interim reports follows:

<u>45-1 "Development of A Skid Test Trailer"</u>

The first interim report described the procedure used to determine the type of friction measuring equipment needed and explained the development of the equipment components of the skid test trailer which was selected. A two wheel trailer was selected which obtained a locked wheel skid while artificially wetting the pavement. Hardware plans were obtained from the Bureau of Public Roads and the Portland Cement Association. The report described the development of the force measuring system, the hydraulic or watering system and the velocity measuring system. The report also contained cost items and methods used in the calibration of each system.

<u>45-2 "Skid Resistance Guidelines for Surface Improvements on Texas Highways"</u>

The second interim report dealt with the selection of minimum skid resistance for use as another guideline for surface improvements by the Highway Department. This problem was approached from an accident standpoint as well as from a design standpoint. Skid resistance and accident data was collected on 517 rural sections to represent a sample of Texas Highways. The Skid resistance information was obtained with the trailer previously mentioned. An analysis of the data collected showed that the possibility of a roadway section having a high accident rate increased as the coefficient of friction decreased.

On the basis of this study, composite skid resistance of 0.4 and 0.3 for testing velocities of 20 and 50 miles per hour, respectively, were selected as guidelines for considering surface improvements. Presently, 0.32 is the recommended guideline for a testing velocity of 40 miles per hour. Skid resistance values of 0.31 and 0.24 at 20 and 50 miles per hour, respectively, were recommended as minimum design values. The reader may note that these values were recommended to the District personnel as guidelines, primarily, to assist field personnel in judging pavement condition surveys.

45-3 "A Study of Factors Affecting The Operation of A Locked Wheel Skid Trailer"

In 1966 and 1967 it had become apparent that friction availability on the pavement surface was playing a vital role in providing safety to the people of this state and to the nation. Implementation of the findings of this project was started when the Equipment and Procurement Division began the fabrication of three additional skid test trailers which were patterned from the research skid test trailer. The third interim report was developed as the basis of an Operations Manual to be used as a guide in analysing friction values obtained with the trailers. The report contained the results of the study of several variables associated with trailer friction measurements. These variables included trailer precision, surface variation (from which sample sizes were determined), chart reading error, and the effects of ASTM tire wear. Equations for correcting friction values for temperature and road film were developed and explained.

45-4 "Pavement Surface Texture as Related to Skid Resistance"

This report described the development of a very sensitive texture profile measuring apparatus. The equipment measured vertical profile excursions as small as 42 micro inches and as large as one inch. Essentially, the instrument was designed to probe vertically as the probe was traversed horizontally. Elevation measurements were obtained each time the needle probe was brought to rest on the pavement surface. Horizontal distance between probes was 0.0033 inch.

A computer program was devised to obtain values of variables which could be considered as texture. The computer program also separated the micro and macro texture profiles from the measured profile by a rounding procedure. Finally, macro and micro texture measurements were collected on 77 cores obtained from the sections reported in Research Report 45-2 above and studied in conjunction with skid resistance values obtained on these sections at 20 mph and 50 mph. The major conclusion of this report was that friction values were high when both the macro and micro texture values were high.

III. METHOD OF DATA COLLECTION

Data for the "Material Properties" phase of this research project was collected during 1964 and 1965 (the same time as the "accident data" which was reported in Research Report 45-2). Both sets of data have been indicated in the following information; however, only the "material properties" data has been treated in this report.

Sources of Data

Information contained in this report was obtained from three sources. Most of the materials information came from data collected in an existing Research Project 2-8-62-32 "EXTENSION OF AASHO ROAD TEST RESULTS". Mr. Frank Scrivner, the Project Supervisor, graciously consented to supply the needed information. Without this source, much duplication would have resulted in the data collection effort.

Since the 2-8-62-32 project was aimed toward the study of the structural properties of the roadway, it was found that additional information concerned with the pavement surface properties was needed. Consequently, the second source of information was the permanent files of the Texas Highway Department.

The third source of information was the skid test trailer and the trailer operator. The skid test trailer supplied the velocity and friction values while the operator supplied the trailer placement-condition, surface condition, and weather information.

Data Type and Storage

At the time of data collection, there were very few reported projects in the nation of the magnitude concieved for this study. Therefore much of the background information needed for an experimental design was not available. However, it should be stated that the type of data which was collected was heavily influenced by a unique report by Prof. R. A. Moyer contained in the "PROCEEDINGS-FIRST INTERNATIONAL SKID PREVENTION CONFERENCE."(5)* The paper contained what

* Numbers in parenthesis refer to items in the Reference.

was believed to be (and is still believed to be) the most complete list of variables known to influence the friction properties of the pavement surface.

Basically, data was obtained on 517 test sections scattered throughout Texas. Some 115 of the sections had concrete surfaces, 186 had asphaltic concrete surfaces, and 216 had surfaces consisting of penetration (seals or surface) treatments. The section length was 2500 ft. and was in only one travel direction and one lane. The sections were marked by each District with 4 in. by 4 in. posts.

The data was coded and stored on IBM cards for further analysis with the computer. The code sheet used and the description of coding are given in the Appendix. A list of the data which was collected is given as follows, along with an explanation of several items which are necessary for a better understanding of the information:

A. Section Identification

1. District - The Departmental District Number was coded to define the district in which the test was conducted.
2. County - The County Number was coded to define the county in which the test was conducted.
3. Highway No. - The Highway Number was coded to indicate the highway on which the test was conducted.
4. Control - Section - Job - The Control and section were numbers previously established for each individual length of highway in the state and the numbers were unique to that length of highway in the state and the numbers were unique to that length. The job number was related to the certain 2500 ft. test section explained previously and was the same number as that established by Scrivner in Research Project 2-8-62-32.
5. Regional Code - The original regional code established in Research Project 2-8-62-32 was used. This code divided the state into three

regions - East, Central and West.

6. Type of Section - A code indicated whether the 2500 ft. section was in a cut or fill or "grass roots grade".

B. Age Conditions

1. Date of Test - This code indicated the date the section was tested.

2. Date of Placement - The date of construction of the tested surface was recorded. This information was not coded on the cards but was used in manual calculations for the total number of vehicles which had passed over the 2500 ft. section.

3. Total Vehicle Passages - The total number of vehicles passing over the section was obtained by (1) multiplying the yearly "ADT" by the number of days that the pavement surface had been under traffic and (2) accumulating these yearly products. This total was divided by two in order to obtain directional distribution. No attempt was made to determine the lane distribution. In several cases no information was used for a section because the date of surface placement could not be found.

4. Equivalent 18 kip Axles per Month - The number of equivalent 18 kip axles per month passing over the test section was coded. The data was obtained from Research Project 2-8-62-32; however, the data was not in a form which could be used in further analysis of this project. Based on the time involved in obtaining the Total Vehicle Passages, no further attempt was made to utilize this information despite reports of the greater influence of truck traffic on the wear or polish characteristics of the pavement surface.

C. Properties of the Surface Course

1. Pavement Type - The pavement types were classified and coded as follows:

   a. Continuously Reinforced Concrete

   b. Jointed Concrete

c. Jointed Reinforced Concrete

d. Surface Treatments or Seals

e. Hot Mix Asphaltic Concrete

f. Limestone Rock Asphaltic Concrete (Naturally Impregnated)

g. Hot Mixed-Cold Laid Asphaltic Concrete

h. Slurry Seals

2. Coarse Aggregate Type - Most of the state used two basic aggregate types - a river gravel or a crushed limestone. River gravel was dominant in the Eastern and Southern portions of Texas where many of the (geologically) older rivers had deposited sand and gravel bars.

Central Texas had a rather large fault zone in which an abundance of Limestone was found. Consequently several large aggregate producers were located in the area from North of the Dallas - Fort Worth region to an area South of San Antonio. The influence of this region was rather widespread; especially to the East, reaching as far as Tyler, Lufkin and Beaumont. There were several river gravel producers in the Central Texas area, but crushed limestone was dominant.

West Texas sources were predominently limestone, especially in those areas where the producers crushed the "cap rock". There were large areas in West Texas where a dense igneous type material was used, and on several pavements in this area (near El Paso) the surfacing material was crushed from the roadway cuts. There were several more unusual areas found. For example, in West Texas a material resembling lava was found. Tis material had a bubble or blib structure, but the material surrounding the holes was very dense and hard (and apparently polishes readily under traffic). This material was placed in a trap rock catagory as explained below.

A geological formation, the "Llano Uplift" was found near the center of the state and large igneous deposits were located in this area. Granite was found in this area also, but little surfacing aggregate was made and no surfaces were tested where granite aggregate was used. Near this area, a material classified as dolomitic limestone was being quarried. The material was curshed and individual aggregate which closely resembled marble could be found in the stockpile. This material was placed in the limestone catagory as explained below..

West of San Antonio two producers were found in which the crushed aggregate material was classified as trap rock. There were a few sandstone sources in the state from which the material, when curshed, was found to be composed mainly of a silicious quartz-like substance. Also, there were areas in the East and Southeast portions of the state where an Iron Ore gravel was used. The material was basically a sandstone composed of small quartz grains cemented together with hematite or other iron oxide substances. A few surfaces were found in which a synthetic "lightweight" aggregate was used. There were four producers of this material at the time the data was collected, but most of the material tested was obtained from a source near Ranger, Texas. Oyster shell was used often in asphaltic concretes, particularly in the Gulf Coast Districts; and several surfaces were found in which an aluminum slag was used. Also, West of San Antonio two sources of Limestone Rock Asphalt were found. The coarse aggregate was coded in ten types as follows:

1. Silicious
2. Limestone
3. Limestone and Silicious
4. Shell
5. Lightweight
6. Iron Ore
7. Trap Rock

8. Limestone Rock Asphalt

9. Precoat

10. Slag

The silicious and the limestone-silicious are basically river gravels. The type "limestone-silicious" was used because in some river gravels part of the material was of a hard limestone origin rather than all silicious.

3. Coarse Aggregate Shape - The aggregate shape was broken into four types - Angular, Subangular, Rounded and Subrounded.

4. Fine Aggregate Type - This information was used to classify the intermediate size aggregate used in mixes and concretes. The same ten types as explained in the Coarse Aggregate Type above were used.

5. Fine Aggregate Shape - The same information explained in Coarse Aggregate Shape was used.

6. Asphalt or Cement Content - The amount of asphalt or cement binder used was coded. The unit "gallons per square yard" was used for surface or penetration treatments, "percent asphalt" (by weight) was used for asphaltic concretes and "sacks per cubic yard" was used for portland cement concretes.

7. Grading of Aggregate - The grade or approximate size of the aggregate was coded. The THD aggregate grade was used for surface or penetration treatments, and the THD specification type was used for asphaltic concretes. No size coding was used for portland cement concretes.

8. Present Serviceability Index - The roughness of the pavement, in terms of PSI, as measured with a CHLOE profilometer was not coded but used in a special study. This information was available from the 2-8-62-32 study.(6)

9. Texture Reading - The texture of the section surface was coded. The texture was measured with the Texas Texuremeter developed and described

in the 2-8-62-32 study and Research Report 32-1.

10. Hardness - The hardness of the coarse aggregate as obtained by the Los Angeles Abrasion test was coded. This information was collected from the Permanent Files records, and the least that can be said is that the information was very difficult to collect. In fact, little information was found.

D. Testing Conditions

1. Speed - Two test speeds were used to determine friction information. these speeds were 20 and 50 mph. The actual speed of test was obtained from the recorder strip chart and coded.

2. Surface Temperature - The temperature of the pavement surface at the time of the friction tests was determined by using a disk type thermometer.

3. Wheel Locking Condition - The skid test trailer described in Report 45-1 was fabricated with the ability to test with either the left wheel, right wheel or with both wheels. A code was provided to indicate which condition was being used. It should be noted that only the left wheel was used to collect data, which was and presently is the national trend.

4. Lane - The lane (that is, outside, inside, etc.) being tested was coded.

5. Flushed Surface - On many occasions, flushed or bleeding surfaces were found, especially on surface or penetration treatments. The flushed surface condition was coded in one of three conditions - flushed, medium flushing, or no flushing.

6. Speed or Lateral Placement - The frictionvalue of each section was obtained in two positions. These positions were - in the left wheel path and between the left and right wheel paths. It was believed that some measure of the friction value of the original (as placed) surface

could be obtained by testing out of the wheel path; preferably near the center line or possibly between the wheel paths. Since testing near the centerline was dangerous on the predominately two lane-two directional pavement sections and since many of the sections had paved shoulders, between the wheel paths was selected.

7. Weather - A code for the weather condition during friction testing was established for the following:

   1. Dry
   2. Raining
   3. Misting
   4. Ice
   5. Snow

   Later in the project and after some discussion, the operator was instructed not to conduct tests in the rain, and no ice or snow was encountered during the testing. Therefore, the skid tests were performed in dry conditions (with artificial watering) with a few tests occuring in a misting rain near the first period of the testing. The self contained watering system on the skid equipment was used throughout.

8. Days to Last Rain - The number of days since the last rain and prior to the date of friction test was obtained from local informants and where necessary from the nearest Weather Bureau Station. Research Report 45-3 describes a method for using this value in correcting skid values for road film. Corrections were not used in this report and it has recently been found that corrections for days greater than 38 are not valid for the correction equation found in Research Report 45-3.

E. Coefficient of Friction - The friction value was obtained as follows:

   1. At 20 mph in the left wheel path
   2. At 50 mph in the left wheel path

3. At 20 mph between the wheel paths. On a few occasions the 50 mph test was not performed because of restricted speed zoning. All tests were performed "wet" as explained in D-7 above.

IV. DESCRIPTION OF EQUIPMENT

The equipment used in this project has been mentioned in the previous chapters of this report. The skid test trailer was fabricated in 1963 and at that time met a tentative ASTM specification. The trailer was described in Research Report 45-1 and the force measuring system was basically a parallelogram - drag link system (the drag link being strain gaged to measure the friction force developed at the tire-pavement interface). The equipment contained the usual watering and velocity measuring instrumentation. The watering during the tests was approximately 22 gallons per minute at 20 mph and 55 gallons per minute at 50 mph with the water covering approximately a 12 inch wide strip just prior to the trailer wheel passage.

The CHLOE profilometer used to obtain pavement roughness is reported in Research Report 32-1.[6] The PSI values used in this report did include the corrections for cracking and patching.

The texturemeter used to obtain the pavement surface texture was also reported in Research Report 32-1.[6] The report contained a full description of the development of this equipment.

The thermometer used to obtain surface temperature was of the disc type in which the size was approximately 3/16 inch in height and 1-1/2 inches in diameter. A small metal coil responded to a temperature change by a change in coil length. This change in coil length activated a pointer. Readings were obtained from the dial gage face corresponding to the pointer position.

V. ANALYSIS AND RESULTS

The procedure used in analysis was to study the effects of the following on friction values.

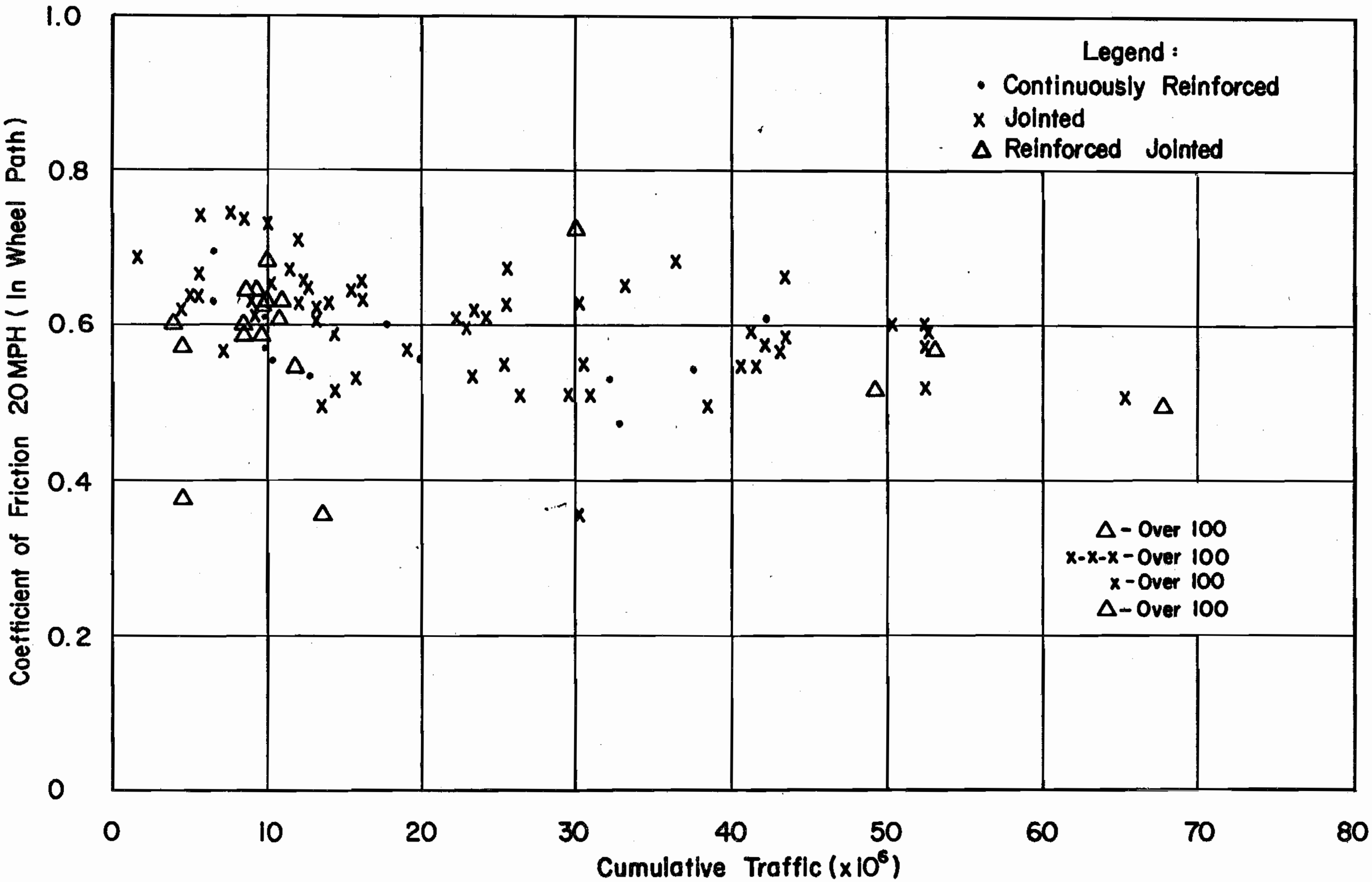
1. Pavement Types
2. Aggregate Material Types
3. Aggregate Shape
4. Aggregate Hardness
5. Aggregate Size
6. Asphalt or Cement (Binder) Content

Since there was apparently a polishing effect by traffic application it appeared that the correct way to analyze the problem would be not only to determine the initial (soon after construction) friction value but also to determine the friction value after some period of traffic applications. Therefore, friction was plotted in terms of traffic applications while the other variables were being studied.

"Coefficient (20 mph) - Traffic" equations were developed and attempts were made to hold the traffic or polish variable constant by correcting or transposing the friction value to a constant 10 million applications. The other variables were then evaluated or re-evaluated. A multiple regression procedure was also used in studying the relationship of several variables. Finally, the effects of pavement roughness and pavement texture were studied in relation to friction.

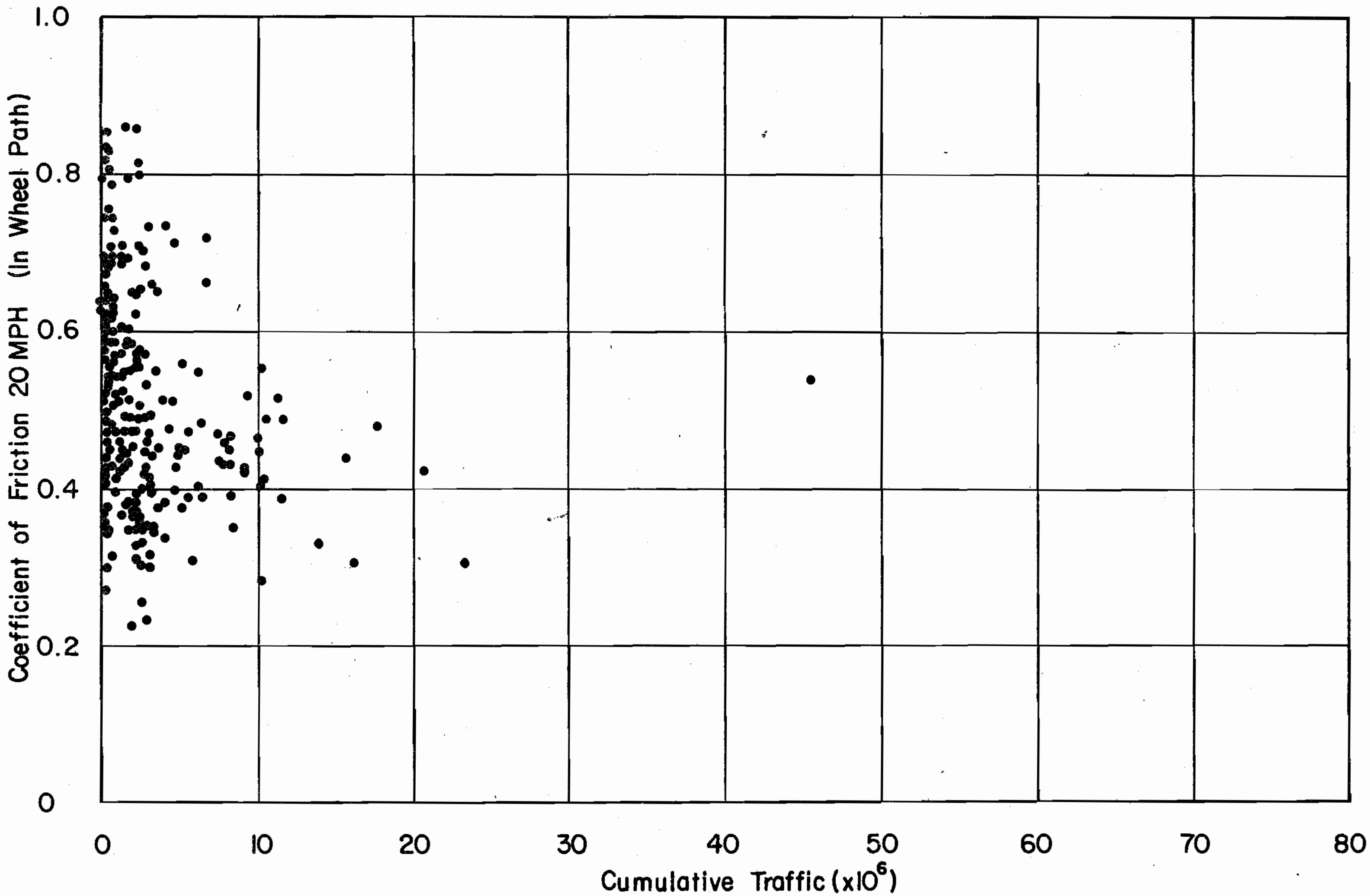
<u>Pavement Type</u>

Figures 1 through 6 compared the coefficient of friction at 20 mph and traffic applications for each of the pavement types, and Figures 7 through 12 indicate the same information for friction values at 50 mph. All pavement types were analyzed in these plots. Both sets of friction values were obtained in the wheel path. The most striking feature about every plot that was made in this study was the tremendous scatter found. For example, in Figure 1, it was possible to find concrete pavements with friction values (at 20 mph) measured



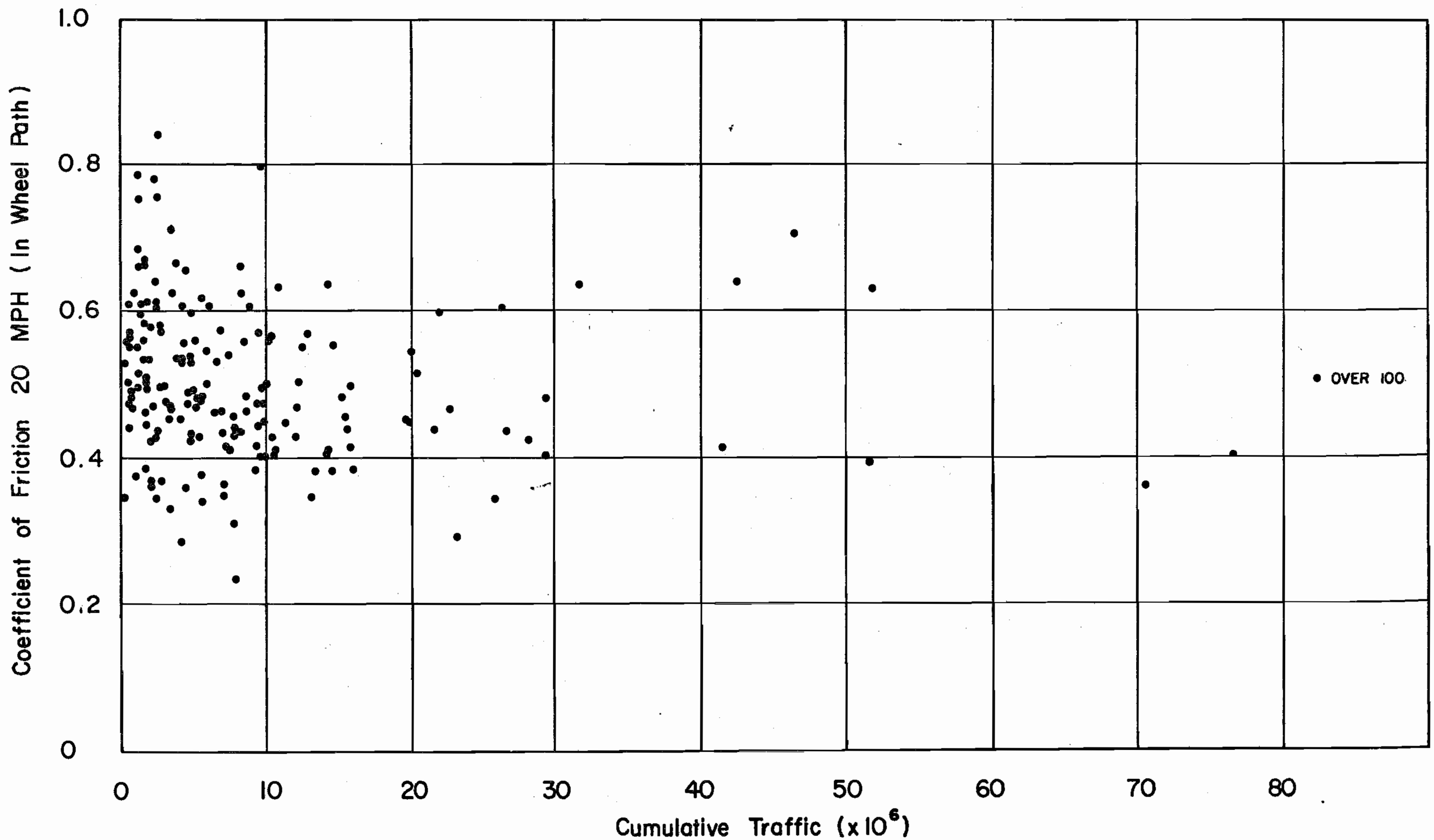
WEAR PLOT — CONCRETE PAVING-C_{20}

Figure 1



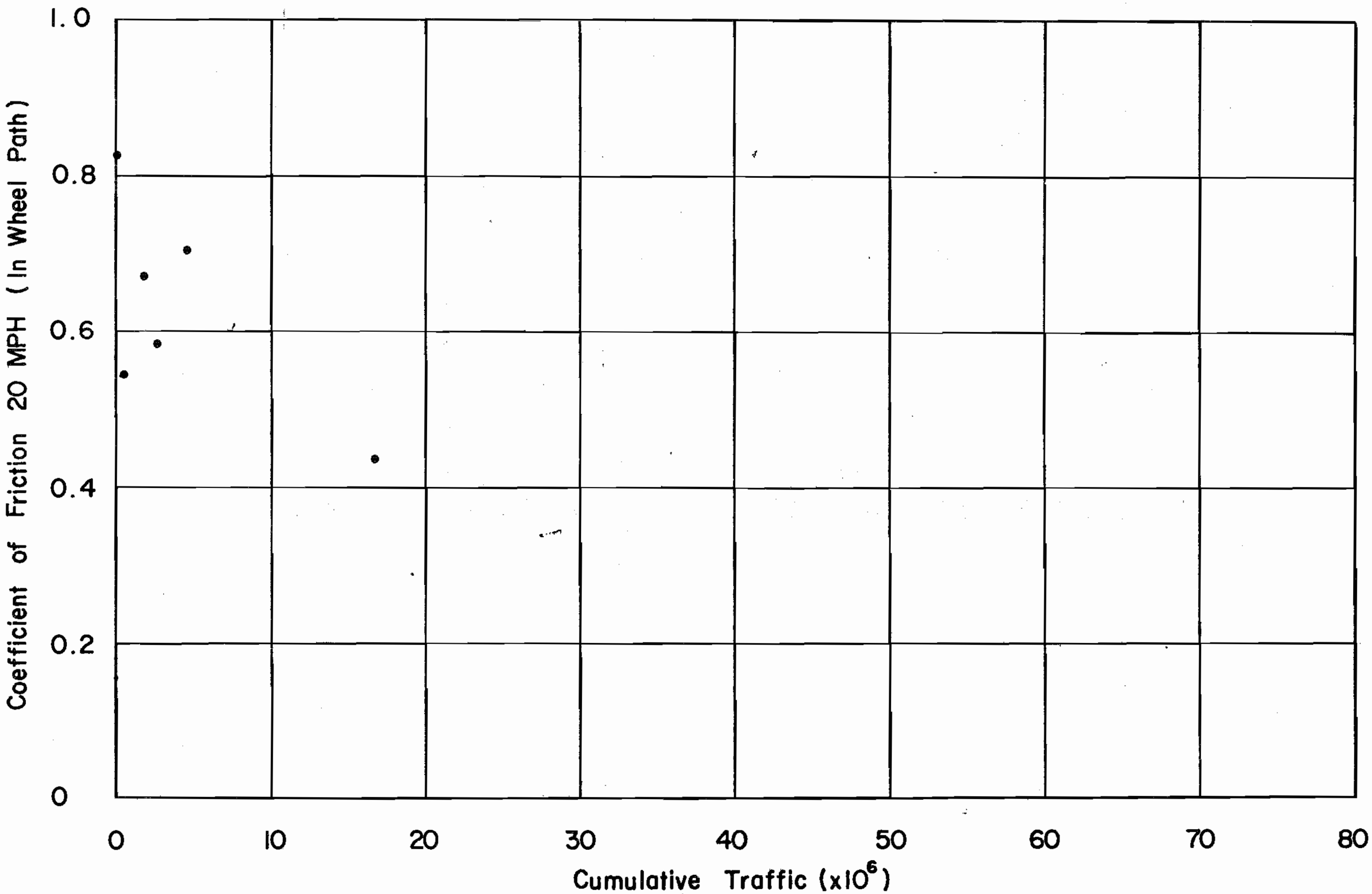
WEAR PLOT — SURFACE TREATMENT — C_{20}

Figure 2



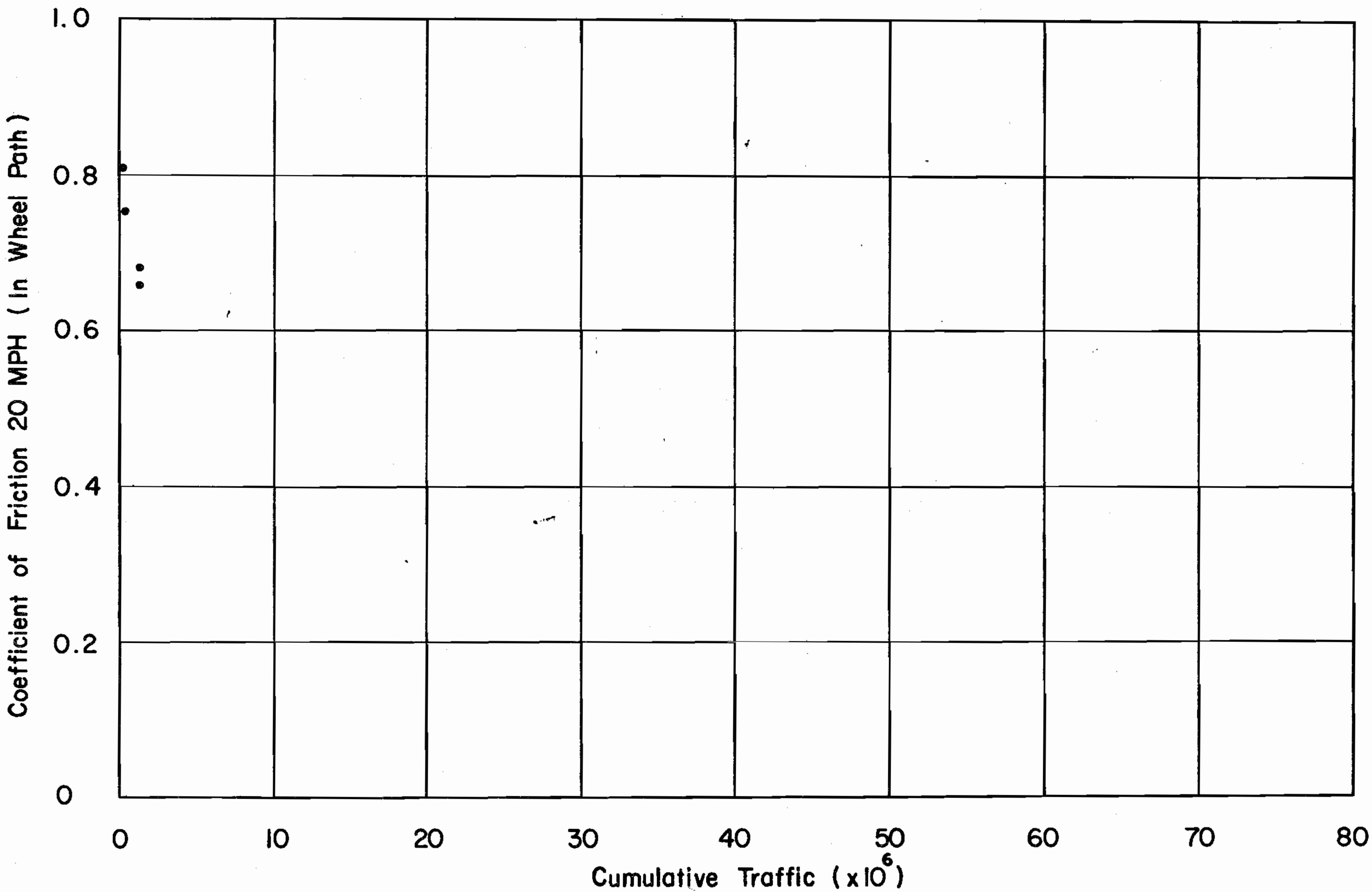
WEAR PLOT—HOT MIXED ASPHALTIC CONCRETE – C_{20}

Figure 3



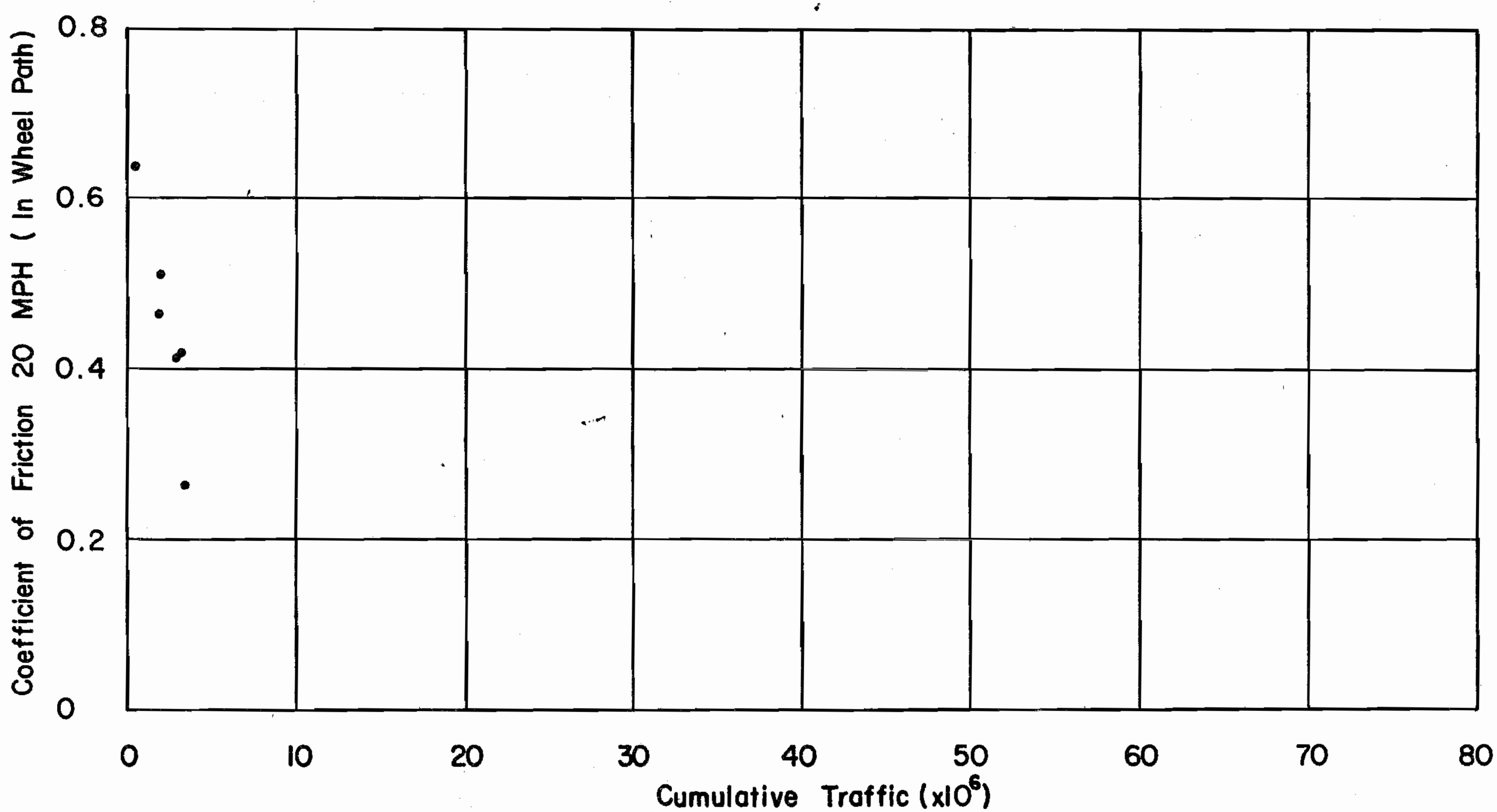
WEAR PLOT — HOT MIX-COLD LAY ASPHALTIC CONCRETE-C_{20}

Figure 4

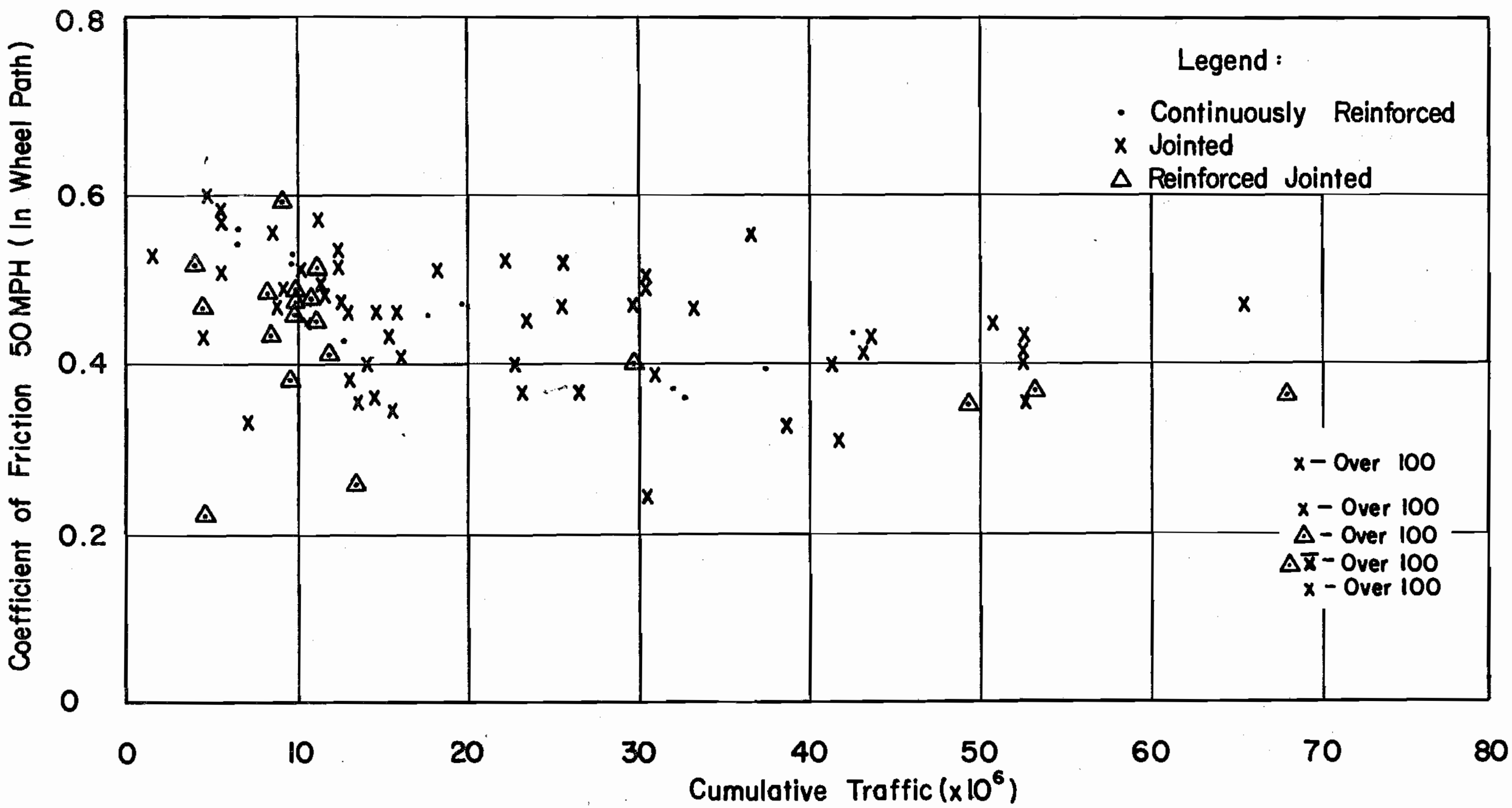


WEAR PLOT - LIMESTONE ROCK ASPHALT — C_{20}

Figure 5

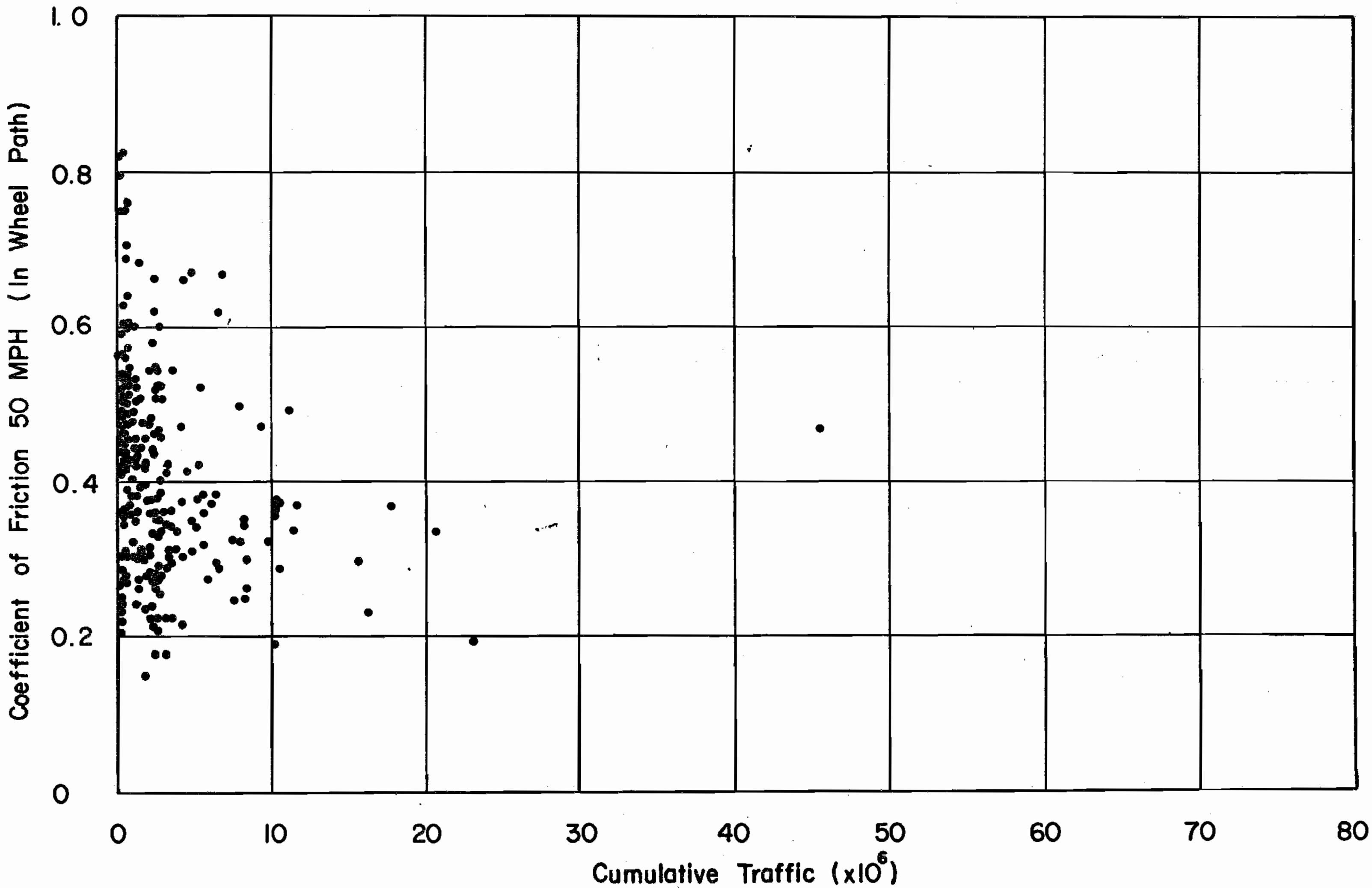


WEAR PLOT – SLURRY SEAL – C_{20}
Figure 6



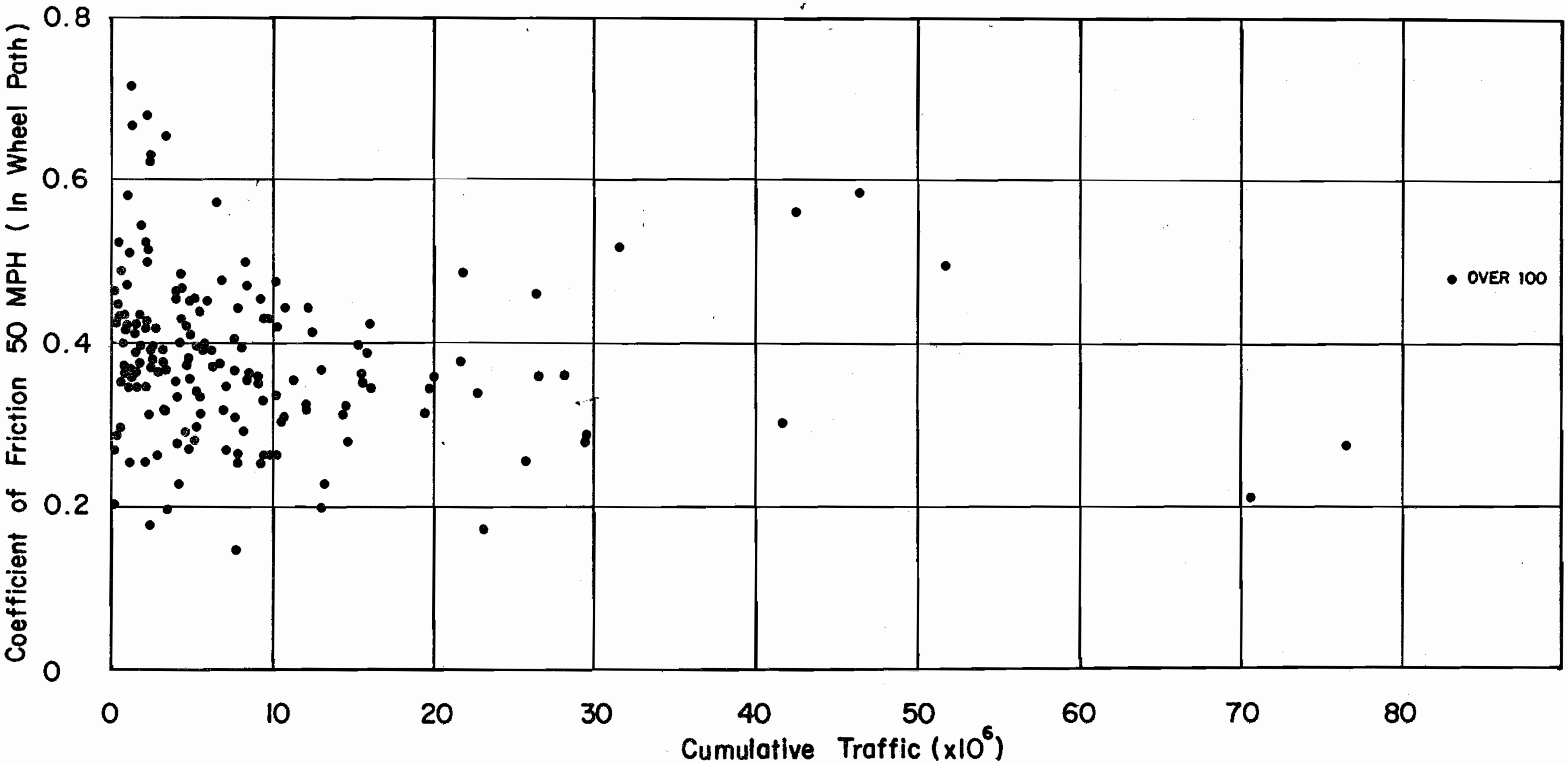
WEAR PLOT – CONCRETE PAVING – C_{50}

Figure 7



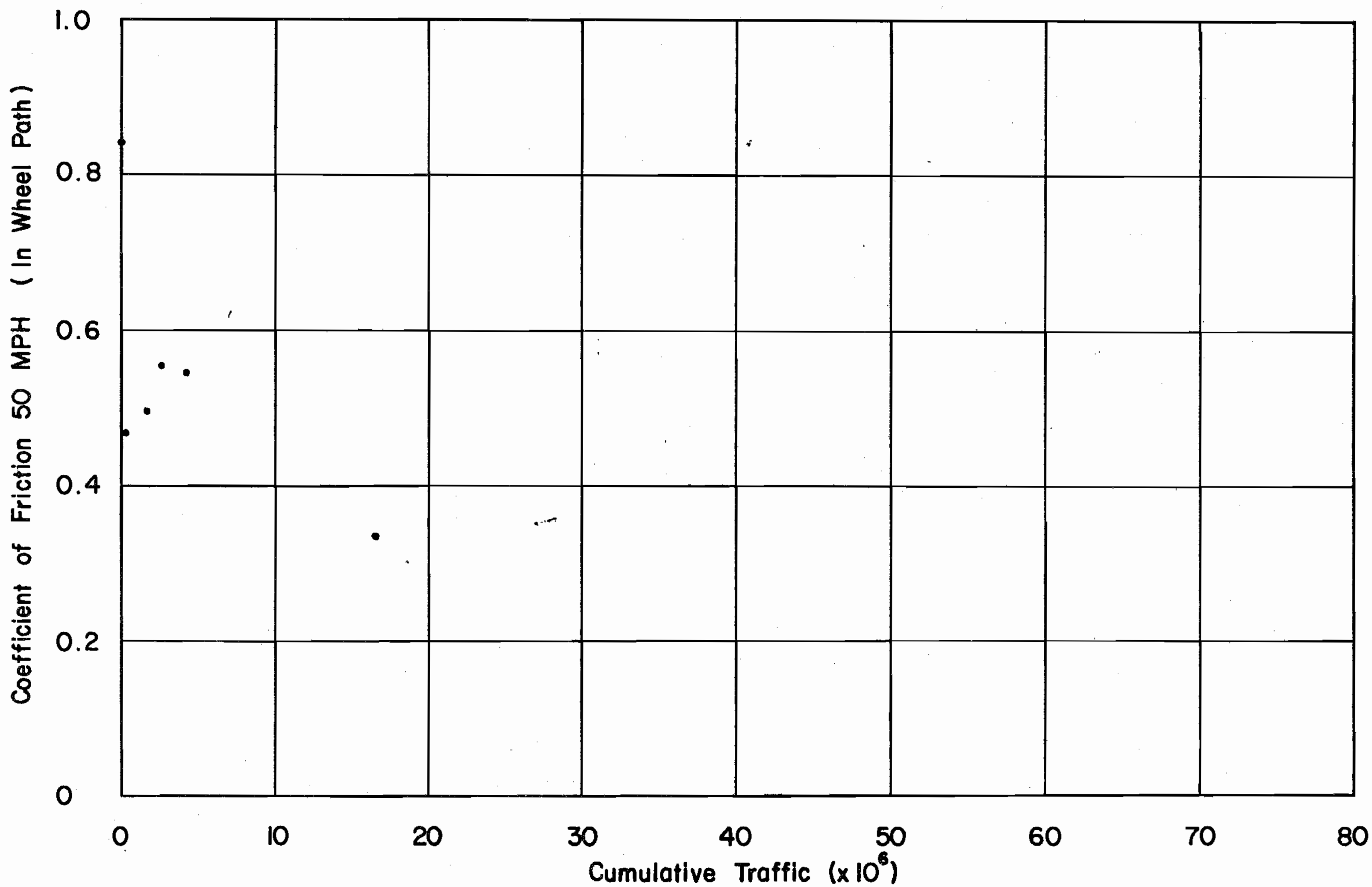
WEAR PLOT-SURFACE TREATMENT —C_{50}

Figure 8



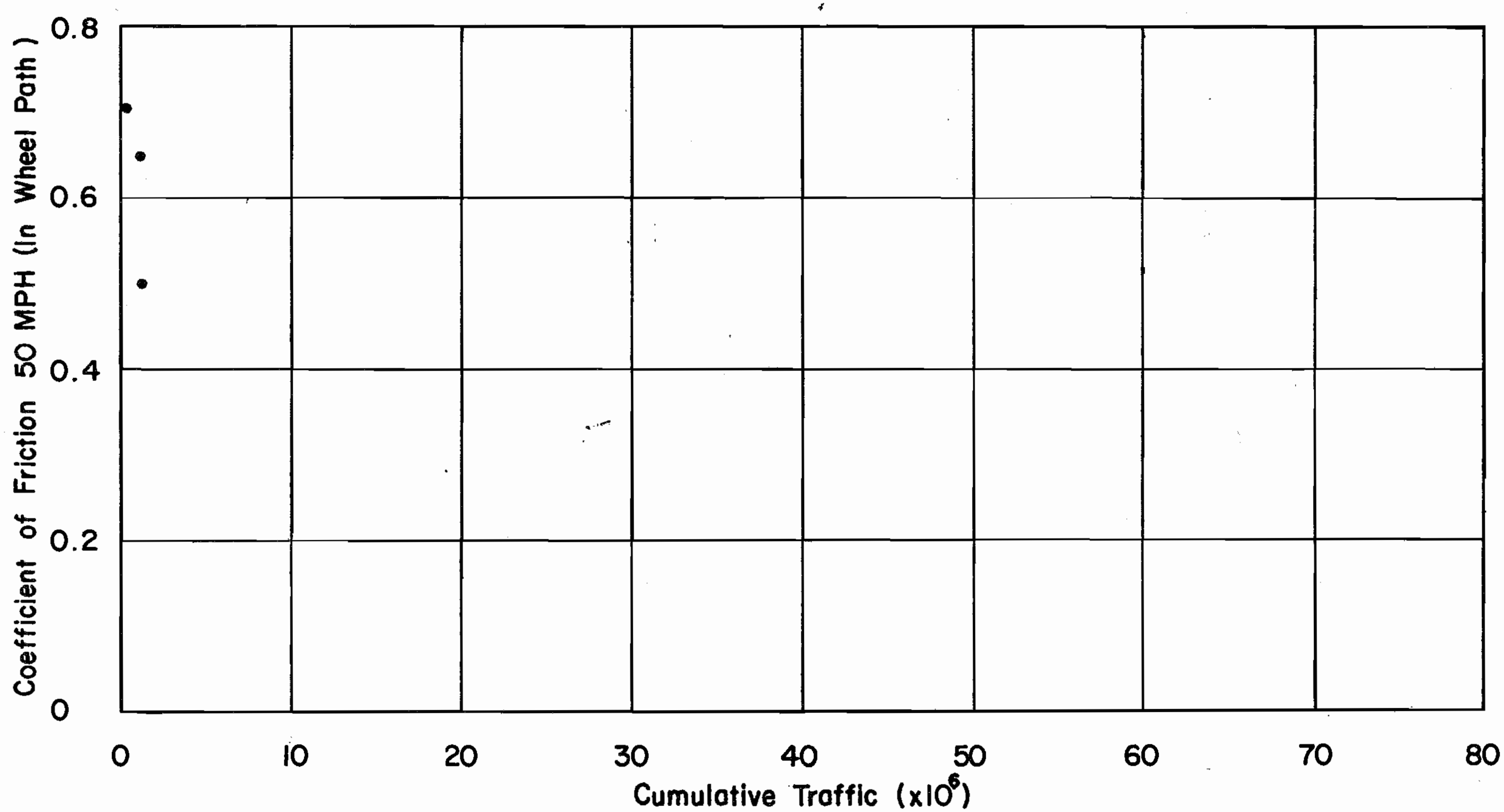
WEAR PLOT — HOT MIX ASPHALTIC CONCRETE - C_{50}

Figure 9



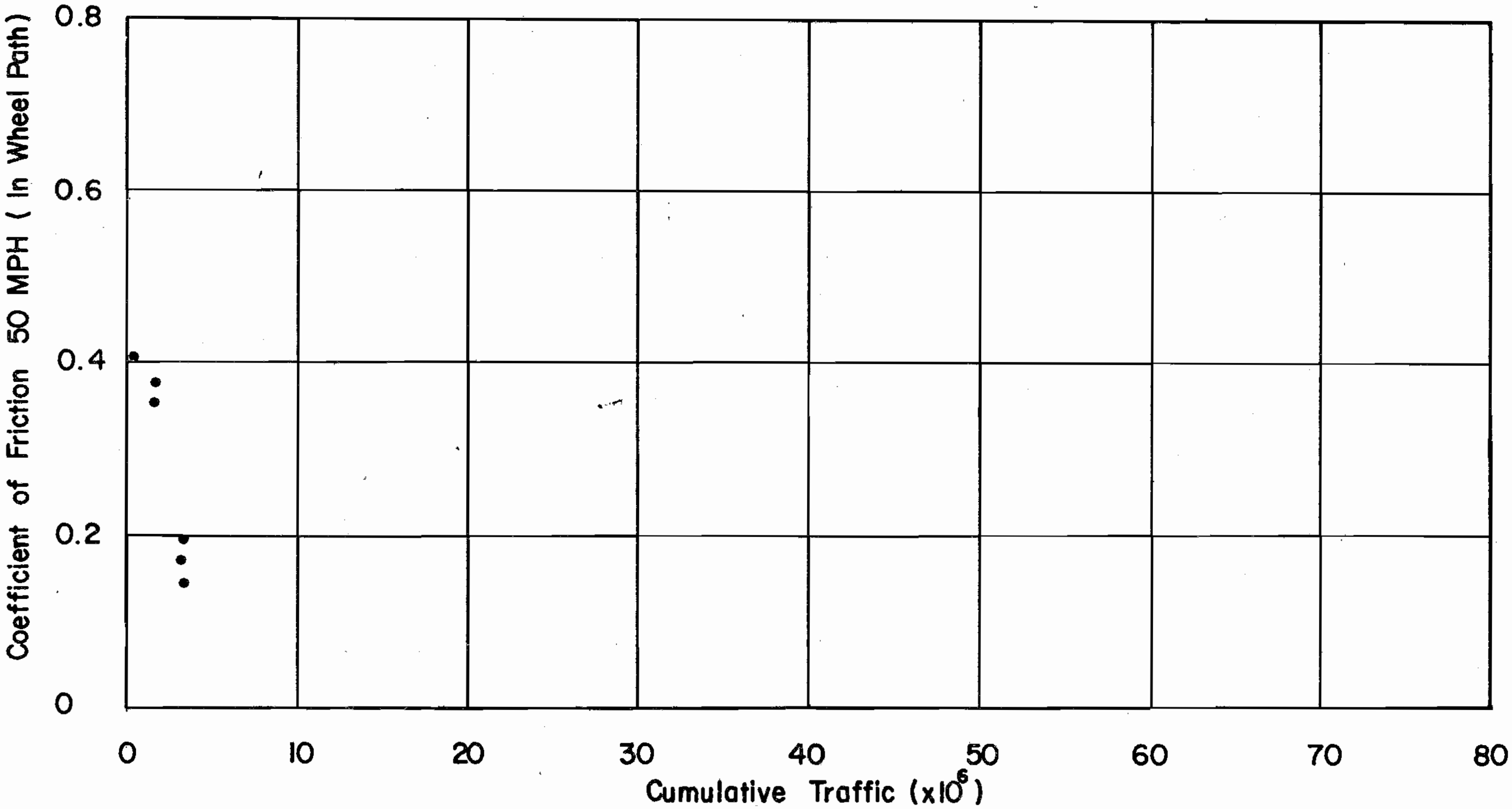
WEAR PLOT – HOT MIX COLD LAY ASPHALTIC CONCRETE – C_{50}

Figure 10



WEAR PLOT – LIMESTONE ROCK ASPHALT-C_{50}

Figure 11



WEAR PLOT — SLURRY SEAL — C_{50}

Figure 12

as low as 0.37 and as high as 0.74, a difference of approximately 0.4 after only 5 million traffic applications. About the same scatter was found after 30 million applications. However, in general terms, it would appear that the average coefficients, initially or shortly after construction, were about the same for each pavement type, beginning on the average around 0.60 at 20 mph. Concrete seemed to wear or polish at a slow rate and the surface treatments at the most rapid rate with the asphaltic concrete wear rate between. Insufficient data was collected on the other pavement types to estimate trends.

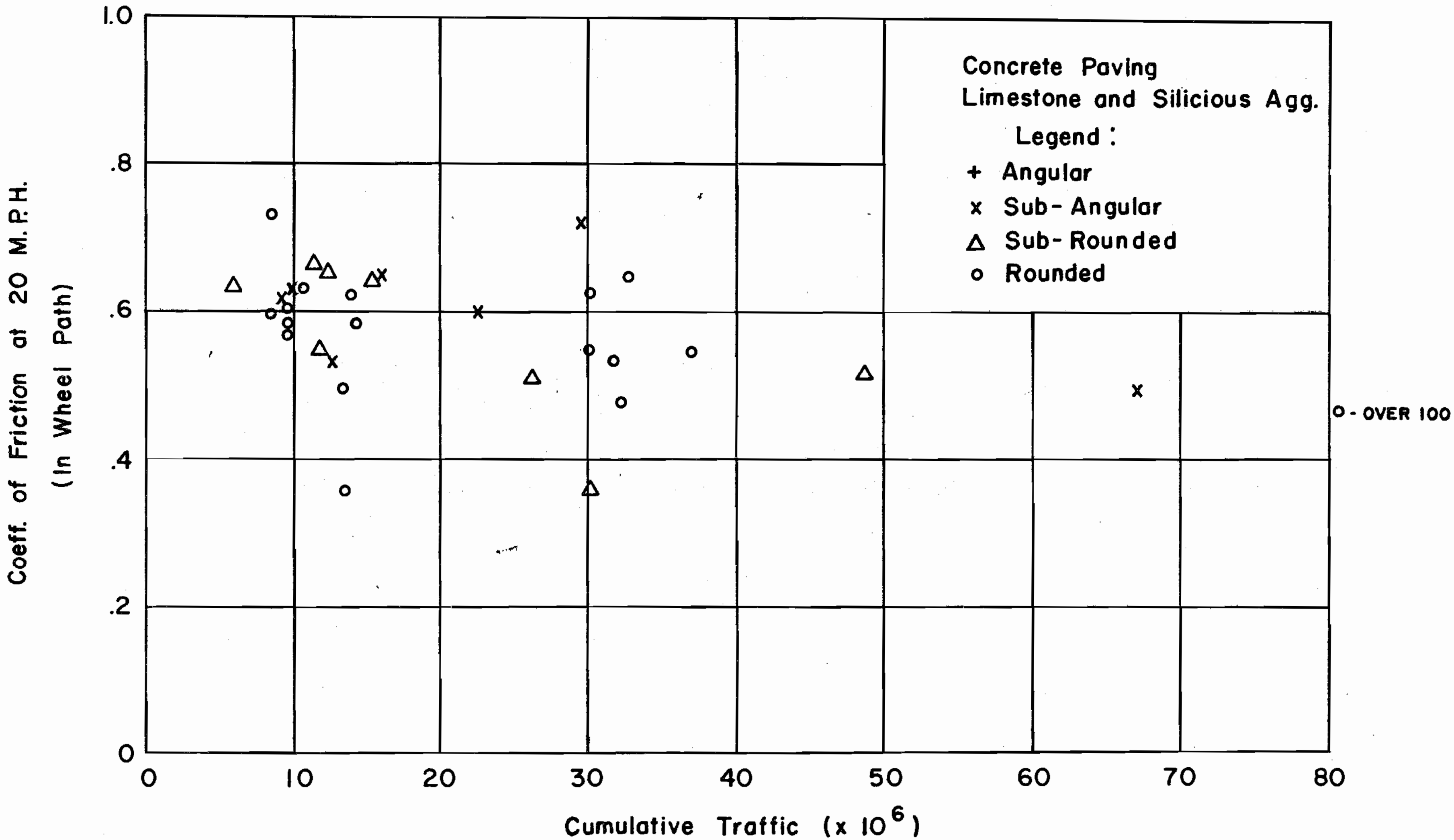
In the comparative plots at 50 mph in Figures 7 through 12 the same trends were evident with the exception that the friction data was approximately 0.10 to 0.15 lower. There was apparently little difference in the polish rate or initial friction values between the three types of concrete paving shown in Figures 1 and 7.

Aggregate Material Type

Aggregate material was studied by using the wear or polish plots also (that is, friction vs. cummulative traffic applications). Figures 13 through 23 show the plots of this study. Only the major pavement types - portland cement concrete, asphaltic concrete and surface treatments - were analyzed. Each individual plot was of a particular material within a given pavement type. The analysis was subdivided further by using symbols to indicate the material shape.

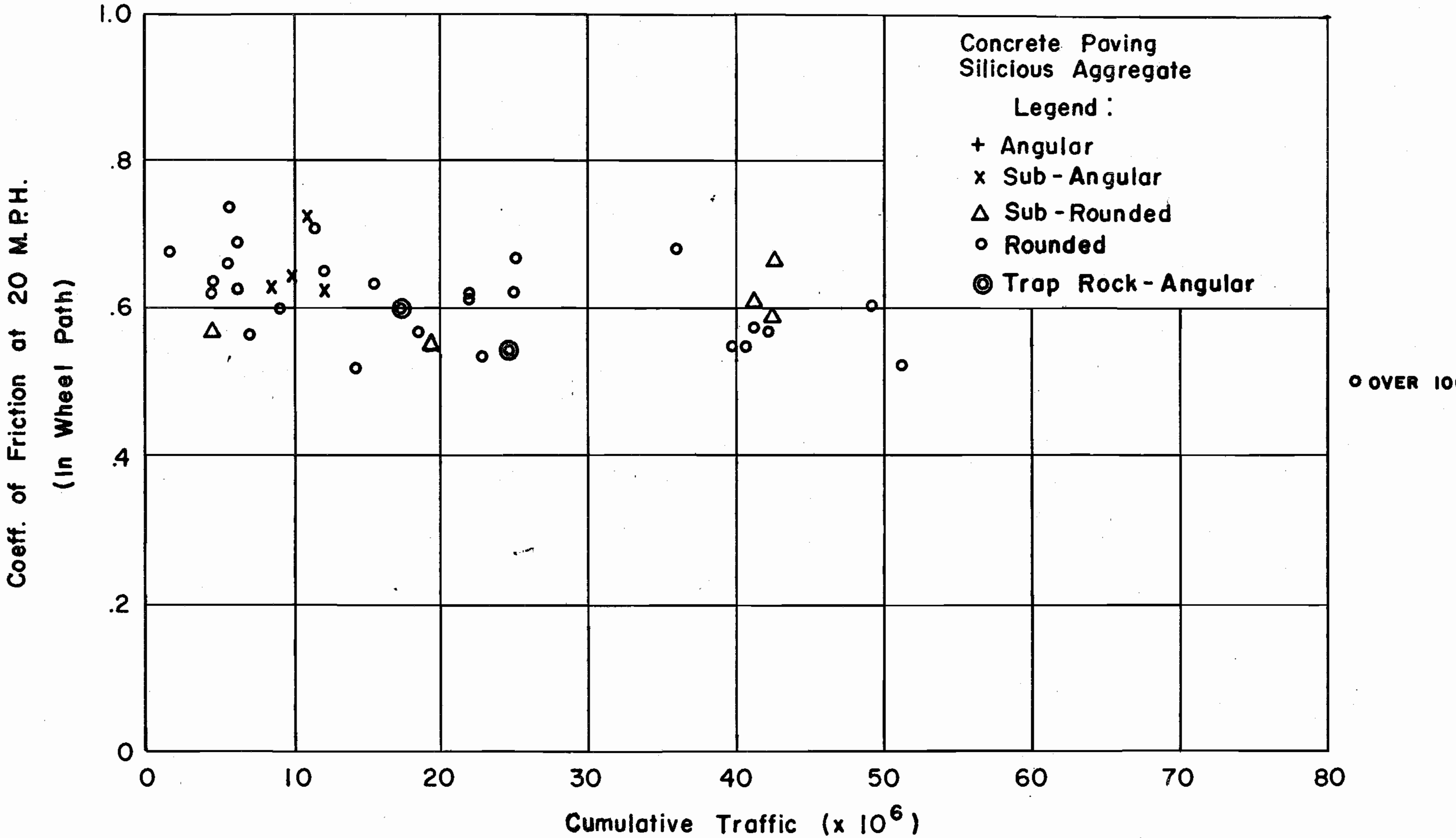
Concrete Paving

By comparing the vertical position of the points in the plots of figures 13, 14 and 15 there appeared to be no significant difference between the 20 mph friction properties of the limestone-silicious, silicious and limestone materials. There was a slight indication that the silicious material had higher values, but the overriding scatter in the plots of the three materials prevented a definite conclusion to this indication. It will be recalled that both silicious and the limestone-silicious material types were basically river gravels; where silicious was all silicious (quartz like) and limestone-silicious had the hard



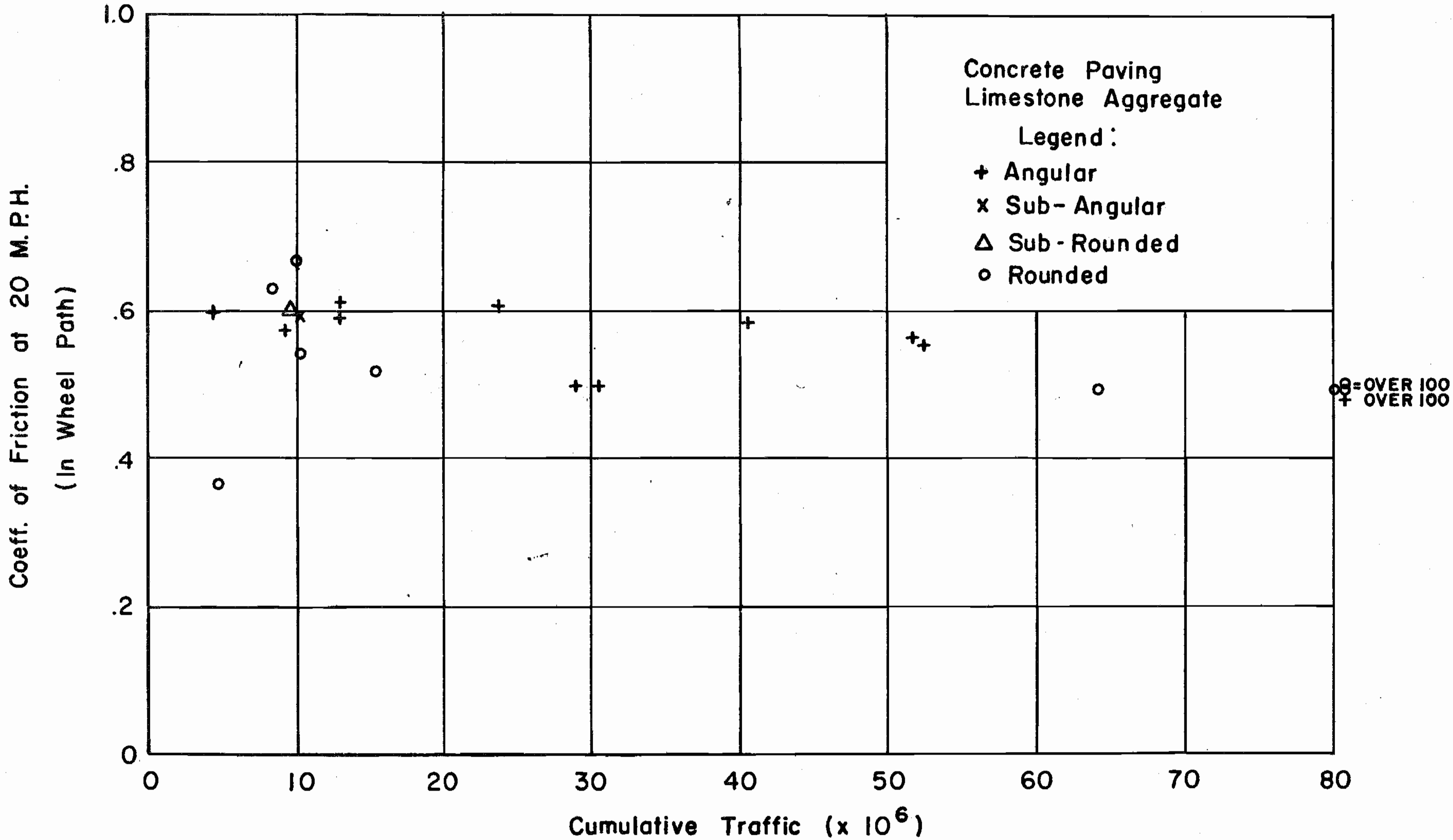
STUDY OF AGGREGATE MATERIAL TYPE AND SHAPE FOR CONCRETE PAVING-LIMESTONE AND SILICIOUS

Figure 13



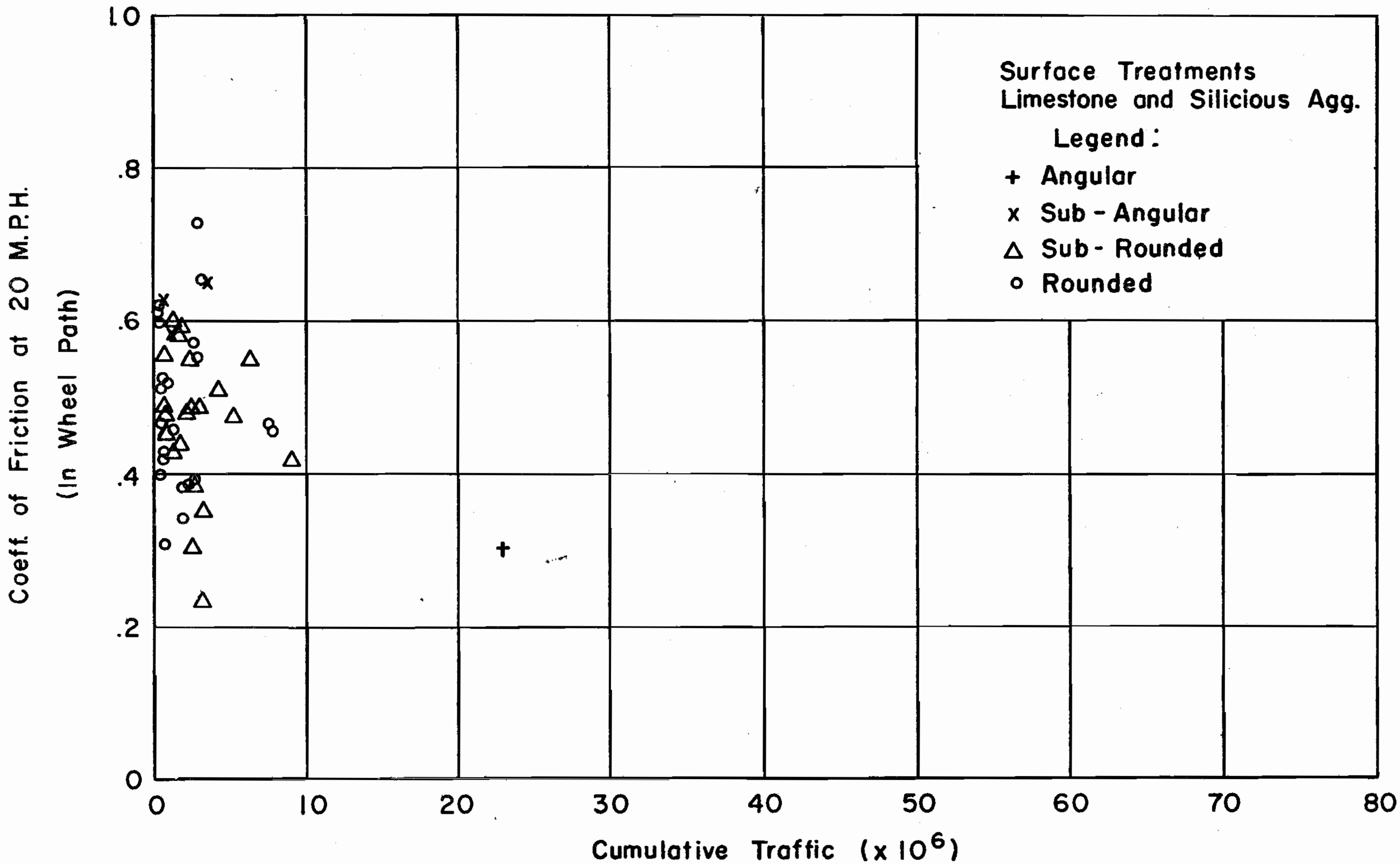
STUDY OF AGGREGATE MATERIAL TYPE AND SHAPE FOR CONCRETE PAVING-SILICIOUS

Figure 14



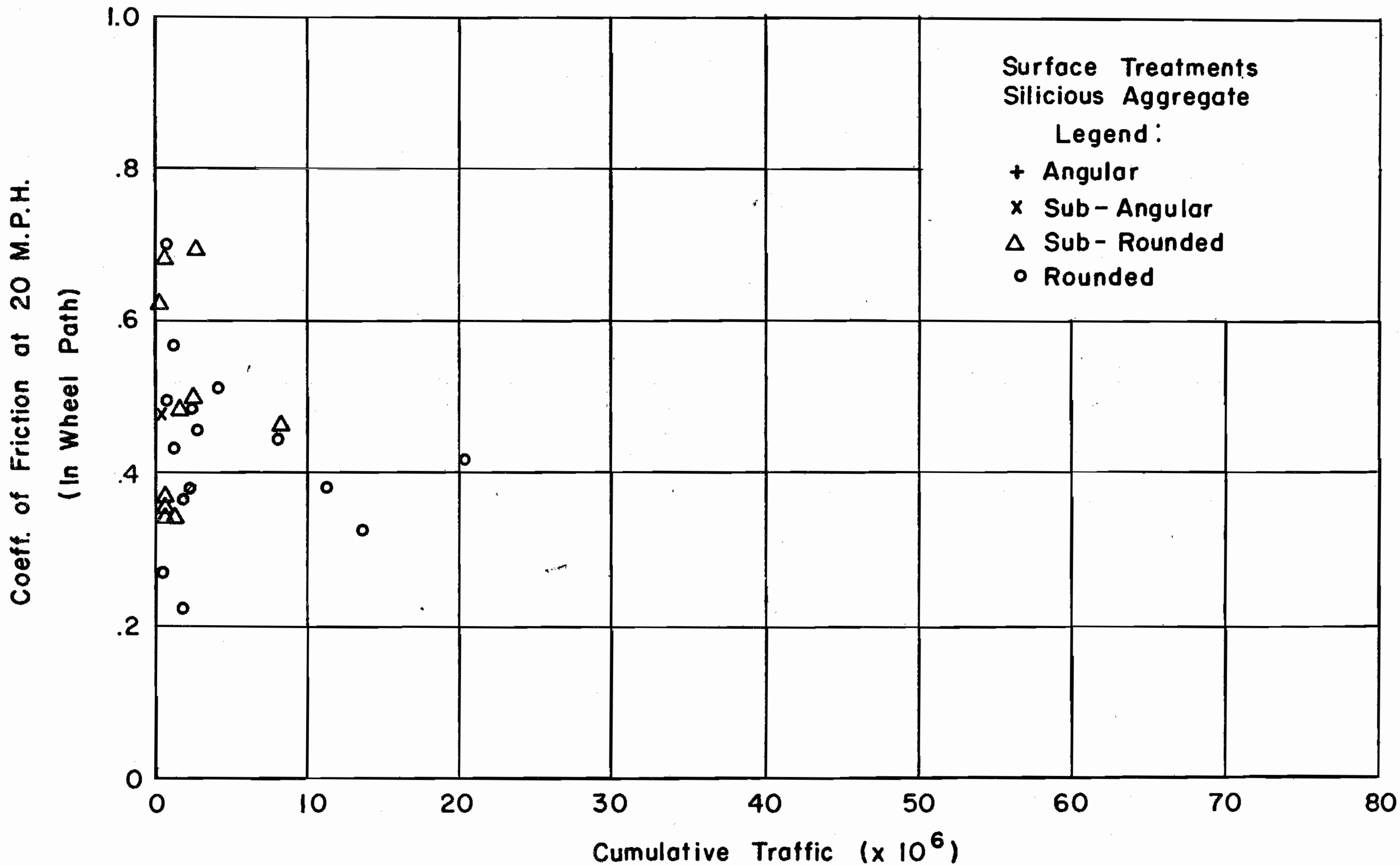
STUDY OF AGGREGATE MATERIAL TYPE AND SHAPE FOR CONCRETE PAVING-LIMESTONE

Figure 15



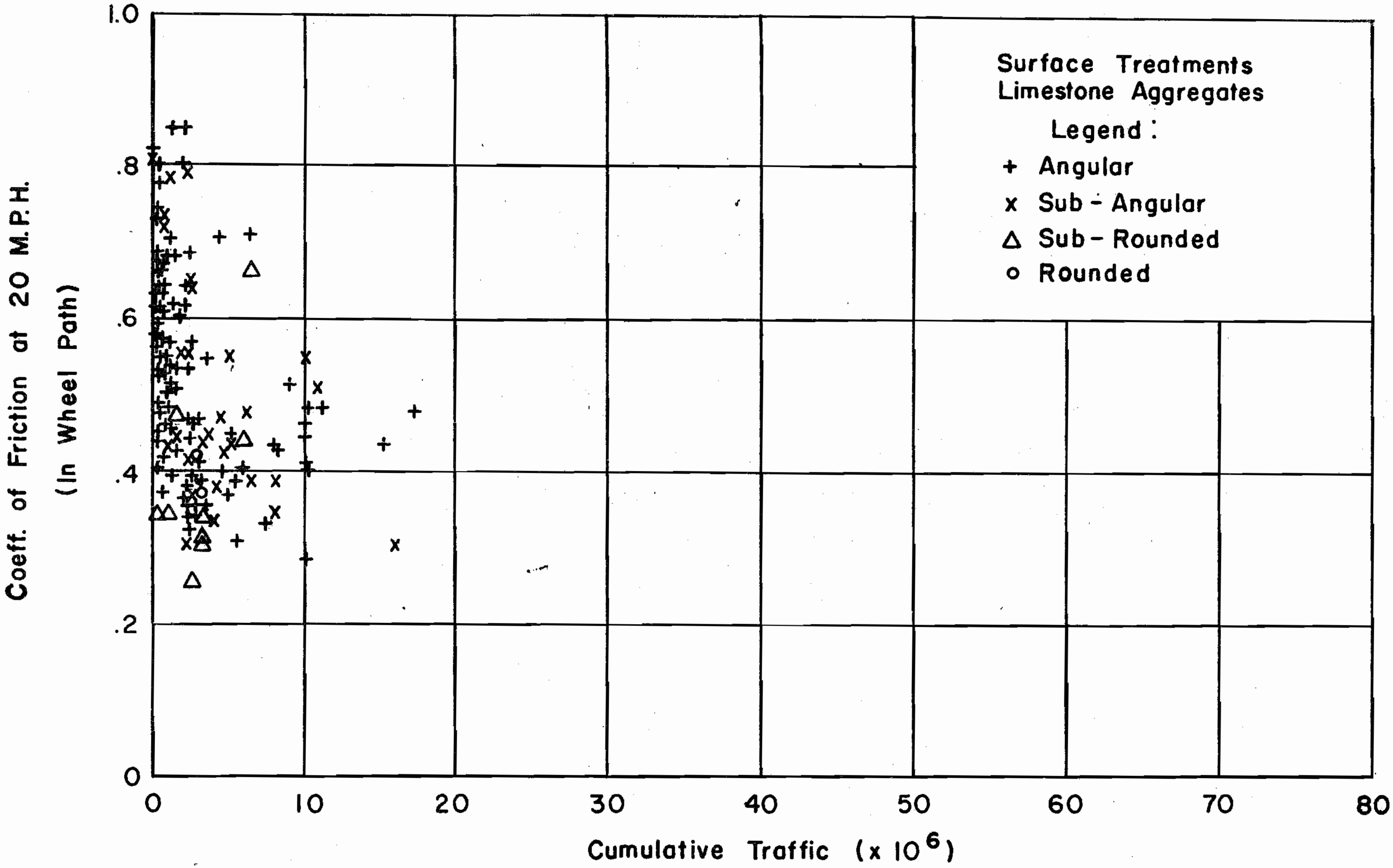
STUDY OF AGGREGATE MATERIAL TYPE AND SHAPE FOR SURFACE TREATMENTS - LIMESTONE AND SILICIOUS

Figure 16



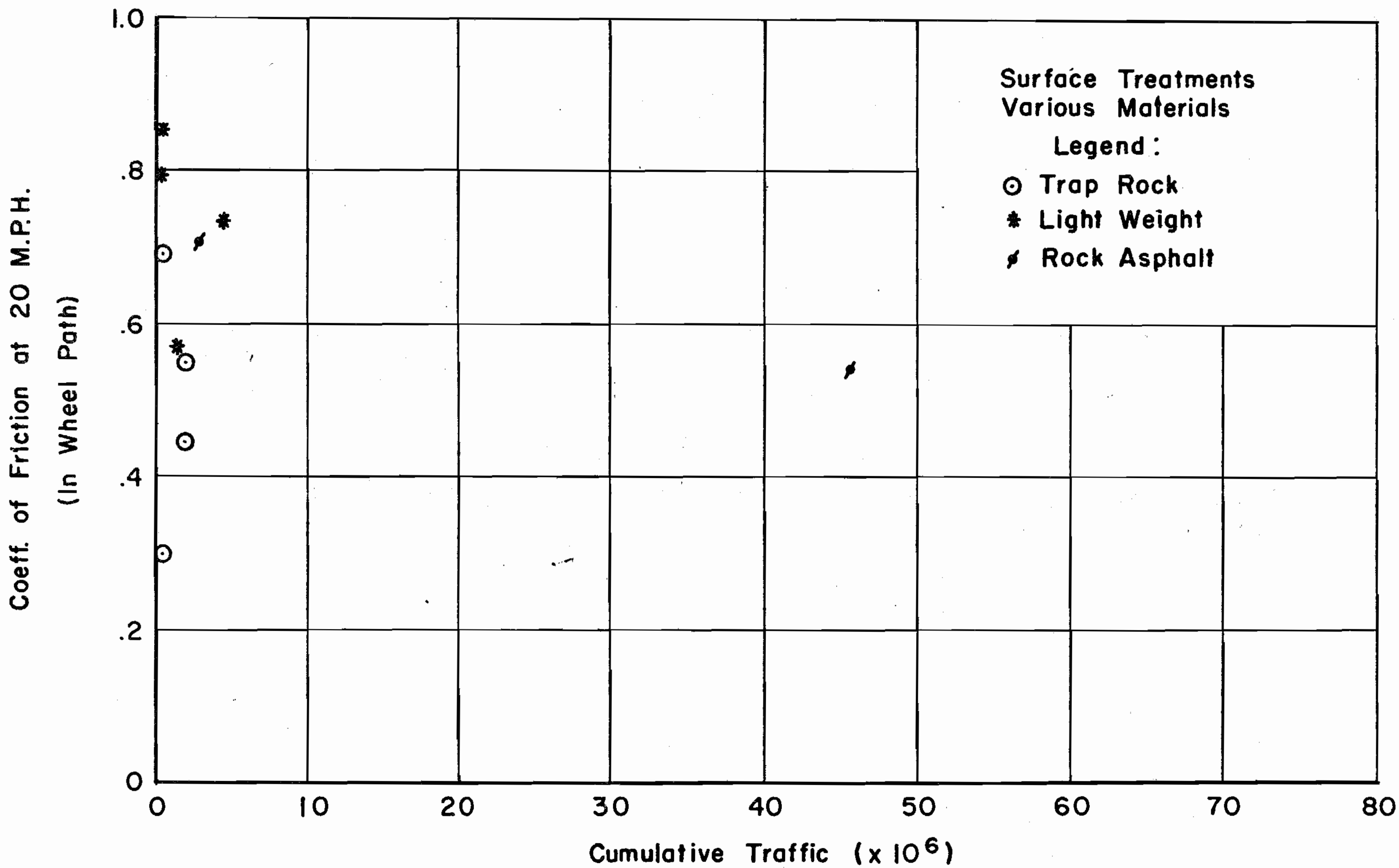
STUDY OF AGGREGATE MATERIAL TYPE AND SHAPE FOR SURFACE TREATMENTS - SILICIOUS

Figure 17



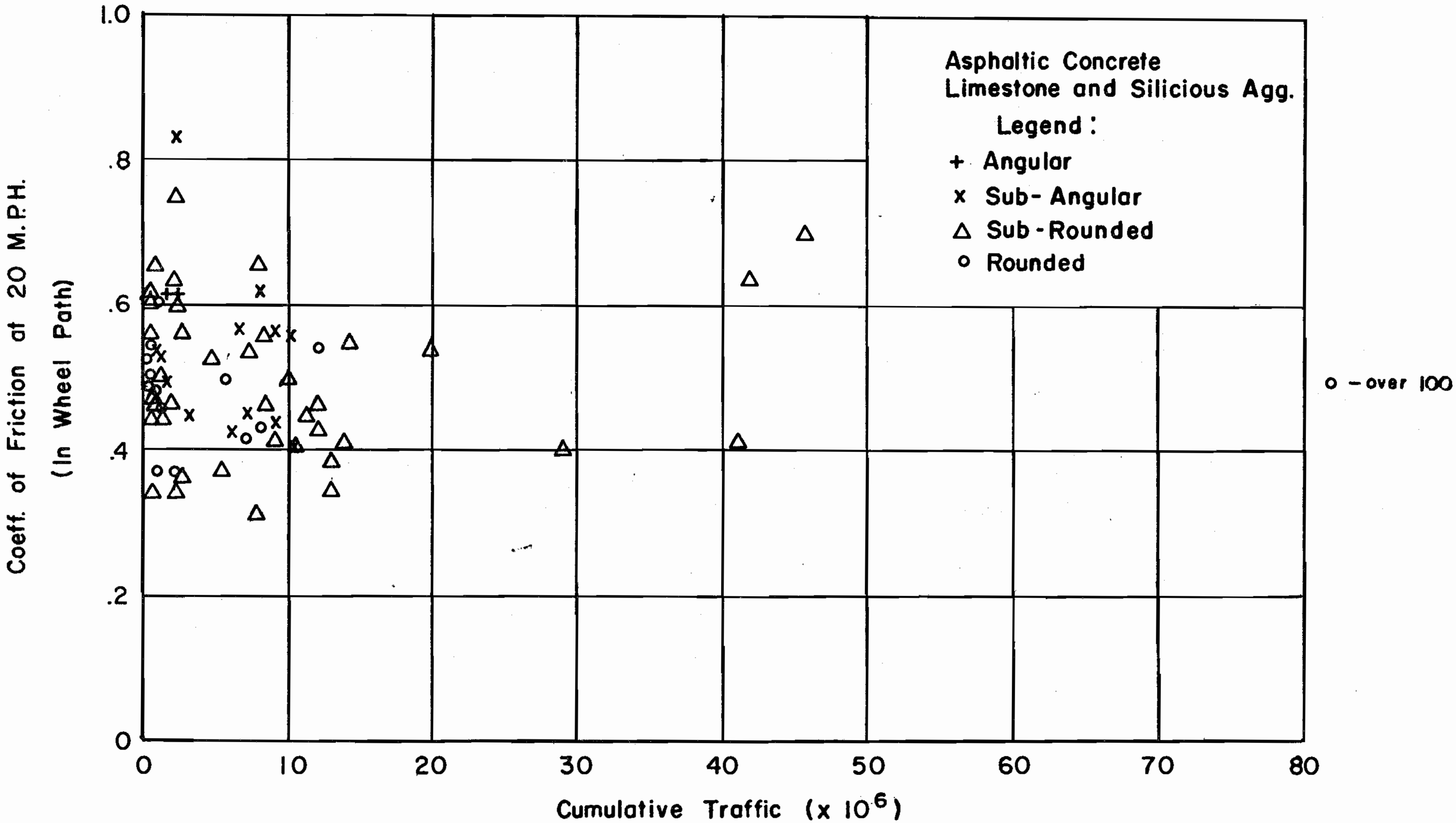
STUDY OF AGGREGATE MATERIAL TYPE AND SHAPE FOR SURFACE TREATMENTS-LIMESTONE

Figure 18



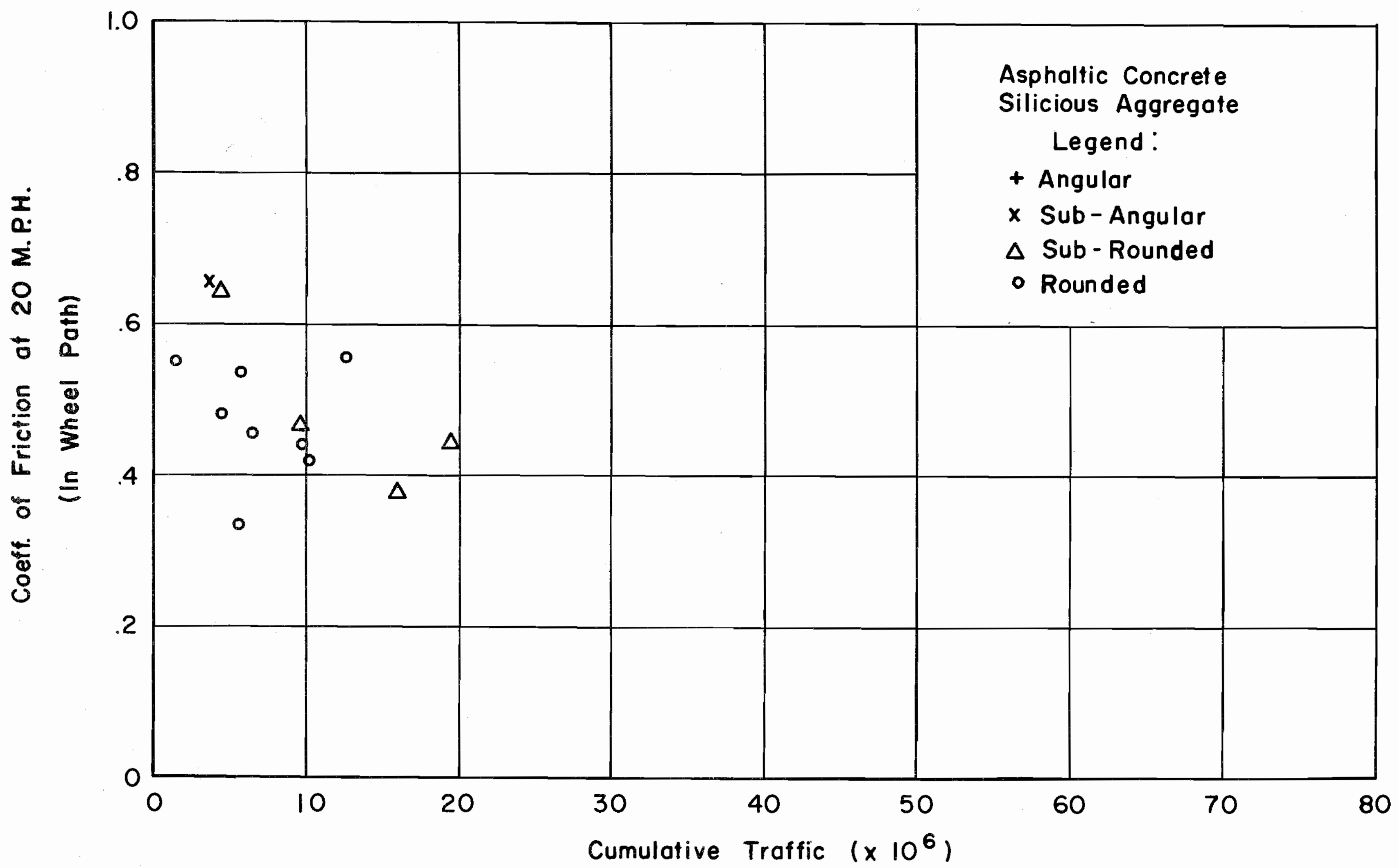
STUDY OF AGGREGATE MATERIAL TYPE AND SHAPE FOR SURFACE TREATMENTS - VARIOUS MATERIALS

Figure 19



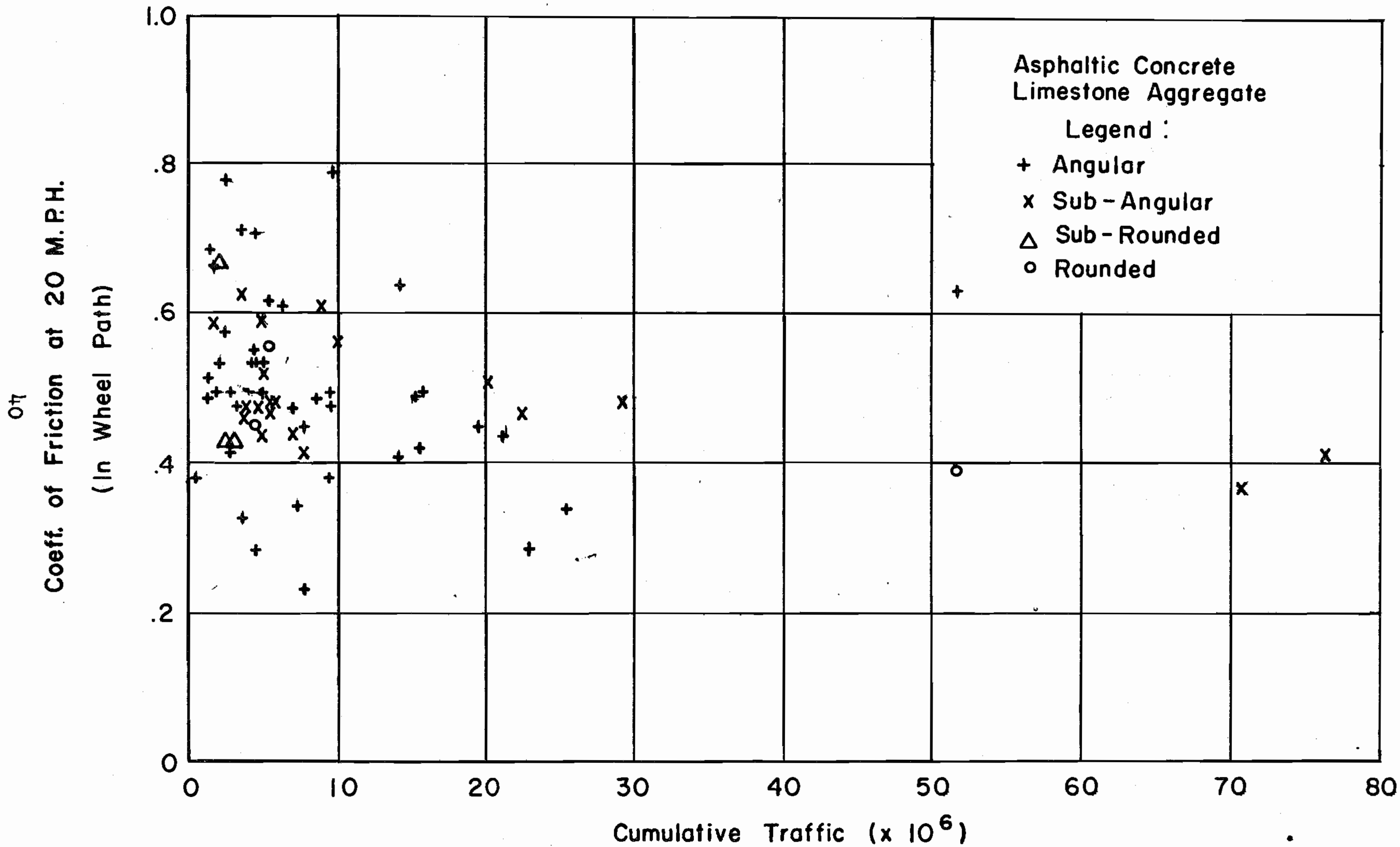
STUDY OF AGGREGATE MATERIAL TYPE AND SHAPE FOR ASPHALTIC CONCRETE-LIMESTONE AND SILICIOUS

Figure 20



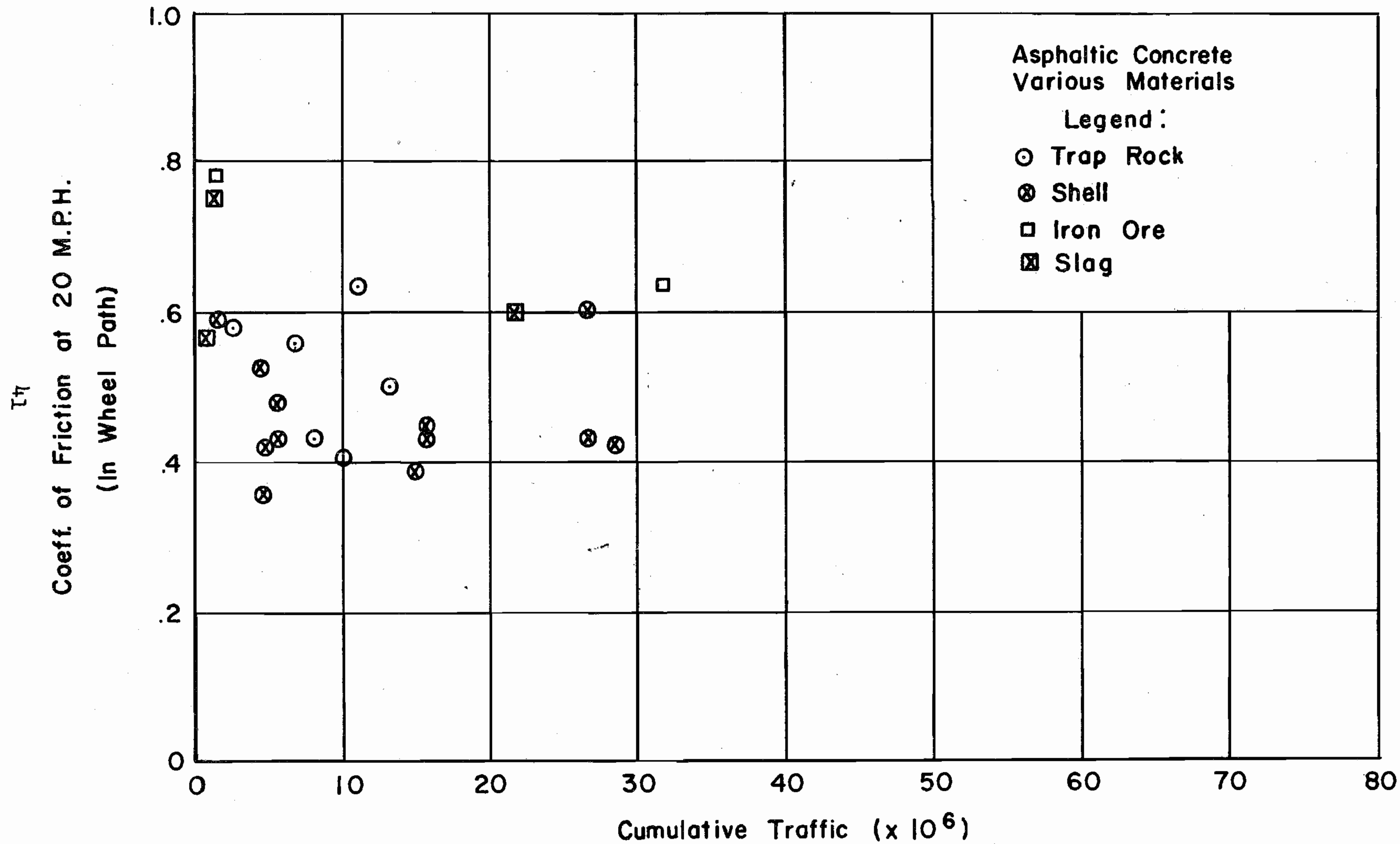
STUDY OF AGGREGATE MATERIAL TYPE AND SHAPE FOR ASPHALTIC CONCRETE-SILICIOUS

Figure 21



STUDY OF AGGREGATE MATERIAL TYPE AND SHAPE FOR ASPHALTIC CONCRETE - LIMESTONE

Figure 22



STUDY OF AGGREGATE MATERIAL TYPE AND SHAPE FOR ASPHALTIC CONCRETE - VARIOUS MATERIALS

Figure 23

rounded limestone mixed with the quartz like material. On the other hand, limestone was a crushed material which was calcareous in nature.

Each individual plot was studied for the effect of aggregate shape. It appeared that the shape of the coarse aggregate had little effect on the friction properties when used in portland cement concrete paving.

Surface Treatments

The effect of material type on the friction properties was studied by comparing the vertical position of the data points between each plot on Figures 16 through 19 and the coarse aggregate shape was studied by comparing the symbols on Figures 16, 17 and 18. It should be remembered, at this point, that the sections represented by each data point were subject to a bleeding or flushed condition, often after a few thousand traffic applications. In any event, after studying these plots there appeared to be a trend toward higher initial values when crushed limestone materials were used (or when angular materials were used). There was a wide scatter of data on each plot, but a slight trend toward higher initial friction values was observed when the angular shaped limestone was used. The small amount of data in Figure 19 indicated lightweight and rock asphalt could perform well.

Asphaltic Concrete

Aggregate material type used in asphaltic concrete was studied by analyzing the data points between the plots on Figures 20 through 22 and by analyzing the symbols on Figure 23. Aggregate shape was analyzed by observing the symbols in Figure 20 through 22. The scatter in data was such that no trends could be found with either material type or coarse aggregate shape. There was a slight possibility that the angular shape performs better in the silicious material (Figure 21) and in the limestone material (Figure 22), but the scatter was such that little faith could be placed in this possibility. It was interesting that one section of a rounded limestone-silicious material revealed a coefficient (at 20 mph) above 0.50 after 100 million vehicle applications.

Of the four materials which were plotted in Figure 23 the average increasing friction order indicated on the plot is:

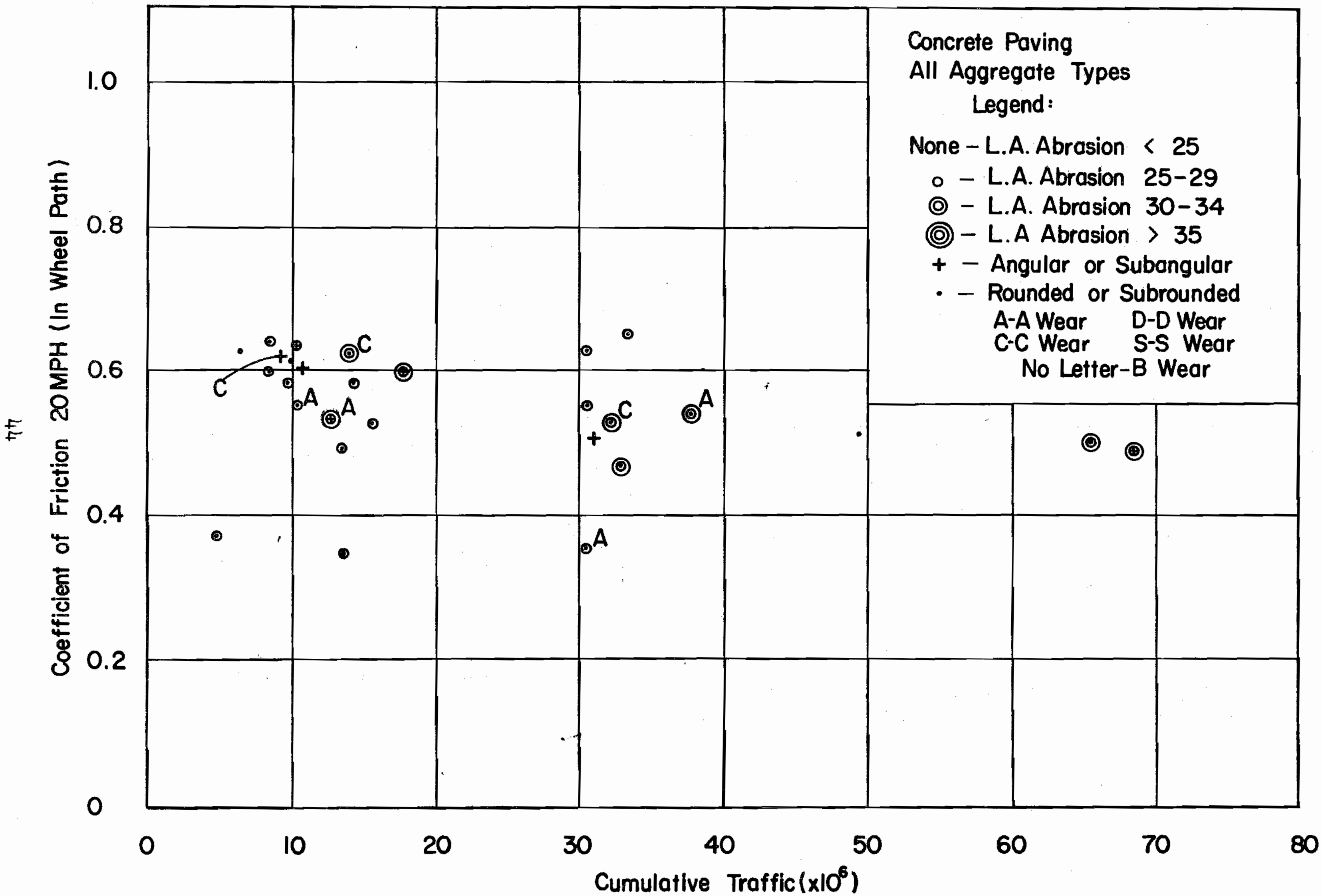
1. Oyster shell
2. Trap Rock
3. Slag
4. Iron Ore

Oyster shell was found to have the lowest average values for the four materials. Shell was used in asphaltic concretes on several pavements found in the coastal areas of the state and was apparently well liked by construction personnel because of good structural properties. After further contact with District personnel it was found that shell is classified as either new or old, with the old being weathered or having a flaked or layered appearance. This fact was not known at the time the data was collected and no attempt was made to subdivide the information presented in Figure 23.

The slag reported was the aluminum slag previously mentioned. The gradation of the slag was small with the larger size particles being around a Number 10 mesh screen size. The correct nomenclature was found to be "wet bottom boiler slag". Visual examination of a newly placed surface revealed a close gritty sandpaper texture.

Aggregate Hardness and Shape

The measure of aggregate hardness used in this study was that obtained from the Los Angeles Abrasion test. Even though this form of test did not indicate hardness as in the Moh's hardness scale, it was thought that an abrasive hardness test would tend to indicate aggregate attrition (or the wearing away, spalling off, or flakiness of the micro size particals of an individual aggregate). Aggregate hardness was studied by using the polish plots shown in Figures 24 through 28. Only portland cement concrete, surface treatments and asphaltic concretes were analyzed. Symbols were used to indicate both aggregate shape and hardness for the concrete pavements shown in Figure 24. Surface treatments



STUDY OF AGGREGATE HARDNESS AND SHAPE FOR CONCRETE PAVING

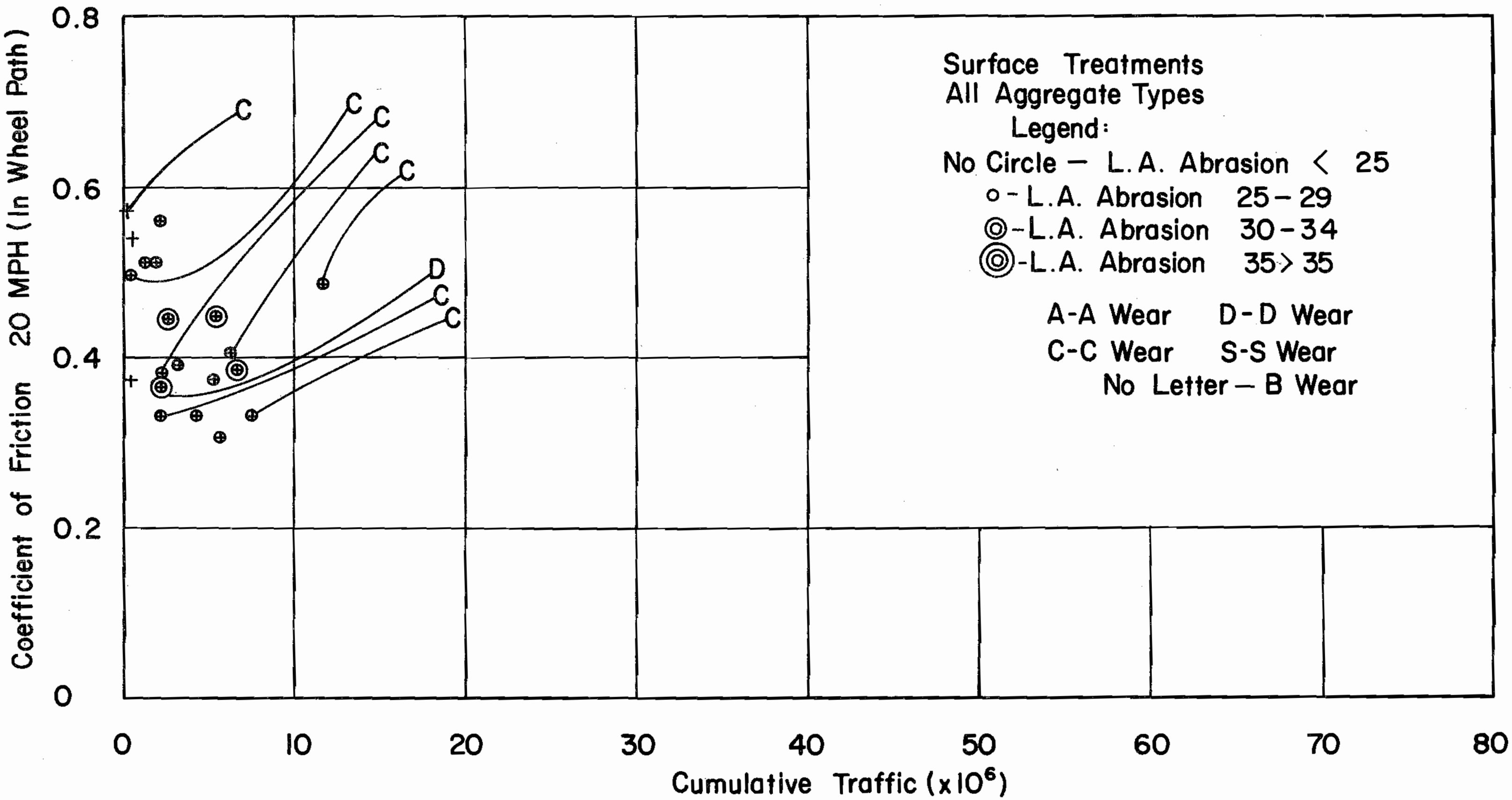
Figure 24

Cumulative Traffic (x 10^6)

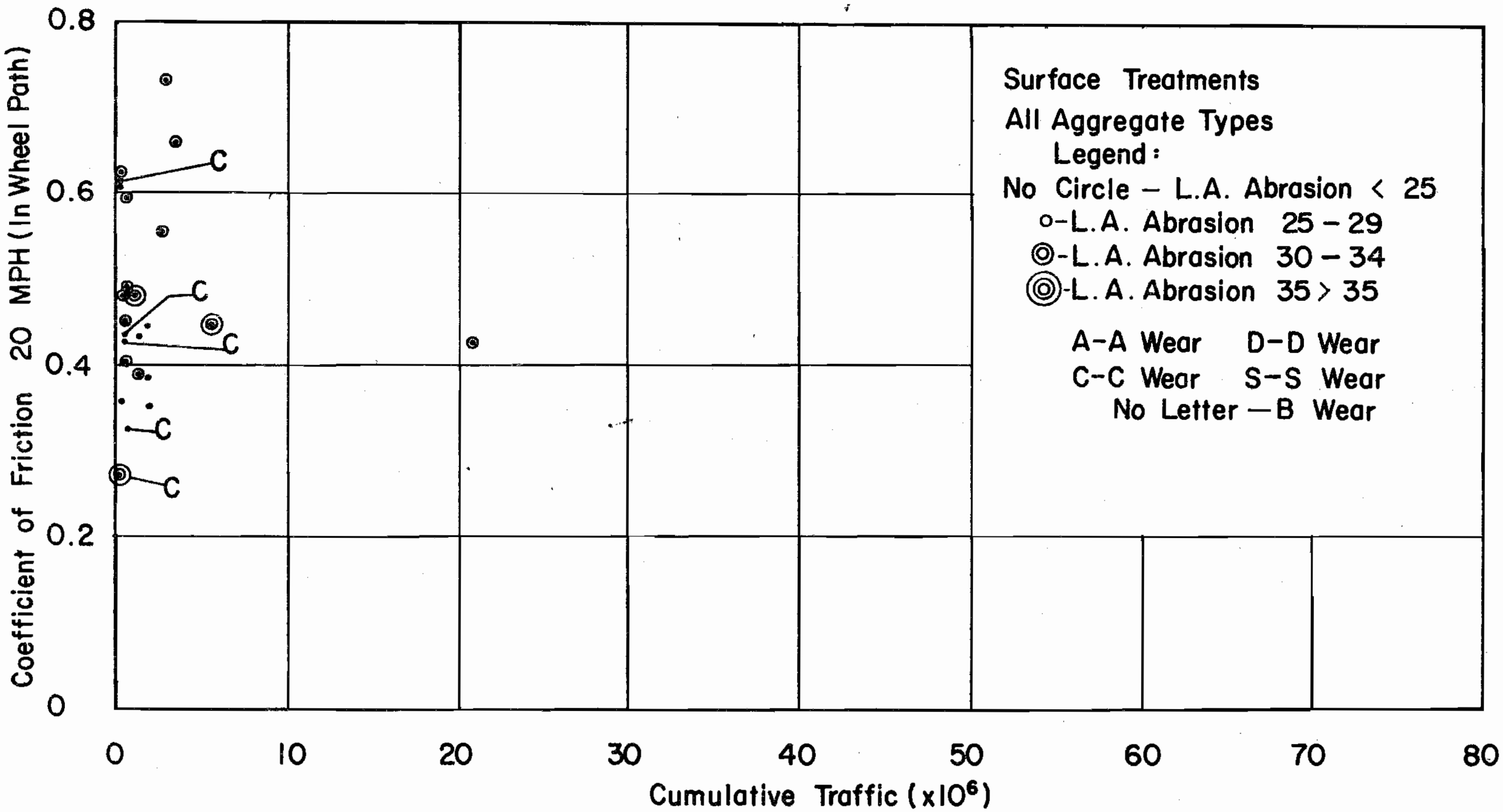
STUDY OF AGGREGATE HARDNESS AND SHAPE FOR SURFACE TREATMENTS

ANGULAR AND SUBANGULAR

Figure 25

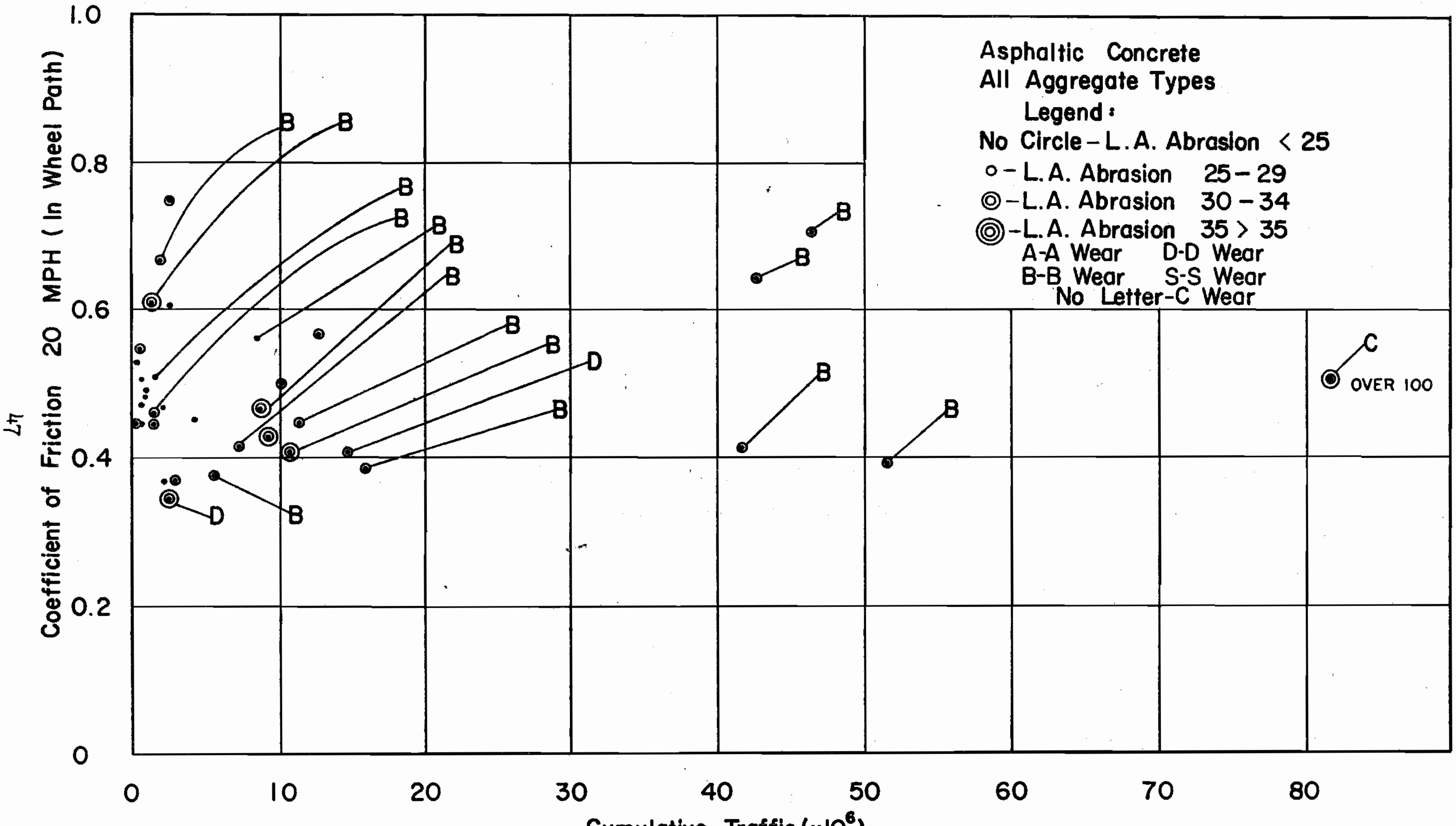


STUDY OF AGGREGATE HARDNESS AND SHAPE FOR SURFACE TREATMENTS
ANGULAR AND SUBANGULAR
Figure 25



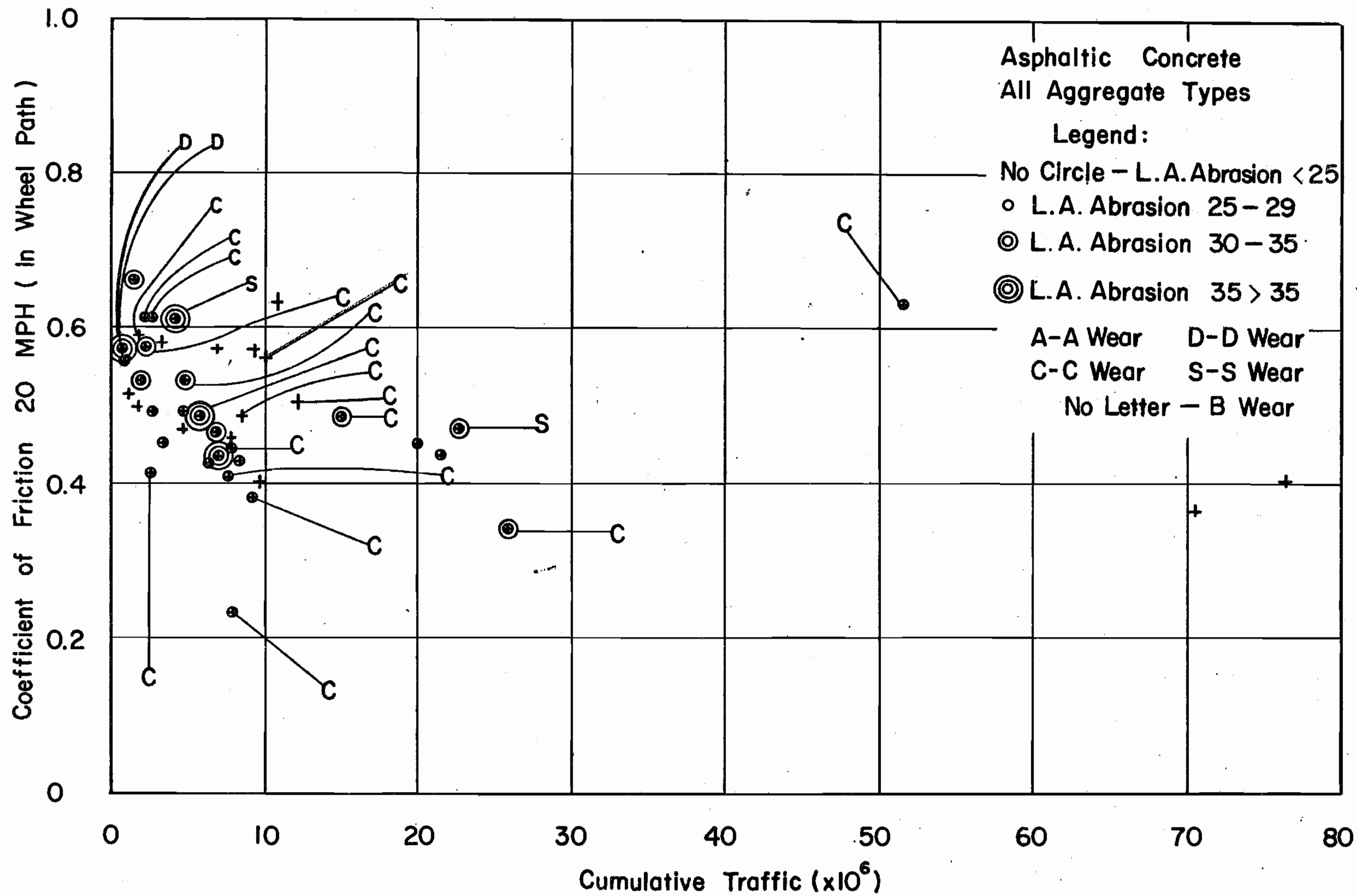
STUDY OF AGGREGATE HARDNESS AND SHAPE FOR SURFACE TREATMENTS
ROUNDED AND SUBROUNDED

Figure 26



STUDY OF AGGREGATE HARDNESS AND SHAPE FOR ASPHALTIC CONCRETE
ROUNDED AND SUBROUNDED

Figure 27



STUDY OF AGGREGATE HARDNESS AND SHAPE FOR ASPHALTIC CONCRETE
ANGULAR AND SUBANGULAR
Figure 28

and asphaltic concretes were studied by combining the angular and subangular shapes on a different plot from the rounded and subrounded combinations. Symbols were used in Figures 25 through 28 to denote ranges of L. A. wear loss. As may be recalled, the Los Angeles Abrasion test may be conducted using different sizes (grades) of aggregate. These size ranges are generally denoted by letters (A, B, C, etc.). The same letter connotation used in the test was also used in the plots to indicate size and material type.

No relationship could be found between the friction performance and the aggregate hardness in any of the pavement types studied in the above plots. Also, trends were not evident when hardness was studied in combination with aggregate shape.

Friction Performance Equations

At this point an attempt was made to fit curves through the "coefficient (20 mph) vs. traffic" plots. Only the major pavement types were considered, and the curves are shown in Figures 29 through 31. Arbitrarily, a linear fit was selected for portland cement concrete and fourth order equations were selected for Surface Treatments and asphaltic concretes. The equations found were as follows:

Portland Cement Concrete

$$Y = 0.63 - 0.012X$$

Surface Treatments

$$Y = 0.62 - 0.348X + 0.267X^2 - 0.135X^3 + 0.0267X^4$$

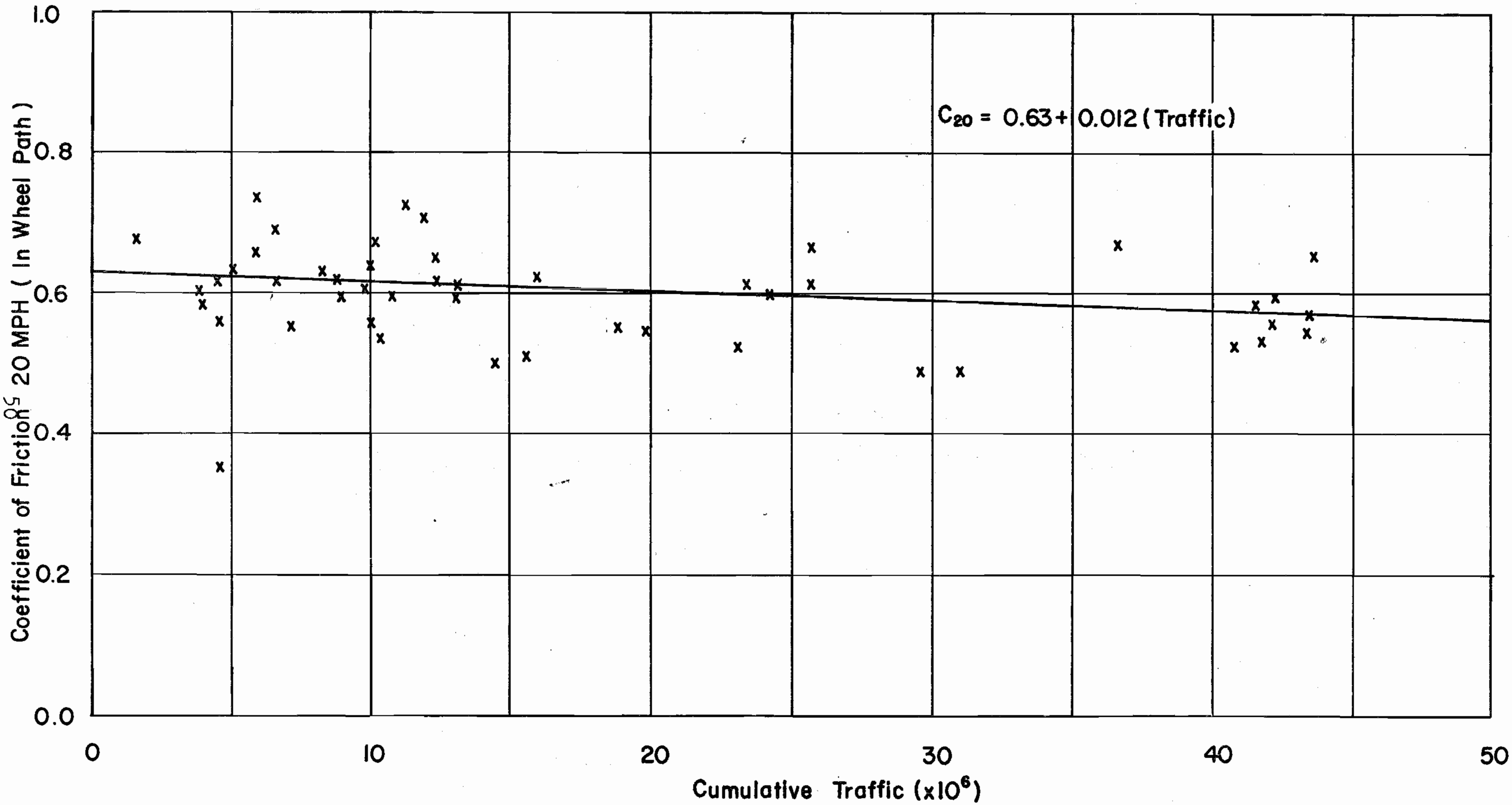
Asphaltic Concretes

$$Y = 0.60 - 0.162X + 0.070X^2 - 0.020X^3 + 0.003X^4$$

Where Y = Trailer Coefficient of Friction at 20 mph

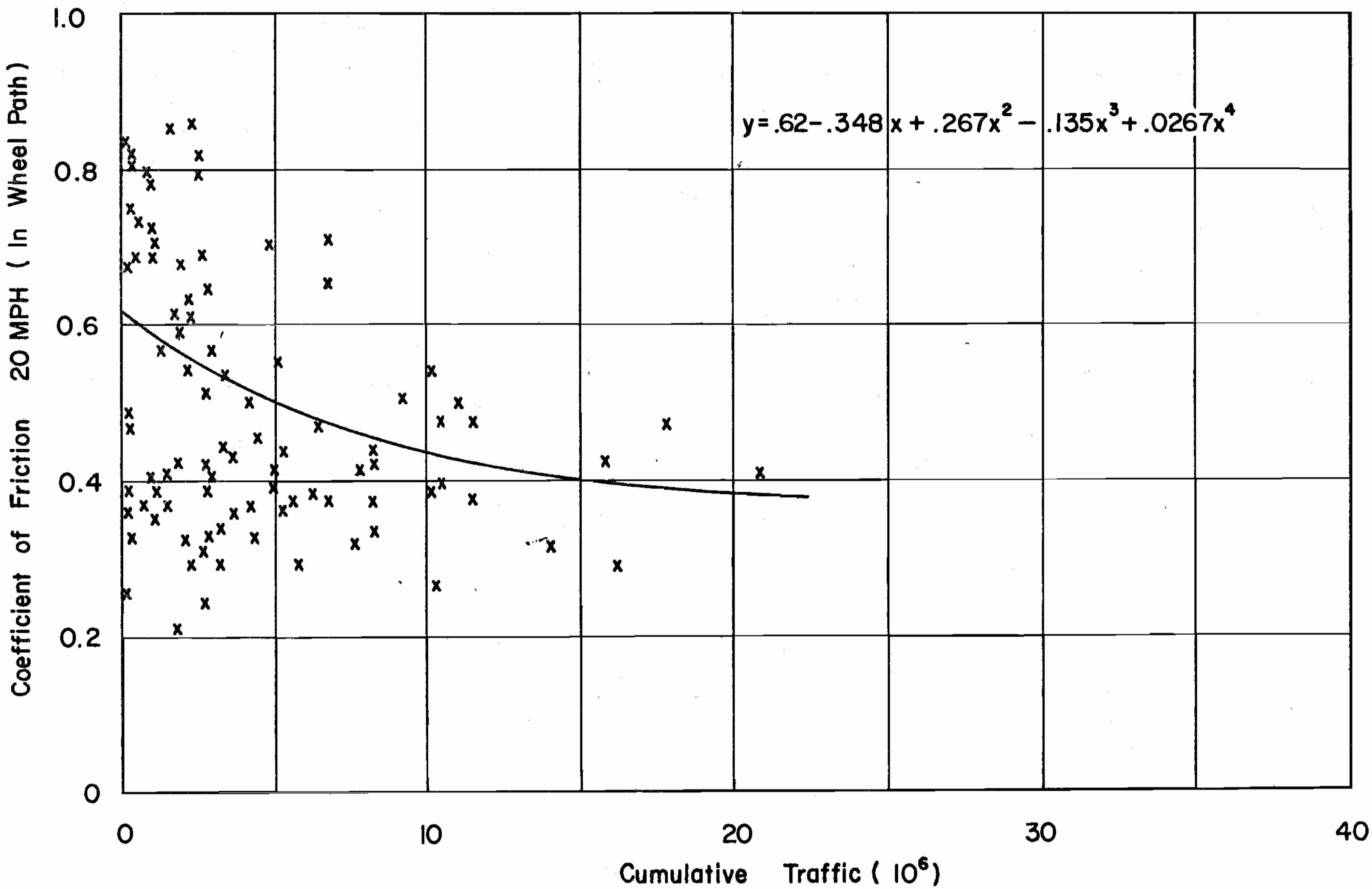
X = Total Vehicle Passages

It was postulated that the scatter of data or variance about the curve(s) could be explained by the variables measured. Next, each data point was corrected to ten million vehicle passages. This was done with a computer program which,



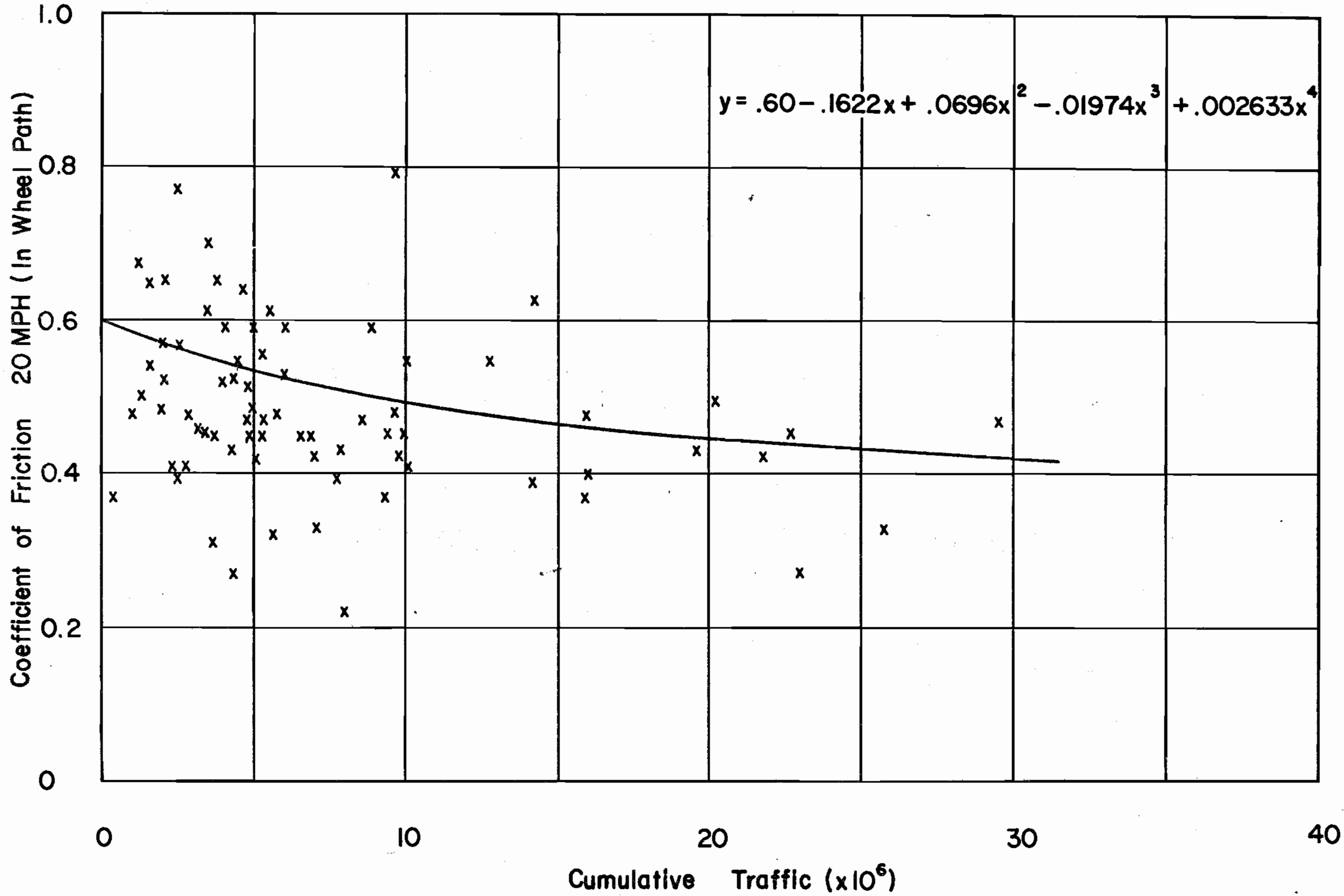
PERFORMANCE EQUATION - PORTLAND CEMENT CONCRETE

Figure 29



PERFORMANCE EQUATION – SURFACE TREATMENT

Figure 30



PERFORMANCE EQUATION – ASPHALTIC CONCRETE

Figure 31

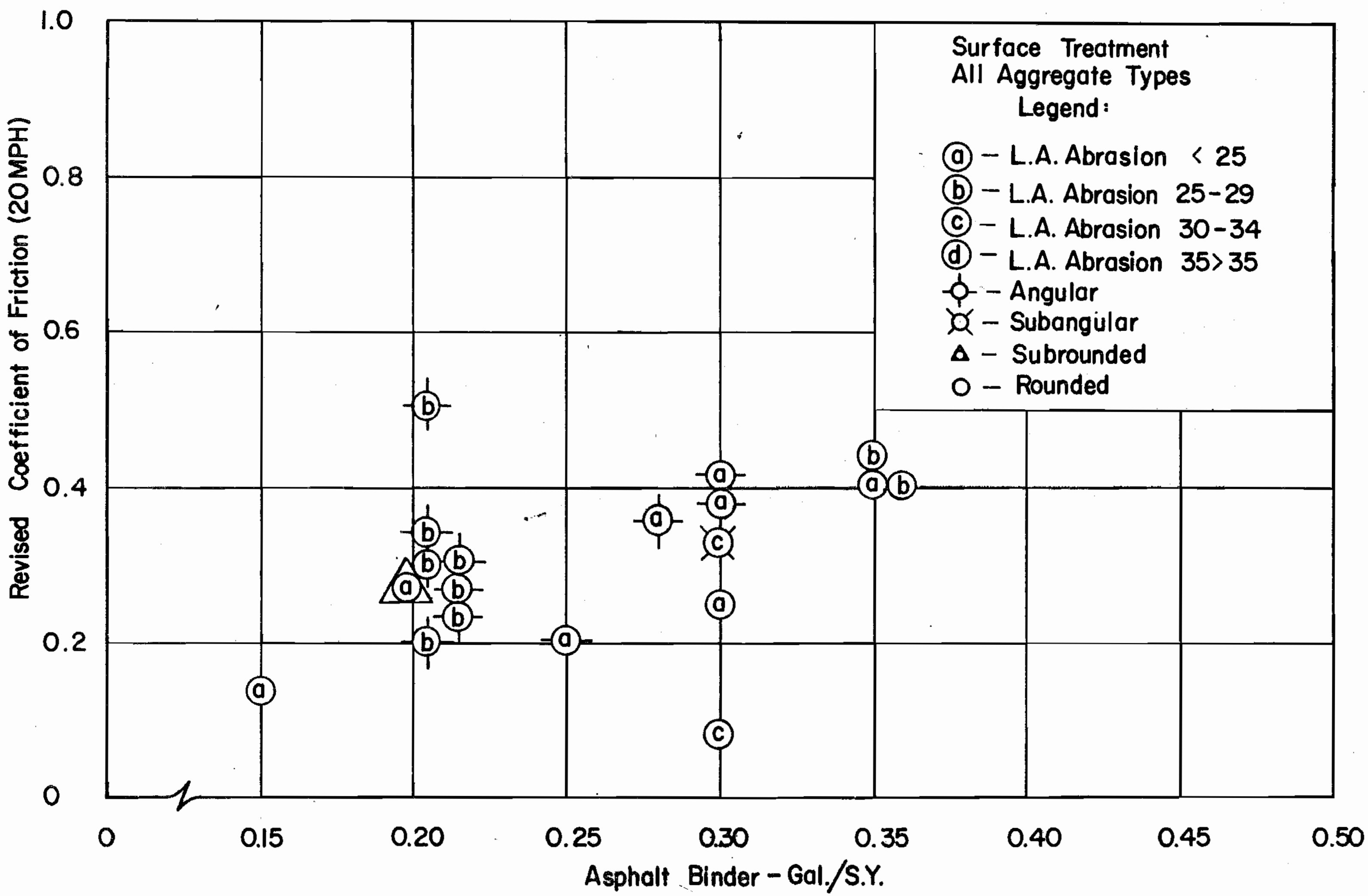
in effect, slid each data point along the curve, either forward or backward until all points were arrayed at ten million traffic applications. Ten million applications was arbitrarily selected because it was believed that the polish trend would level off on individual pavements at this point. The coefficient of friction at 20 mph in the wheel path was used in this study, and the array of coefficients at ten million vehicle applications was termed - "Revised Coefficient" (Rev. C.O.F.). It was believed that, using this method, the traffic polishing variable could be held constant while the other variables which were measured could be studied for trends in friction characteristics.

Binder Content and Aggregate Grade

Figure 32 reveals an example of the influence of the binder content on the skid resistance of pavement surfaces. The example used is of Surface Treatments in which the information of the L. A. Abrasion Test and aggregate shape was available. Symbols were used to denote shape and hardness levels. No attempt was made to separate the type of material in the L. A. Abrasion test (that is the gradation of the material).

Binder content has previously been described and was referred to as being the cementing agent of a particular pavement type. The example shown in Figure 32 was concerned with Surface Treatments, but it was representative of the information collected on all pavement types. No discernible trends were evident in any of the individual or combined analyses performed. Departmental personnel had postulated that the higher cement contents of portland cement concrete pavements would provide a more durable or longer lasting quality to the surface finish (that is, the belting, burlap drag, etc.); however, no trends were found indicating this effect.

Realizing that the selection of an asphalt application rate required much experience and was dictated by many factors, it was believed that a general optimum application rate would be found. However, these postulations were not evident in the data collected. Table I reveals the average Revised Coefficient



STUDY OF BINDER CONTENT

Figure 32

Table I

Study of Revised Coefficients

And Binder Contents

Surface Treatments

Interval Gal./S.Y.	Number Studied	Average Rev. C.O.F.
0.13-0.18	8	0.41
0.19-0.23	19	0.39
0.24-0.28	36	0.40
0.29-0.33	57	0.38
0.34-0.38	12	0.38
0.38-0.43	9	0.20
All	141	0.38

Asphaltic Concrete

Interval % Asphalt	Number Studied	Average Rev. C.O.F.
3.8-4.3	6	0.39
4.4-4.8	29	0.45
4.9-5.3	52	0.41
5.4-5.8	16	0.48
5.9-6.3	7	0.60
6.3-6.8	7	0.51
6.8	5	0.47
All	122	0.45

Table II

Study of Revised Coefficients

And Aggregate Grade

Aggregate Grade	Number Studied	Average Rev. C.O.F.
1	1	0.22
2	37	0.42
3	15	0.42
4	83	0.38
5	30	0.36
6	3	0.38
7	12	0.29
8	6	0.32

for each of the binder groups (or intervals) analyzed for the flexible pavements studied. An example of the influence of aggregate size or grade on friction values is given in Table II. Again the Revised Coefficient was used with the aggregate grades as established by THD specifications. Grade 1 is the larger size aggregate and Grade 8 is the smallest size. There was an apparent trend toward higher friction values with larger aggregate sizes as can be observed in Table II, but a plot of individual data (not shown) again revealed a wide scatter of points. Asphaltic Concrete types produced results similar to that described for Surface Treatments above, but the information is not included in order to shorten the report content.

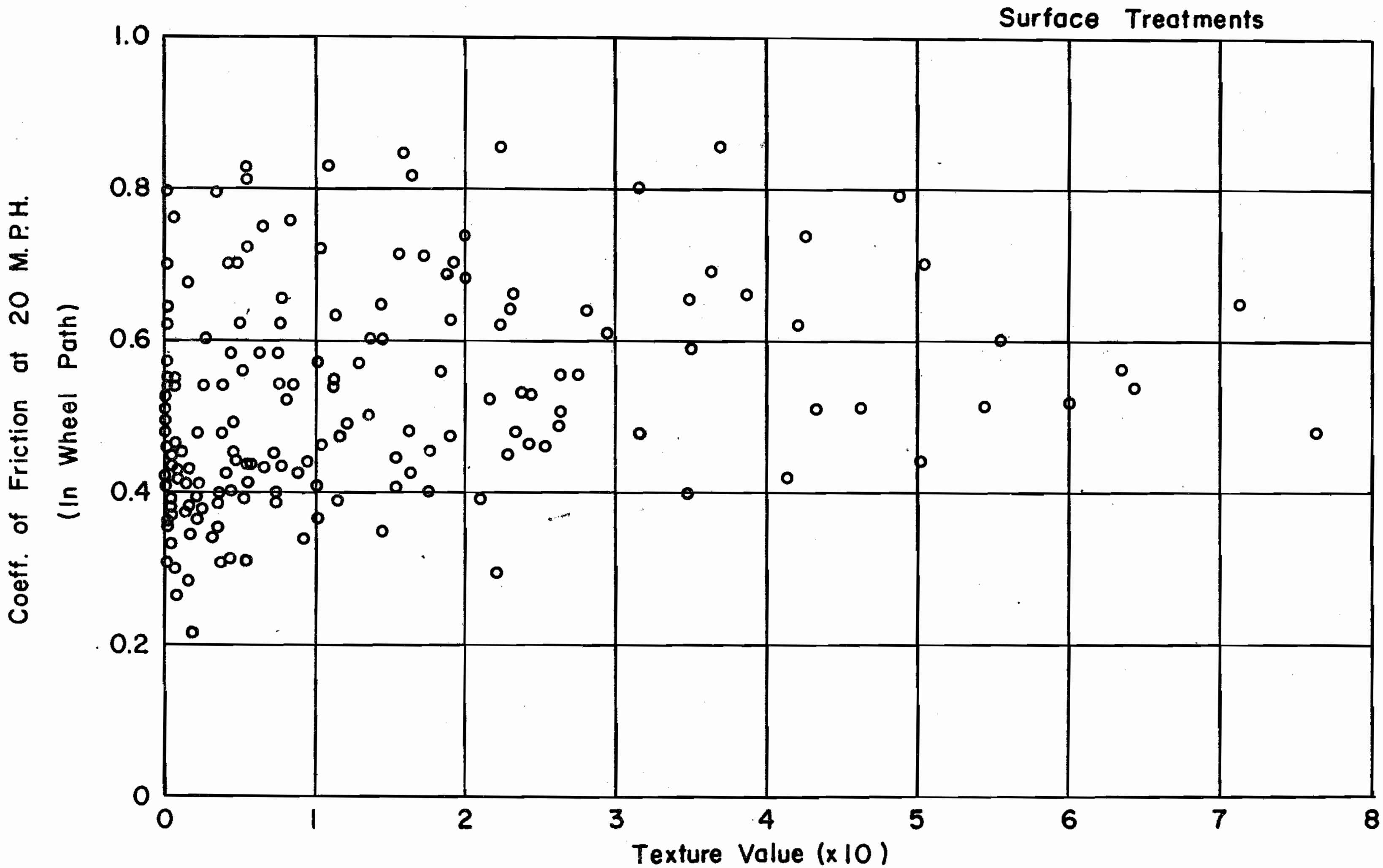
Texture

As stated previously, the analysis of texture reported herein led to a greater study which was reported in Research Report 45-4.[4] The data which was collected with the Texas Texturemeter in this study, probably is a measure of the macro texture as defined in Research Report 45-4.

Figure 33 reveals a plot of the coefficient of friction at 20 mph vs. the texture value as measured with the Texas Texturemeter. The scatter is wide and no relationship could be found. The data shown in Figure 33 was for pavements with Surface Treatments, however, the plots for other types appeared similar.

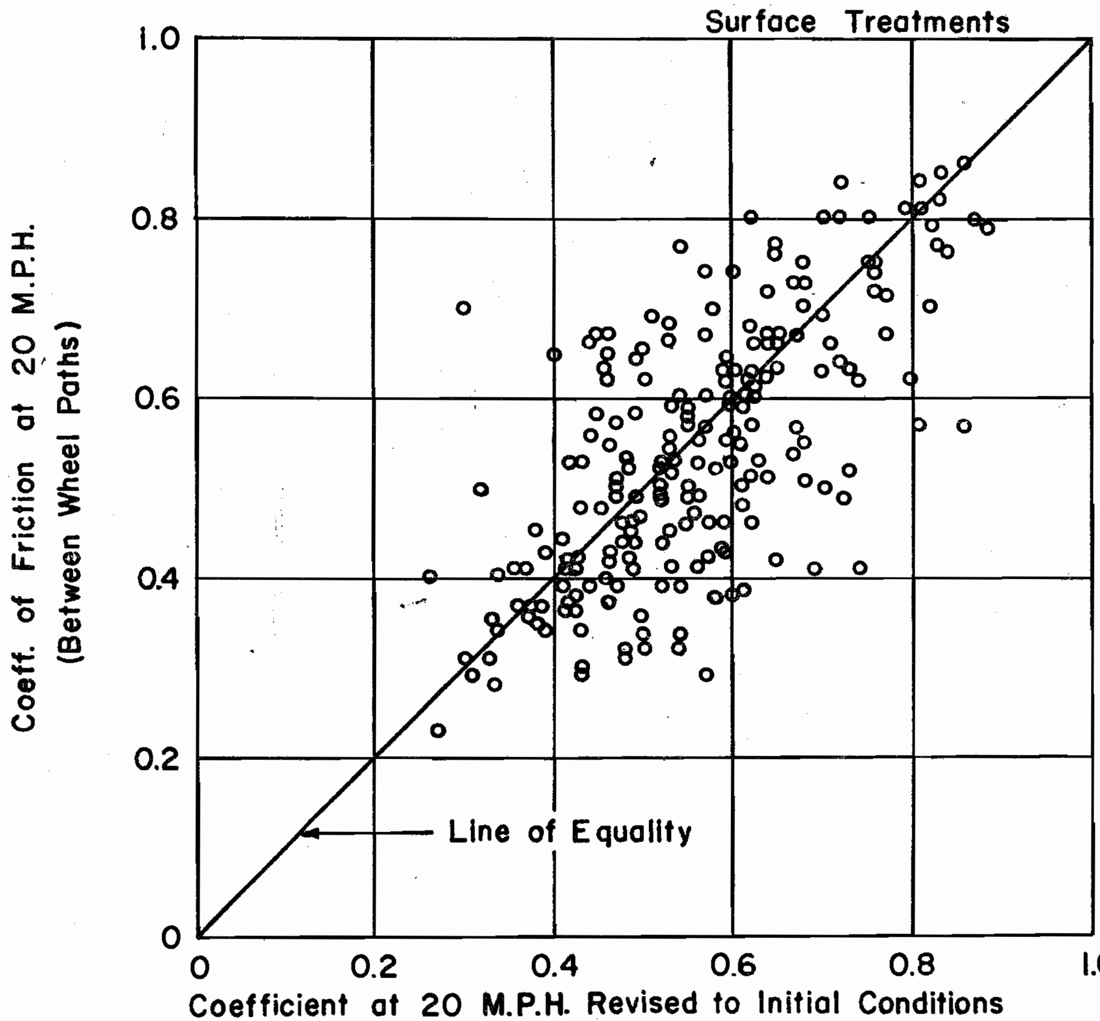
Friction at 20 mph in the Wheel Path Compared to Friction at 20 mph Between the Wheel Paths

The object of this analysis was to attempt to determine if friction measurement made between the wheel paths could be used to predict the initial or "as constructed" friction value. The data collected for Surface Treatments was used for the example plot shown in Figure 34, and the data for the independant variable used in this plot was developed by using the Friction Performance Equations mentioned previously in this chapter. Using these equations, each data point was corrected to the "initial condition". This, in effect, assumed each surface had polished according to the predicted equation, and each data point



STUDY OF SURFACE TEXTURE

Figure 33



BETWEEN WHEEL PATH FRICTION RELATED TO INITIAL CONDITIONS
Figure 34

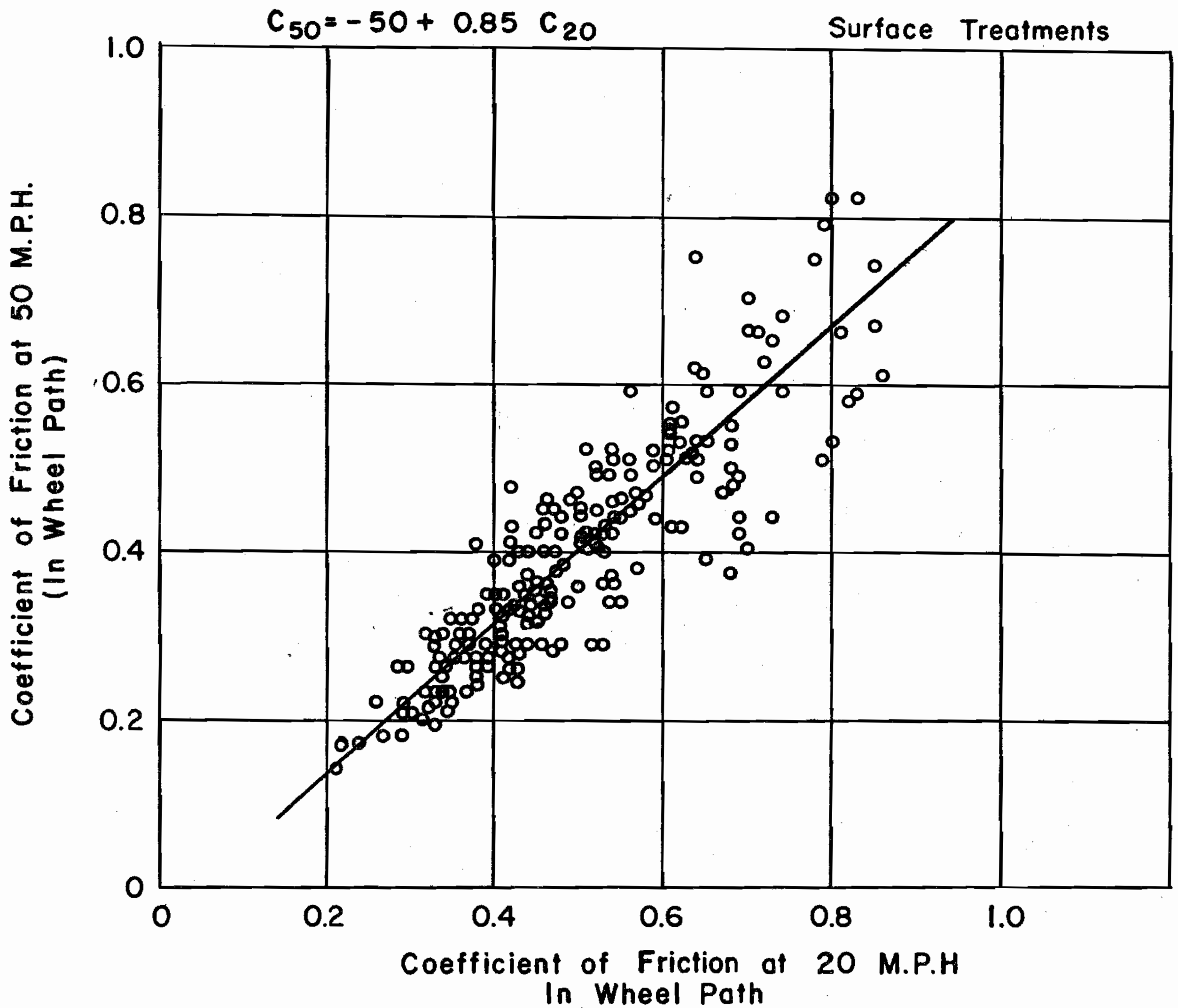
was moved along and parallel to the predicting curve until the zero traffic condition was encountered.

The plot revealed a slight degree of equality with points equally distributed about the one-to-one line, however, at the 95 percent confidence limit the variance was about 0.2. The large variance obviously limited the use of "between the wheel path" measurements to predict the "as constructed" friction value.

The method which was used to analyze the "between wheel paths" measurements could be controversial, especially when the Friction Performance Equations were used to predict the initial friction value. For instance, the loss in friction due to traffic must vary considerably depending on the flushed or bleeding asphalt condition. Therefore, it was believed that "between wheel paths" measurements were not a good measure of initial values; and no further work was accomplished using the measurement.

<u>Friction Values at 50 mph Compared With Friction Values at 20 mph</u>

The plot in Figure 35 compared the friction values measured at 50 mph to the friction values measured at 20 mph. Each data point represented one Surface Treatment test section. There appeared to be a relationship between the friction values measured (on the same section) at two different speeds; even though there is some scatter with the greater variance from the line occurring at the larger friction values. This relationship indicated that a large part of the loss in friction with increased speed (or a speed gradient curve) could be explained by the friction value at a low speed. Stated in other terms, there will be a large drop in friction as the speed increases - if the friction value at a low speed is high. In general, there is a small difference between the friction values at 20 mph and the friction values at 50 mph if the 20 mph friction value is low. A similar relationship has been determined between friction values at 7 mph and 40 mph in work occurring on another project which is not reported herein.



FRICTION AT 20 M.P.H. RELATED TO FRICTION AT 50 M.P.H.
Figure 35

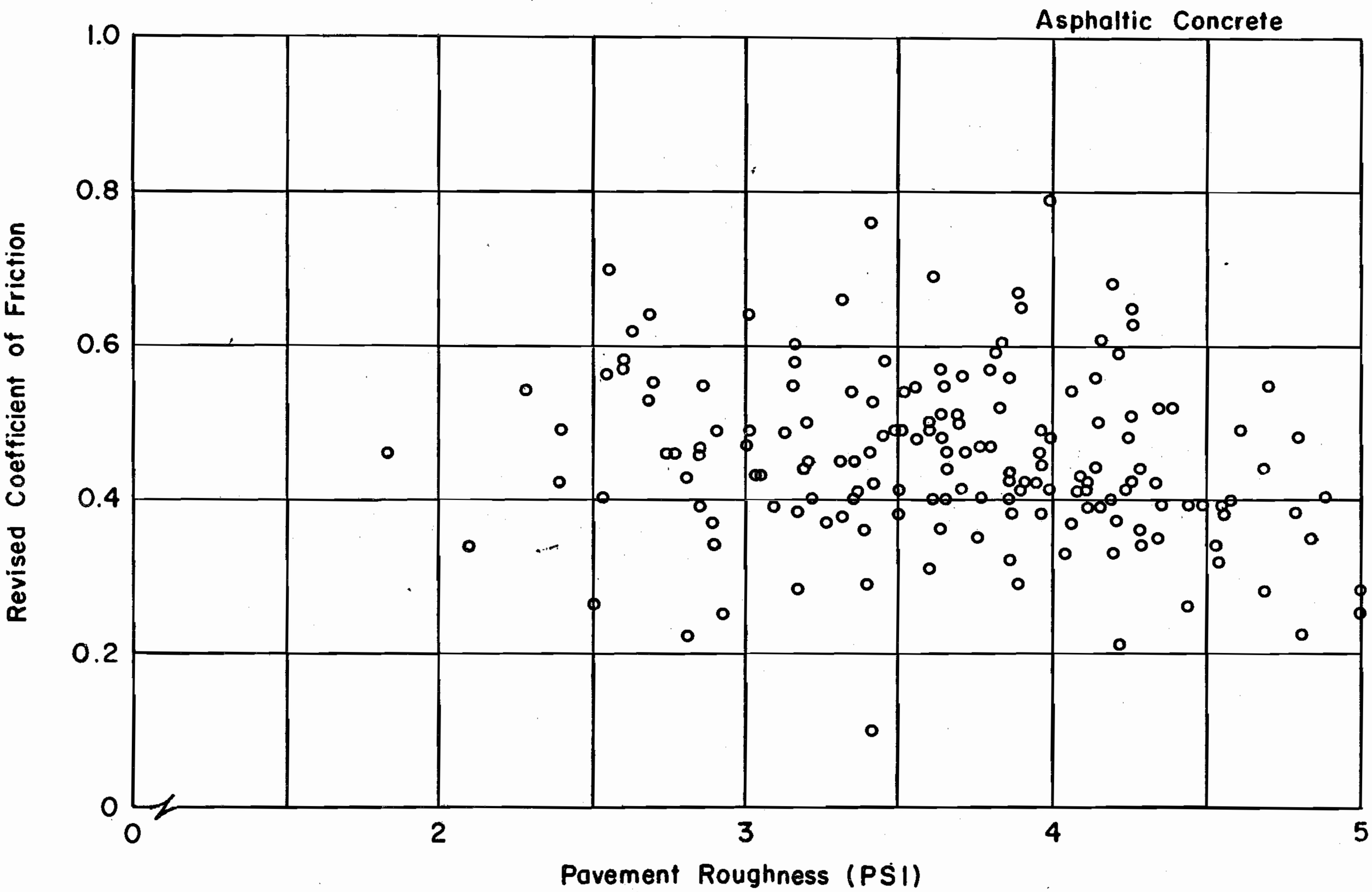
The significance of this information will be realized when attempting to use the speed gradient curve to predict friction values at increased speeds (even to the point of zero friction at the speed of hydroplaning). It is possible, especially at the smaller water film depths such as those emitted by the trailer, that the friction level (probably caused by the micro texture, see Report 45-4) is important in determining the speed of hydroplaning.

Skid Resistance and Pavement Roughness

The plot in Figure 36 compares friction values to pavement roughness. As mentioned previously, the pavement roughness was measured with a CHLOE profilometer and has no relationship with the minute roughness which is termed texture in this report.

As expected, no correlation was apparent between pavement roughness and pavement friction as indicated in the data obtained using asphaltic concrete pavements as an example. Analyses of individual skids, as recorded on the strip chart, revealed a fluctuation of the recorded friction force on rough pavements. This fluctuation was believed to be due to the roughness because the trailer suspension allowed the trailer to bounce slightly. A vertical force was set up due to the vertical excursions of mass and acceleration. The usual procedure for determining the friction force from the strip chart was to "average" the resulting trace. Apparently, this averaging process eleiminated the variation due to roughness when the coefficient was calculated (using a constant trailer weight).

The above information should not be construed to indicate that roughness is not important when studying the friction availability to a vehicle. Since the suspension of a vehicle carrying passengers develops the same vertical movements as described in the preceding paragraph, it could be disastrous for a driver to attempt a critical maneuver when the mass of the vehicle is accelerating vertically upward. In this case the available friction force could be very small.



STUDY OF PAVEMENT ROUGHNESS AND FRICTION

Figure 36

Regression Analysis

A step-wise multiple regression computer program originating at Health Sciencies Computing Facility, UCLA was used to analyze several pertinent variables in combination. The Revised Coefficient was used as the dependent variable, or variable to be predicted, and only linear forms were used for the independent variables. The regression program was run on the data for each of the major pavement types for all information available. Then, regressions were obtained for each of the three major pavement types eliminating hardness (L.A. Abrasion) as a variable. The elimination of the hardness variable allowed the use of a larger quantity of data.

The results of the analyses are contained in Tables III through VIII; each table may be separated into three parts. The first part is a list of each variable along with the Multiple Correlation Coefficient (R) and the Standard Error of Estimate (S.E.). The stepwise regression program computed regression equations as each independent variable was added in the order of significant influence (actually, according to the greatest reduction in the error sum of squares). For example, in Table III, the Binder Content was selected as the most significant contributor resulting in a R of 0.51 (1.00 being the best) with a variance (SE) in Revised Coefficient of 0.06. The Coarse Aggregate Shape was selected as the second most significant variable, and Binder Content with Coarse Aggregate Shape was treated in combination to predict the Revised Coefficient. The R was increased by this combination from 0.51 to 0.53, but the S.E. was not changed. In like manner, Hardness and Coarse Aggregate Type were added respectively.

The second part of the tables reveals the equation offered by the computer program. Only the last equation calculated, which includes all the variables for a particular study, was included in the tables.

The third part of the tables is the summary. The variables were listed along with the average value for each variable. The range of data for a variable was also given (or values which were twice the standard deviation). Then the

Table III

Regression Analysis

Portland Cement Concrete

5 Variables - 20 Cases

	R	S.E.
Rev. Coef. at 20 mph - (Rev. C.O.F.) - Dependant		
Binder Content (B.C.)	0.51	0.06
Coarse Agg. Shape (CAS)	0.53	0.06
Hardness (H)	0.55	0.06
Coarse Agg. Type (CAT)	0.55	0.06

Rev. C.O.F. = 0.72-0.077(B.C.)+0.004(H)-0.004(CAT)+0.019(CAS)

<u>Summary</u>

Variable	Mean	2(S.D.) or Range	Constant	Range of Variables		Range in Rev. C.O.F. Due to Variables		
Rev. COF	0.54						0.72	
B.C.	4.83	1.00	-0.077	3.83	5.83	-0.295		-0.449
CAS	3.80	1-4	+0.019	1	4	+0.019		+0.076
H	28.3	5.22	+0.004	23.1	33.5	+0.092		+0.134
CAT	0.30	0-4	-0.004	0	4	0		-0.016

Table IV

Regression Analysis

Portland Cement Concrete

5 Variables - 31 Cases

Rev. Coef. at 20 mph - (Ref. C.O.F.) - Dependant	R	S.E.
Texture (T)	0.21	0.06
Binder Content (B.C.)	0.26	0.06
Coarse Agg. Type (CAT)	0.31	0.06
Coarse Agg. Shape (CAS)	0.36	0.06

Rev. C.O.F. = 0.30+0.073(B.C.)-0.016(CAT)-0.012(CAS)-0.002(T)

Summary

Variable	Mean	2(S.D.) or Range	Constant	Range of Variables		Range in Rev. C.O.F. Due to Variables	
Rev. COF	0.60					0.30	
T	3.90	9.06	-0.002	0	22	0	-0.044
B.C.	4.95	.48	+0.073	3.99	5.91	+0.292	+0.431
CAT	0.97	0-4	-0.016	0	4	0	-0.064
CAS	2.97	1-4	-0.012	1	4	-0.012	-0.048

Table V

Regression Analysis

Surface Treatment

7 Variables - 18 Cases

Rev. Coef. at 20 mph - (Rev. C.O.F.) - Dependant	R	S.E.
Texture (T)	0.49	0.09
Coarse Agg. Shape (CAS)	0.66	0.08
Coarse Agg. Grade (CAG)	0.69	0.08
Hardness (H)	0.72	0.08
Binder Content (B.C.)	0.72	0.08
Coarse Agg. Type (CAT)	0.72	0.09

Rev. C.O.F. = 0.42+0.220(B.C.)-0.005(H)-0.012(CAG)
-0.005(CAT)-0.038(CAS)+0.0009(T)

<u>Summary</u>

Variable	Mean	2(S.D.) or Range	Constant	Range of Variables		Range in Rev. C.O.F. Due to Variables	
Rev. COF	(0.30)					0.42	
B.C.	0.248	.102	+0.220	0.146	0.350	+.032	+.077
H	26.1	7.86	-0.005	18.2	34.0	-.091	-.170
CAG	4.17	1-8	-0.012	1	8	-.012	-.096
CAT	1.72	0-5	-0.005	0	5	-.000	-.025
CAS	1.83	1-4	-0.038	1	4	-.038	-.152
T	82.6	116	+0.0009	0	299	+.000	+.269

Table VI

Regression Analysis

Surface Treatment

6 Variables - 134 Cases

		R	S.E.
Rev.	Coef. at 20 mph - (Rev. C.O.F.) - Dependant		
	Coarse Agg. Shape (CAS)	0.30	0.14
	Texture (T)	0.36	0.14
	Binder Content (B.C)	0.37	0.14
	Coarse Agg. Grade (CAG)	0.38	0.14
	Coarse Agg. Type (CAT)	0.38	0.14

Rev. C.O.F. = 0.51-0.027(B.C.)-0.008(CAG)+0.004(CAT)-0.031(CAS)+0.0002(T)

Summary

Variable	Mean	2(S.D.) or Range	Constant	Range of Variables		Range in Rev. C.O.F. Due to Variables	
Rev. COF	(0.38)					0.51	
CAS	1.77	1-4	-0.031	1	4	-0.031	-0.124
T	156	350	+0.0002	0	506	0	+0.101
B.C.	0.27	0.12	-0.027	0.15	0.39	-0.004	-0.010
CAG	3.78	1-8	-0.008	1	8	-0.008	-0.064
CAT	1.79	0-5	+0.004	0	5	0	+0.020

Table VII

Regression Analysis

Asphaltic Concrete

6 Variables - 73 Cases

	R	S.E.
Rev. Coef. at 20 mph - (Rev. C.O.F.) - Dependant		
Coarse Agg. Shape (CAS)	0.25	0.09
Texture (T)	0.26	0.09
Coarse Agg. Type (CAT)	0.27	0.09
Binder Content (B.C.)	0.27	0.10
Hardness (H)	0.27	0.10

Rev. C.O.F. = 0.47+0.003(B.C.)-0.00001(H)-0.002(CAT)-0.022(CAS)-.001(T)

Summary

Variable	Mean	2(S.D.) or Range	Constant	Range of Variables		Range in Rev. C.O.F. Due to Variables	
Rev. COF	0.43					0.47	
CAS	2.26	1-4	-0.022	1	4	-0.022	-0.088
T	35.6	110.8	-0.0001	0	146	0	-0.015
CAT	1.40	0-6	-0.002	0	6	0	-0.012
B.C.	4.88	1.04	+0.003	3.84	5.92	+0.011	+0.018
H	27.0	9.42	-0.00001	17.6	36.4	0	0

Table VIII

Regression Analysis

Asphaltic Concrete

5 Variables - 124 Cases

	R	S.E.
Rev. Coef. at 20 mph - (Rev. C.O.F.) - Dependant		
Binder Content (B.C.)	0.21	0.11
Coarse Agg. Type (CAT)	0.23	0.11
Texture (T)	0.23	0.11
Coarse Agg. Shape (CAS)	0.23	0.11

Rev. C.O.F. = 0.32+0.025(B.C.)+0.005(CAT)-0.002(CAS)-0.00004(T)

Summary

Variable	Mean	2(S.D.) or Range	Constant	Range of Variables		Range in Rev. C.O.F. Due to Variables	
Rev. COF	0.45					0.32	
B.C.	5.12	1.54	+0.025	3.58	6.66	+0.090	+0.167
CAT	1.40	0-6	+0.005	0	6	0	+0.030
T	34.4	106	-0.00004	0	140	0	-0.006
CAS	2.27	1-4	-0.002	1	4	-0.002	-0.008

equation constant for the variables was listed. To indicate the range in friction values due to a given variable, a range in values for a variable was found and each was multiplied by the constant. Therefore, the columns labeled "Range in Rev. C.O.F. Due to Variables" indicated the range in friction values that developed because of a given variable range. This range in friction values is found only in the data collected on this project, and the algebraic signs should be observed.

The Multiple Correlation Coefficient (R) for most of the regressions was small and this suggested that the data reported herein could explain only a small portion of the Revised Coefficient. The largest R value (0.72) occurred in the date reported in Table V. It was interesting to note the algebraic signs of the constants which were calculated. A positive sign indicated a higher friction value associated with a larger variable value; whereas, a negative sign denoted a lower friction value associated with a larger variable value.

The following is a summary of the findings for each of the variables found in Table V:

Variable	Sign	Explanation
Texture	+	As surface texture increased, friction increased.
CAS	-	As the coarse aggregate shape value increased, friction decreased. (Note: 1 was used for angular shapes and 4 was used for rounded shapes. Therefore, lower friction values were found with the rounded shapes.)
CAG	-	As the coarse aggregate grade increased, friction decreased, or there was a trend toward lower friction values where smaller sized aggregates were used.
Hardness	-	As the L. A. wear numbers increased, friction decreased, or the softer the aggregate, the lower the friction.
B.C.	+	As the rate of asphalt application increased, friction increased.

CAT The coarse aggregate type was coded randomly, with no indication of quality associated with the code number.

After reviewing all the regression analyses, there appeared to be inconsistancies in the results. For example, texture had a negative sign in both Portland Cement concrete and Asphaltic Concrete, but a positive sign resulted for Surface Treatments. Since the texture measurement was basically of macro (large, coarse) texture, it was thought that macro-texture was needed for Surface Treatments; but, actually, macro texture indicated an old, weathered, surface when associated with Asphaltic Concrete or Portland Cement Concrete.

In each case where hardness was dropped as a variable and the regression rerun, the R value was lowered. This could mean that the L. A. wear was a significant variable; or it could mean that the lower R value might be attributable to the fact that more data (a larger number of data) was available when the L. A. wear results were not being considered.

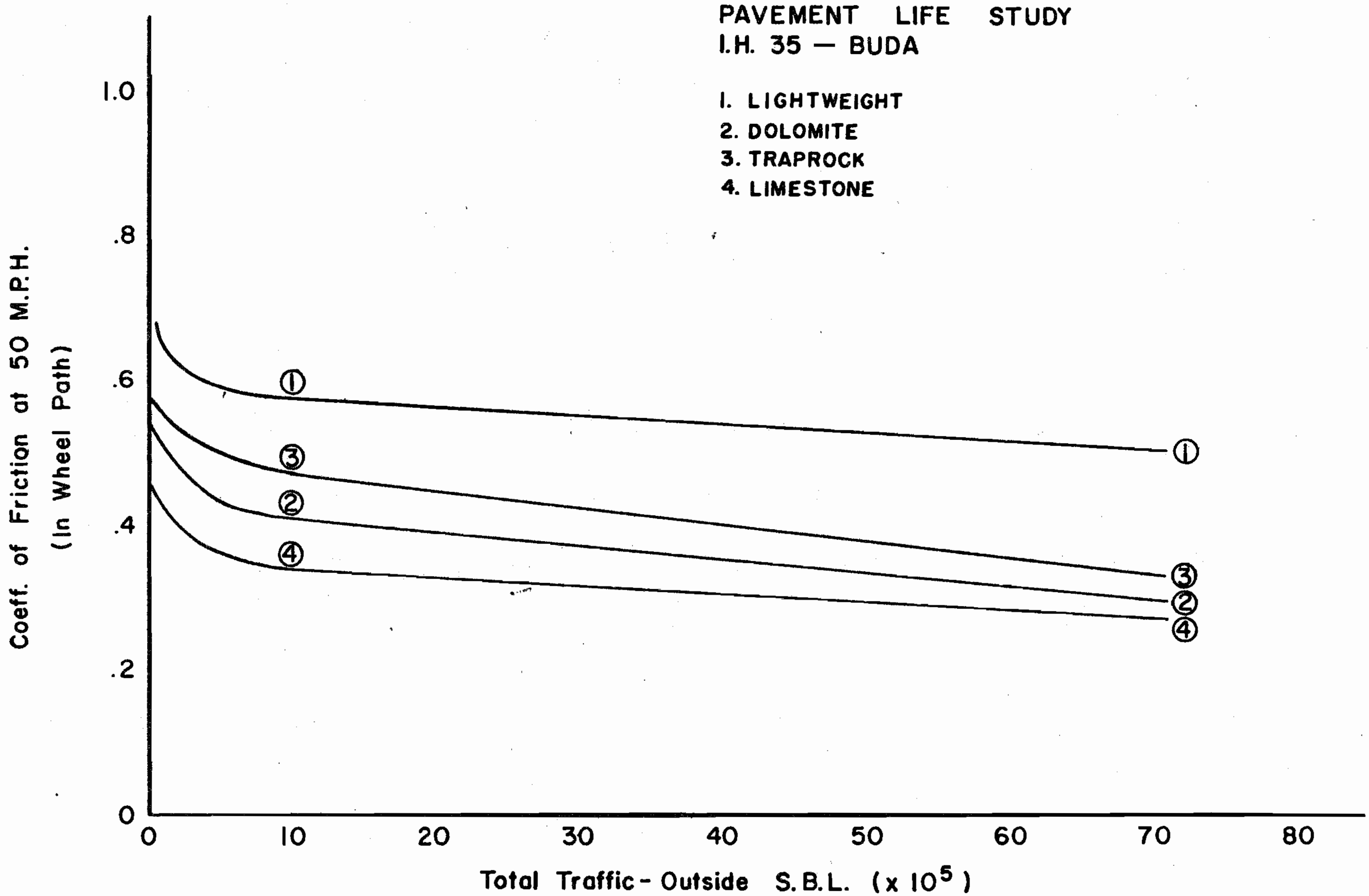
Reference is again made to the low R values found throughout the results of the regression analysis. It is suggested that the reader place little significance on the equations which were produced.

Friction Performance Test Sections

After reviewing the results obtained from this materials study it was decided to construct several test sections in which the experimental design would be more controlled. An attempt was made to hold all variables constant except aggregate type.

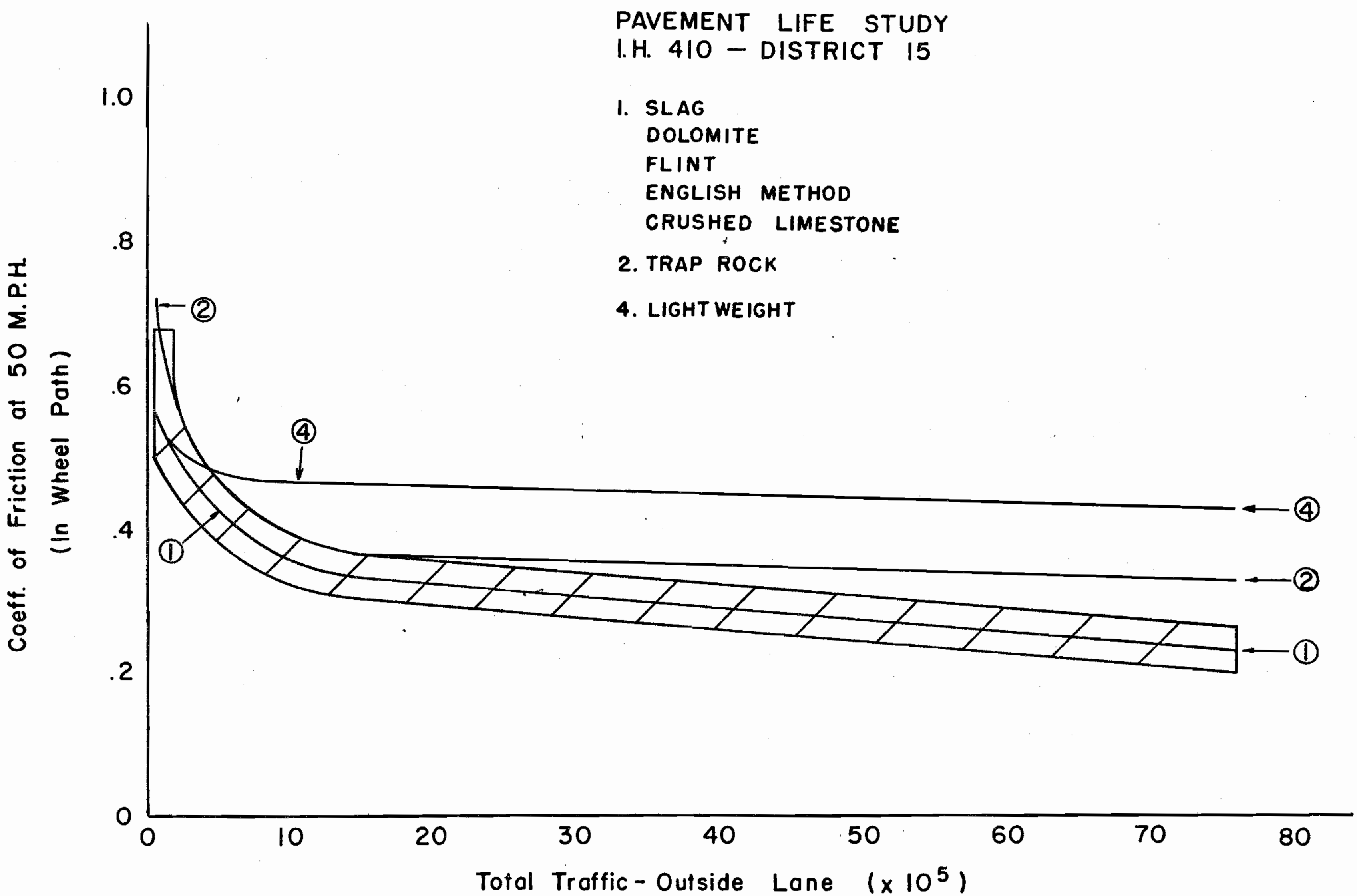
Figure 37 is a friction performance plot of four different aggregate types used in a Surface Treatment near Buda, Texas on IH-35. The sections were placed end to end between entrance and exit ramps so that traffic volumes would be the same for each section. The same aggregate grade, aggregate application rates, and asphalt application rates were used with each aggregate type.

Figure 38 is a performance plot of Hot Mixed Asphaltic Concrete which was placed on I.H. 410 in San Antonio. Again attempts were made to hold traffic,



EXPERIMENTAL SECTION — FRICTION PERFORMANCE - SURFACE TREATMENT

Figure 37



EXPERIMENTAL SECTION — FRICTION PERFORMANCE - ASPHALTIC CONCRETE

Figure 38

asphalt quantities and aggregate gradation constant. The coarse aggregate type was varied as indicated on the plot.

In the above two performance studies, four of the aggregate sources were repeated or used in both Surface Treatments and in Asphaltic Concrete. Observations of these plots indicated that the aggregate type was important to the friction performance of the pavement surface.

VI. DISCUSSION AND CONCLUSIONS

Pavement surface friction is a problem which is enormously complex. The subject is honey combed with items which cause extreme variation. Apparently, there is much interaction of known variables which, when acting in combination, dictate friction availability. The basic problem occurs at the tire-pavement interface. With a vehicle traveling along the pavement, and at any one instant in time, the factors which affect friction at this interface must be the vehicle, velocity, weather or pavement conditions and the surface texture. The Department has no control over the vehicle or weather conditions, and only small control on speed. It is believed that effort should be given to providing and maintaining texture. This is not to say that the vehicle velocities, and weather conditions should not be studied. However, the tire and texture are the factors which will provide the friction as the velocity and weather vary.

There are two other items which must be considered in the frictional components mentioned above. These are the type of friction required and the extent the available friction is used. Unknown at present, it is possible that cornering friction is different from either stopping or rolling friction. It is assumed that stopping friction relates to both acceleration and deceleration. Probably, the three types of friction are closely associated; the factors that influence one have the same influence on the other. Also, it is probable that stopping and cornering may be required simultaneously a small percent of the time.

In referring to "the extent the available friction is used", the connotation is toward wheel balance due to pavement roughness and to hydroplaning or partial hydroplaning. The study of wheel bounce, as related to friction, is rather new and confounded. There are indications, as yet unpublished, that the tire can bounce completely free of the surface (or zero friction): but in all the measurements made with the skid trailer, a zero force has never been recorded. However, it is possible that the response of the skid trailer recorder is not quick enough to record this phenomenon, or the recorder stylus might not move quickly enough to record a zero force before the tire again touches the surface. Also, the trailer tire is in a skidding mode, whereas in the above reference to wheel bounce, the tire is in a rolling mode.

A vehicle at the point of full hydroplaning does not use the available friction offered by the tire and pavement surfaces. Partial hydroplaning is used here to denote the partial separation of the tire and surface (ranging from static friction to full hydroplaning).

Presently, many agencies are studying texture as related to wet skid resistance, and meaningful information is beginning to be collected. The staggering problem in the study of texture is development of an instrument(s) which will measure both macro- and micro-textures. Attempts have been made in the project to define the properties, however these attempts were, in general, inconclusive. When equipment is developed which can adequately measure texture, the problem can be shifted to materials analysts for the development of surfacing materials to meet friction needs.

Common material properties which the highway engineer uses are pavement type, aggregate type, binder content, and type and aggregate gradation. A specific aggregate source ordinarily includes a given shape, hardness, and aggregate micro texture. Friction performance or polish depends on the same properties. Friction of Portland Cement concrete pavement apparently depends upon the finish and fine aggregate; while friction of asphaltic concretes apparently depends upon the coarse aggregate properties. Friction of Surface Treatments is developed from the aggregate; and this friction is influenced by the shelling out of the aggregate and by flushing.

Portland Cement Concretes

Figures 1 and 7, as well as the equation established in Figure 29, indicate Portland Cement concrete pavement to be the most polish resistant of the pavement types studied. However, there are several pavements of this type (some of which are not reported herein) in which the friction values are extremely low. Visual observations of the concrete pavements with low friction values indicate the surface finish has worn away completely. The plots in Figures 13, 14, 15, and 24 reveal the coarse aggregate type, shape, and hardness to be relatively unimportant. The regression analysis in Tables III and IV indicate the cement content to be one of the most important variables; however, the collected data was so arranged as to result in a negative effect in Table III and a positive effect in Table IV.

In summary, it is believed that the fine aggregate and the surface finish are important to skid resistance in Portland Cement Concrete. To provide skid resistance care should be taken to insure a good finish through finishing techniques and a lasting finish through proper cement content and a non-polishable fine aggregate. Construction problems such as excessive water migrating to the surface or a rain on the fresh surface are difficult problems to face, but some relief may be experienced through requiring a specified macro texture. It is suggested that a test requiring a non-polished fine aggregate be developed or adopted. Since the fine aggregate is the micro texture (even though relatively large for micro texture), a test to insure adequate hardness would be sufficient.

Surface Treatments

Figures 2, 8 and 30 indicate that the Surface Treatment pavement type could wear away rapidly but the data is the most scattered of the three major pavement types. Included in this scatter are pavements that have the highest initial friction values and some the lowest. Figures 16, 17 and especially 18 reveal either shape or material type to be important. Figures 19 and 37 indicate that it is possible for the material type to influence both the initial friction value and the polish rate. Little effect is found from Hardness or Aggregate Shape (Figures 25 and 26), and again no trend is found from the asphalt application rate in Figure 32 or Table I. The regression analysis in Tables V and VI indicate both coarse aggregate shape and texture to be the most important variables. If aggregate shelling or asphalt flushing could be controlled on Surface

Treatment pavements, the aggregate would remain to provide friction. It is believed that effort should be given to providing the correct aggregate properties such as aggregate type, shape and grade. A test is needed to specify aggregate with sufficient friction and polish properties, and it appears that only the larger sizes of crushed or angular shaped aggregate should be used.

Asphaltic Concretes

The wear rate for asphaltic concrete appears similar to that of Surface Treatments, as revealed in Figures 3, 9 and 31. Figures 20, 21 and 22 indicate little influence of aggregate shape on friction. It is believed that Figures 23 and 38 indicate the coarse aggregate type to be important in the initial friction values and in subsequent friction performance. Little can be determined from the amount of asphalt used in the mix in the ranges reported in Table I; however, it is apparent that the larger asphalt contents do not reduce the friction availability. The plots in Figures 27 and 28 reveal little information as to aggregate hardness. Of the three pavement types, asphaltic concretes are believed to be the most confounded. No consistent trends are available, even in the regression analyses reported on Tables VII and VIII.

It is postulated that the micro texture must be of great importance in this pavement type; and the micro texture is probably derived from both the coarse aggregate and from the fine aggregate in the surrounding matrix. After a period of abrasion by the traffic, the coarse aggregate protrudes. When this protrusion occurs, the coarse aggregate must provide most of the friction to the tire.

In this project, there has been opportunity to collect information on many of the producers of the aggregate which was used in the test sections. Therefore, performance plots of individual aggregate pits have been studied. Pavement surfaces have been found in which material from the same source, with the same gradation, and with the same asphalt content have been used in different areas of the state; and a wide variance in friction performance is evident. It is recognized that the method of obtaining traffic applications used in this analysis (for comparing the sections), is not flawless, however, it is still evident that other unmeasured variables are (1) pavement weathering and (2) differences in construction. Since large differences in friction are also found in the initial construction, it is further believed that construction methods are very important in providing friction availability. The evidence presented above for asphaltic concretes appears pertinent to Surface Treatments and, to a small degree, for Portland Cement concrete pavements.

It is believed that a test to insure a non polishable coarse aggregate is needed for asphaltic concrete pavements. And it is believed that a test for hardness or polishability of fine aggregate is also needed. In addition, texture should be specified or insured by construction procedures.

IMPLEMENTATION

The implementation described in this chapter concerns the research project as a whole. It does not concern, exclusively, the relationship between materials and skid resistance contained in the previous chapters. Implementation can concievably take many forms, and it is believed that a remarkable form of implementation resulted from this project. Researchers define implementation as the use of information developed from research. Long before this project was completed Departmental personnel were using the equipment and the information collected. The Districts, Divisions, and Administration have all demonstrated great interest. This is the most beneficial of all forms of implementation.

Statewide Plan of Maintenance Operations

In May 1968, the fabrication, debugging, and correlation of three skid test trailers was completed. The three test units (maintenance units) were patterned after (and closely resembled) the original research unit. The major difference between the maintenance units and the research unit occurred in the friction force transducer. The force transducer in the maintenance trailers consisted of a Linear Variable Differential Transformer which measured the deflection of a Drag Link, and the Research Trailer used strain gages to measure the strain differential occurring in the Drag Link.

Trailer Correlation

After reviewing the correlation studies by other agencies, a unique opportunity was made available to correlate three duplicate trailers and a fourth (the original research trailer). The results of the development and original correlation are reported in Departmental Report SS 11.2.[7] Basically, it was found that there were differences in all four trailers; but each trailer correlated with the other. It should be stated that only minor differences occurred between the three duplicate trailers. It was decided that each of the three maintenance units would be correlated to the research unit at periodic intervals. This meant that all results in the state would be reported in terms of the research unit; therefore, (1) prior tests would not be lost or confused and (2) future tests would be reported in common terms. The periodic correlation would (1) insure accurate information, (2) establish variance trends with time and/or slosh equipment wear or depreciation, (3) provide a method whereby equipment operators and management could discuss difficulties, gain new insights, interchange ideas, and (4) provide a method whereby modifications or major repairs could be performed. The friction force correlation resulted in three linear equations which were established by a least squares curve fit computer program. These equations were used in the Maintenance Operations Computer Program explained below. At the present time the trailers have been correlated three times and the results of the correlations are found in Departmental Reports SS 11.2, SS 11.3 and SS 11.8.[7,8,9]

Design of the Reporting System

The reporting system is basically a modified manual, information collection and retrieval system. A small attempt has been made to perform the necessary "follow-up" research. Hopefully, it has been so designed that future automation may be accomplished without great difficulty.

Responsibilities of Information and Dissemination

It was decided that the Maintenance Operation Division (File D-18) would provide the general direction of the operation of the trailers. The trailers were stationed in District 5 (Lubbock), District 10 (Tyler) and District 15 (San Antonio). The daily direction was provided by each of the above three Districts. The three Districts are located in different areas of the state and were selected because of the central location with respect to the Districts in a given area.

Method of Testing and Reporting

No direction was given to the Districts as to the number of frequency of periodic tests other than a request that the District use the equipment during the initial testing period. The following procedure was suggested:

1. The District desiring skid resistance work contacts the appropriate District in which a skid trailer is based.
2. The trailer and operator are sent to the requesting District.
3. The District Observer (having been previously orientated as to the desired test locations) and the Operator test the desired locations.
4. The District Observer prepares the skid resistance information for submission to the Division of Automation (File D-19).
5. The Division of Automation processes the skid data and forwards a copy to the maintenance operations Division, the requesting District, and the Design Division (File D-8).
6. The Maintenance Operation Division maintains a statewide file as an assist in maintenance operation; particularly those operations between File D-18 and the District.
7. The Design Division maintains a state-wide file in assistance to plan preparation, particularly between File D-8 and the District.

As a matter of benefit to Departmental administrators (both Division and District) and as an effort toward follow-up research, a yearly report is prepared. The report contains general summary statistics and information related to materials' properties. Report content consists of plots and tables prepared by the Departmental IBM 360 Computer in which the added cost (in addition to obtaining the basic information) is two cards for each section tested (automatically punched by the computer), approximately $200 for computer and programmer time, about 24 man hours in report preparation, and the cost of reproduction-distribution. Presently, two Departmental Reports, SS 11.4 and SS 11.5, have been prepared and forwarded to Departmental personnel.[10,11]

Information To Be Collected

The design for the information collection system is a composite of (1) the pursuance of available reports and letters, (2) experience in data collection contained in this report, and (3) a study of the Districts' data collection and storage systems. (Prior to this implementation event, many Districts had developed various small studies pertinent to "that" District.) A decision was made to collect the following information:

1. District Number
2. County Name
3. Highway Number
4. Date of Test
5. Speed of Test (40 mph, left wheel, and standard trailer watering were suggested)
6. Temperature of the Time of Test
7. Number of Days without Rain (for road film corrections)
8. Yearly-Average Daily Traffic
9. Pavement Type
10. Date of Last Surfacing
11. Coarse Aggregate Type
12. Binder Content
13. Grade (or Size) of Aggregate
14. Equipment Number (Used by the computer program in conjunction with the correlation equations mentioned previously to obtain equivalent trailer output.)
15. Coarse Aggregate (Pit) Source
16. Asphalt or Cement Source
17. Fine Aggregate Source (used with pavements other than surface treatments)
18. General Description of Test Location
19. Description and Odometer Reading of actual beginning location of test.
20. Test Number, Friction Force Value, Comments, and Odometer Reading

(Item 20 is repeated for each individual skid)

The output sheets which are sent to the requesting District, File D-18, and File D-8, contain a print out of the above information where the coefficient of friction (or SN) has been calculated, corrected for road film and/or temperature, and correlated to the research trailer. Also cumulative mileage from the beginning (of test) location for each skid is calculated based on the odometer reading. It should be noted that items 6, 7, 8, 9, 10, 11, 12, 13, 15, 16, and 17 are completed (coded on the input sheet) only at the discretion of the District Observer. The manual for coding the skid resistance data is available to the District, upon request, from File D-8.[12]

Training

Upon completion of the fabrication of the trailers two training sessions were held. The first session consisted of the orientation of the trailer Operators. This orientation contained a study of the calibration and operation of the trailer as well as the repair and maintenance of the equipment.

The second session concerned the training of the District Observers. The Observers were previously selected by the Districts upon request from the Maintenance Operation Division. The Observer training consisted of a review of the "state of the art" in the nation-wide effort in the study of skid resistance, a review of the coding methods and code sheet, and a review of the CONTSKID computer program. During the training period each Observer rode with the Operator in actual operating conditions, collected the raw skid resistance data, and prepared the information for submission to the Division of Automation for processing. The results were returned to the respective Districts.

APPENDIX

SKID RESISTANCE DATA

Phase I

L.A. ABRASION — 1 2 3 4

CONTROL — 5 6 7

SECTION — 8 9

JOB — 10 11

HIGHWAY NUMBER — 12 13 14 15

COUNTY — 16 17 18

MONTHS OF PLACEMENT — 19 20 21

DATE OF TEST — 22 23 24 25 26 27

TOTAL VEH. APPLICATIONS — 28 29 30 31 32

REGIONAL CODE — 33

EQUIV.18 KIP AXLES PER MONTH — 34 35 36 37 38

PAVEMENT TYPE — 39

C.A. TYPE — 40

C.A. SHAPE — 41

F.A. TYPE — 42

F.A. SHAPE — 43

ASPH. OR CEMENT CONTENT — 44 45

GRADING OF AGGREGATE — 46 47

TYPE OF SECTION — 48

MAG. OF RAIN — 49

DAYS TO LAST RAIN — 50 51 52

WEATHER — 53

SURFACE TEMP. — 54 55 56

BLEEDING — 57

TEXTURE — 58 59 60

DISTRICT — 61 62

ACCIDENT RATE F & I — 63 64 65 66

ACCIDENT RATE TOTAL — 67 68 69 70

No. of Test	Wheel Locking Condition (71)	Lane (72)	Speed (73-74)		Force Of Frict. (75-76-77)			Speed & Lat. Place. (78)

Comments:

SKID RESISTANCE DATA

Phase I

L. A. Abrasion (Columns 1, 2, 3, & 4):

L. A. Wear value is inserted in the first three columns with an assumed decimal between columns 2 and 3. The material grade is coded as follows: 1-A, 2-B, 3-C, 4-D, 5-S.

Control (Columns 5, 6, & 7) :

Contract job control number.

Section (Columns 8 & 9) :

Contract section number.

Job (Columns 10 & 11) :

This is the job number which T.T.I. has assigned.

Highway No. (Columns 12, 13, 14, & 15) :

This is the highway number assigned by the state, such as, FM 2222. "2222" would be the numbers to use.

County (Columns 16, 17 & 18) :

This is the county number. For example, Gregg County would be "093".

Months of Placement (Columns 19, 20, & 21) :

This is the number of months since construction or since last overlay.

Date of Test (Columns 22, 23, 24, 25, 26, & 27) :

This is the data of testing, i.e. March 13, 1964, would be 031364.

Total Vehicle Application (Columns 28, 29, 30, 31 & 32) :

The total vehicle passages is inserted in these columns. The values should be divided by 1000 before entry.

Regional Code (Column 33) :

This is a code where:

1 - Eastern region
2 - Central region
3 - Western region

Equivalent 18 Kip Axles Per Month (Columns 34, 35, 36, 37 & 38) :

This is the equivalent number of 18 kip axles on a given roadway per month.

Pavement Type (Column 39) :

This is a code where:

1 - Continuously reinforced rigid
2 - Surface treatment
3 - HMAC
4 - LRAC
5 - HMCAC
6 - Jointed rigid
7 - Slurry

Coarse Aggregate Type (Column 40) :

This is a code where:

0 - Limestone and Siliceous
1 - Siliceous
2 - Limestone
3 - Shell
4 - Lightweight
5 - Iron ore
6 - Trap rock
7 - Limestone Rock Asphalt

Coarse Aggregate Shape (Column 41) :

This is a code where:

1 - Angular
2 - Subangular
3 - Subrounded
4 - Rounded

Fine Aggregate Type (Column 42) :

This is a code where:

0 - Limestone and Siliceous
1 - Siliceous
2 - Limestone
3 - Shell
4 - Lightweight
5 - Iron ore
6 - Trap rock
7 - Limestone Rock Asphalt

Fine Aggregate Shape (Column 43) :

This is a code where:

1 - Angular
2 - Subangular
3 - Subrounded
4 - Rounded

Asphalt or Cement Content (Columns 44 & 45) :

The actual asphalt content will be inserted here. For example:

45 for HMAC, LRAC, or HMCAC - 4.5%
25 for seal and surface treatment - .25 gal/SY
40 for rigid - 4.0 sacks/CY

Grading of Aggregate (Columns 46 & 47) :

This is a code where:

1 - Grade 1
2 - Grade 2
3 - Grade 3
4 - Grade 4
5 - Grade 5
6 - Grade 6
7 - Grade 7
8 - Grade 8
9 - Type A, Hot Mix
10 - Type B, Hot Mix
11 - Type C, Hot Mix
12 - Type D, HMAC
13 - Type E, HMAC
14 - Type F, HMAC
15 - Type AA, HMCAC
16 - Type BB, HMCAC
17 - Type CC, HMCAC
18 - Type DD, HMCAC
19 - Type DDD, HMCAC
20 - Type FF, HMCAC
21 - Type FFF, HMCAC

Type of Section (Column 48) :

This is a code where:

1 - Depressed
2 - Hill
3 - Elevated

Magnitude of Rain (Column 49) :

This is a code where:

1 - 0.05 inch or less
2 - 0.05 to 0.10 inch
3 - 0.10 to 0.30 inch
4 - 0.30 to 0.5 inch
5 - 0.5 to 0.8 inch
6 - 0.8 to 1.5 inches
7 - 0.5 to 2.0 inches
8 - 2.0 to 5.0 inches
9 - 5.0 or over

Days to Last Rain (Columns 50, 51, & 52) :

The number of days since the last rain will be inserted here. This should always be filled in; if it is raining or not. If raining, 000 will be inserted.

Weather (Column 53) :

This is a code where:

1 - Dry
2 - Raining
3 - Misting
4 - Ice
5 - Snow

Surface Temperature (Columns 54, 55, & 56) :

The actual temperature will be inserted here, such as 097 F.

Bleeding (Column 57) :

This is a code where:

1 - Yes - No aggregate showing in wheel path or asphalt covering all aggregate-surface is generally smooth.
2 - Intermediate-Surface looks dark but aggregate is protruding. Asphalt has covered aggregate partially.
3 - No- The surface in the wheel path is the same color as out of wheel path. The asphalt has not covered the rock. Aggregate is generally protruding above the asphalt.

Texture (Columns 58, 59, & 60) :

The texture value will be inserted in these columns.

District Number (Columns 61 & 62) :

The District number is inserted in these columns. For example the Corpus Christi District would be coded 16.

Accident Rate F & I (Columns 63, 64, 65, & 66) :

This is the Fatal and Injury accident rate. In general it is a ratio of the accidents occurring on a given road per 100 million vehicle miles travelled. Obtained from "Highway Traffic Accident Tabulation and Rates by Control and Section".

Accident Rate Total (Columns 67, 68, 69 & 70) :

This is the total accident rate. It is the same as columns 63 through 66 above except total accidents are used in place of the Fatal and Injury accidents.

Wheel Locking Condition (Column 71) :

This is a code where:

1 - Left
2 - Right
3 - Both

Lane (Column 72) :

This is a code where:

1 - First lane from outside (right).
2 - Second lane from outside (right).
3 - Etc.

Speed (Columns 73 and 74) :

The actual speed of the truck will be entered here as 41 MPH.

Force of Friction (Columns 75, 76 & 77) :

This is the actual force measured by the trailer and registered on the recorder, such as - 739 = 739#.

Speed & Lat. Placement (Column 78) :

This is a code where:

1 - A 20 MPH test ran in the wheel path.
2 - A 50 MPH test ran in the wheel path.
3 - A 20 MPH test ran out of the wheel path.

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