AN EVALUATION OF THE ARIZONA LABORATORY FRICTION TESTER

by

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A Thesis Submitted to the Faculty of the

DEPARTMENT OF CIVIL ENGINEERING

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

in the Graduate College

THE UNIVERSITY OF ARIZONA

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ACKNOWLEDGMENTS

The author wishes to express his gratitude to Dr. R. A. Jimenez for his assistance and guidance in the preparation and writing of this thesis.

TABLE OF CONTENTS

TABLE OF CONTENTS--Continued

LIST OF ILLUSTRATIONS

LIST OF TABLES

ABSTRACT

An evaluation of the Arizona Laboratory Friction Tester as a friction detection device was achieved as the result of a two-part investigation. In the first phase of the study, the practical significance of the laboratory tester was determined by the use of a statistical model analysis. In the second part, a correlation study was conducted between the laboratory tester and the stopping-distance method.

A model of three-way classification with interaction was selected for the statistical experiment. The variables of imposed pressure, rotational speed of the testing head, surface treatment, and their subsequent interactions were evaluated for their significance in developing friction.

Pressure was noted to be the eminent factor in developing friction. Surface treatment and speed were shown to be only minor influences in affecting friction.

On the basis of the data collected, the correlation study between the laboratory and stopping-distance methods showed that no relationship existed between the methods.

It was concluded that several improvements to the tester had to be made before it could assume a role of practical significance.

CHAPTER 1

INTRODUCTION

The tractional stability of skidding automobiles has long been a problem of the highway engineer. Though research has unveiled several concepts to friction measurement, certain limitations have curtailed significant advancements. Economic feasibility and automobile testing hazards serve as typical limitations. In order to eliminate such restrictions, friction testing devices have been designed to test pavement sections in the laboratory.

The pavement surfaces tested are usually actual specimens taken from selected pavement sites. The small size of the testing samples facilitates handling and interchanging of specimens, thus valuable time and money is saved through greater efficiency. Specimens can also easily be made to test proposed roadway surfacings, and thus relate the various frictional characteristics of projected roadway surfaces before actual construction.

The laboratory tester provides not only readily accessible data but also visual verification of the mechanism of friction. Greater understanding and "feel" for the mechanics of friction are more easily developed. This first hand observation of the phenomena of friction thus offers a better insight into the theory behind it.

Research Objectives

In order to understand the importance of the laboratory tester, a critical evaluation of the mechanical capabilities of the machine and the theoretical significance of the data must be made. Such an evaluation was made of the Arizona Laboratory Friction Tester and is the basis for this thesis.

The analysis focused on two primary objectives. The first was to analyze statistically the effectiveness of the tester, in other words, to determine whether the test results were of any true significance. Testing limitations, both operational and theoretical, were investigated and taken into account.

The second objective was to determine whether any correlation existed between the friction coeficients obtained by the laboratory method and those by the stopping-distance method. Cores were taken from selected test sites where automobile skid tests had previously been made in order to establish the basis for comparison between the two methods. The results obtained were not only informative but interesting.

To properly extrapolate and evaluate the results obtained, an understanding of certain principles basic to the theory of friction is necessary. These principles are presented in abbreviated form on the following pages.

Basic Laws of Friction

Investigation into the existence and effects of friction as a physical phenomena dates back well into the 1500's. Rizenbergs and Ward (16) report that Leonardo Da Vinci's discovery of the apparent direct

proportional relationship between the friction force and the applied normal force was essentially the beginning of the study of friction. They also reported that subsequent study by Coulomb and Morin in 1781 led to the following classical laws of dry friction. In brief these laws may be stated as follows:

1. The coefficient of friction is independent of the apparent contact area and the load.
2. The static coefficient of friction is greater than the kinetic coefficient of friction.
3. The kinetic coefficient of friction is independent of velocity.

Investigations by Kummer and Meyer (9) have shown that the coefficient of rubber friction depends on normal pressure (load and contact area), velocity, and temperature. They also indicated that the highest friction coefficient value was not a static value but one measured by low skidding velocities of 0.1 to 5.0 inches per second.

Mechanism of Friction

The classical laws are the basis for the testing approaches but can not explain the actual mechanism of friction. Rizenbergs and Ward (16) regard friction phenomenalistically--meaning it can be observed but not explained. Since the reasons or explanations for this phenomenon are not known, other physical laws, such as that of conservation of energy, are used to fill in the gap left by uncertainty to arrive at possible conclusions. Certain pertinent facts with regard to static and sliding friction have been established.

Static friction is felt to be the result of the interlocking of surface asperities, while sliding friction depends on the inherent shear-resistence of the materials and is a function of the interfacial pressures and bearing areas. Adhesion, was considered a mechanism, whereas, fluid lubrication was considered as an anti-mechanism.

Coefficient of Friction Equations

The primary assumption upon which the frictional coefficient equation is based is that Coulomb's law ($F = fN$) is valid. The proportionality constant "f", however, applies only to dry surfaces, low speeds, and low contact pressures when it is used in reference to automobile skid testing.

From the work-energy principle, the resultant force (F_r) for a skidding body is:

$$F_r = M(V_i^2 - V_f^2)/2S \qquad [1]$$

where F_r = Resultant friction force

M = Mass of skidding body

S = Skid distance in ft.

V_i = Initial velocity in ft./sec.

V_f = Final velocity in ft./sec.

Since the weight (W) of the skidding body or vehicle is actually the normal force, Coulomb's equation ($F = fN$) can also be written as follows:

$$F = fW \qquad [2]$$

By equating equations [1] and [2], equation [3] results:

$$fw = \frac{M}{2S}(V_i^2 - V_f^2) \qquad [3]$$

Substituting (W/g) in place of M, equation [3] becomes:

$$fW = W\,(V_i^2 - V_f^2)/2Sg \qquad [4]$$

Changing velocities from ft/sec to mph, and g into 32 ft/sec^2 equation [4] becomes:

$$f = \frac{(V_i^2 - V_f^2)}{30S} \quad \text{and if } V_f = 0, \text{ then} \qquad [5]$$

$$f = \frac{(V_i^2)}{30S} \qquad [5a]$$

If S, the skid distance in ft., were calculated on the basis of the average speed during the skid time, then S could be written as follows:

$$S = \frac{(V_i - V_f)(t_i - t_f)}{2} \qquad [6]$$

where V_i = Initial velocity in ft/sec

V_f = Final velocity in ft/sec

t_i = Time at the beginning of skid test in sec

t_f = Time at the end of skid test in sec

Substituting equation [6] into equation [4] yields:

$$f = \frac{(V_i - V_f)(V_i + V_f)}{(1/2)(2g)(V_i + V_f)(t_i - t_f)} \quad \text{or} \quad f = \frac{V_i - V_f}{g(t_i - t_f)} \qquad [7]$$

Changing velocities from ft/sec into mph and g into 32 ft/sec^2, equation [7] becomes:

$$f = \frac{0.0456\ (V_i - V_f}{(t_i - t_f)} \qquad [8]$$

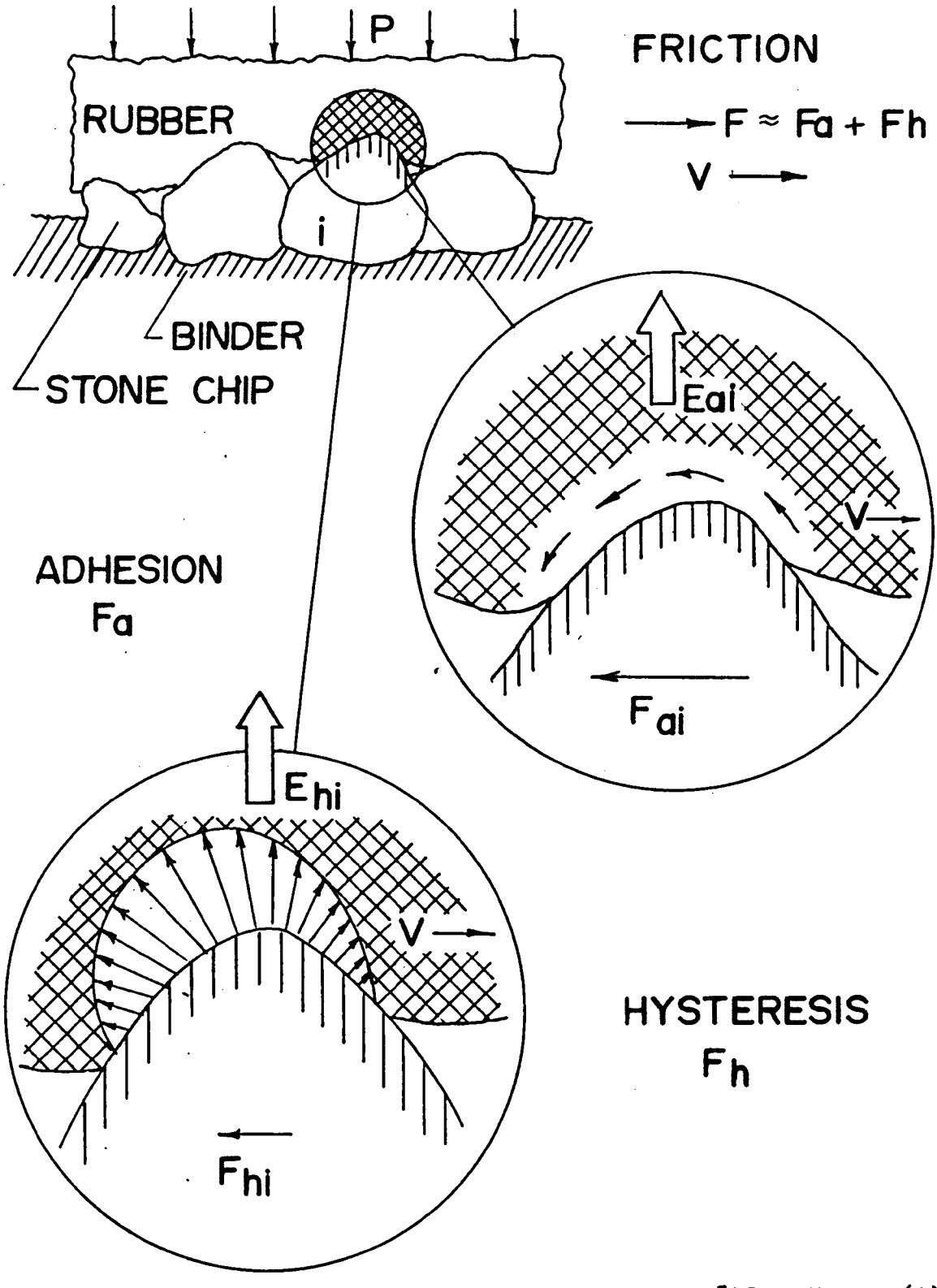
Skid Resistance

The frictional resistance offered by the pavement surface to the skidding tires is called "Skid Resistance." Kummer and Meyer (8), by means of a uniformly loaded rubber block (simulated tire tread), analyzed the principal friction components of skid resistance and relegated them to two major sources. Kummer related that the friction force (F) was the sum of the adhesion force (Fa) and the hysteresis force (Fh), (Figure 1). The adhesion component was considered to be the product of the interface shear stress and the actual contact area (Ai) of the rubber with a single mineral particle; thus for N particles:

$$Fa = S \sum_{1}^{N} Ai = SA$$

where A = actual contact area. The hysteresis component was believed to be caused by damping losses within the rubber while the rubber flows over and around the particle. Tabor (20) was principally responsible for developing the hysteresis analysis component with a two step method. He first integrated the pressure over the affected area and then resolved the resulting force into a vertical and horizontal component which opposed the sliding action. Thus:

$$Fh = \frac{(1)}{(B)} \sum_{1}^{N} Eh_i = \frac{(1)}{(B)} Eh$$



[After Kummer (8)]

Figure 1. The Two Principal Components of Rubber Friction: Adhesion and Hysteresis

where Eh = actual energy dissipated within the rubber due to deformation produced by N particles.

The above analysis offers a logical explanation of the "mechanism" of friction in the case of tire and pavement contact. It also has been found, however, through tests and theoretical considerations that the ultimate friction (coefficient) generated is either directly or indirectly affected by other influencing factors.

Factors Influencing the Coefficient of Friction

Regardless as to which method of friction determination is used in testing, certain basic factors have been found to contribute to the generation of friction. Though these factors are produced differently in the various methods, their effects should generally yield somewhat consistent results with only variation in emphasis. Consequently, if a laboratory tester is to prove itself and simulate tire-pavement friction conditions, it should show correlation with past skid test findings.

Although these factors have been analyzed primarily on skid test results, they are actually general in nature. They represent not only expected results of the skid test method, but every other method as well. For this reason as well as for the sake of clarity, the influencing factors of friction are presented from the viewpoint of skid test findings. A similar presentation will be offered in Chapter 3 showing how the laboratory friction test results parallel the skid test findings. In this way, the role of the mechanical aspects of the laboratory tester can be brought to light.

For the simplicity of discussion these influencing factors have been divided by Tomita (21) into three general categories: (1) Vehicle or Machine Operation Factors, (2) Tire Factors, and (3) Pavement Factors. Included in each category is a subsequent breakdown of pertinent contributing effects.

Vehicle or Machine Operation Factors

A. Speed. According to Moyer (13) and Mecer (11) speed has little effect on friction in the case of dry pavements. This however, was not the case for wet pavements. Values of friction were substantially affected by the degree of pavement wetness. Friction coefficients decreased rapidly with a corresponding increase in speed.

Tire Factors

A. Tread Design. The 1959 Sub-committee on tire factors to the first International Skid Prevention Conference (6) reported that the friction coefficient decreased on dry pavement with an increase in the number of ribs or grooves on the tires. Consequently, bald or non-grooved tires gave the highest friction indication. Conversely, however, for wet pavement the grooves provided vents through which the water at the tire-pavement interface could escape under the pressure between the two, thus causing an increase in the friction developed.

B. Tread Composition. Studies conducted by Reinhart (15) indicated that the friction coefficient was only one of a number of essential service characteristics affecting tread composition. Abrasion resistance, weather and ozone resistance, hysteresis and heat build-up,

cornering noise, and steering ability were also cited as necessary for design consideration.

C. Inflation. Hofelt (6) reported that for a constant load, changes in inflation pressure caused corresponding changes in the contact area, thus directly affecting the friction coefficient. Essentially, then, high inflation pressures gave lower friction values, while lower pressures gave higher friction values. Batterson (1), however, felt that this relationship was the result of the differences in temperature of the contact region. He inferred that as the inflation pressure increased, the contact area decreased, thus allowing the heat generated during skidding to be distributed over a smaller contact area. Consequently, the well heated rubber, molten in some cases, would naturally exhibit lower friction coefficients. The reverse of the above situation, the low inflation case, held true by developing a higher friction coefficient.

Regardless as to which theory is correct or the combination which is more likely, it can still generally be said that for a constant load, high inflation pressures yield lower friction values, with the reverse true for the case of low inflation pressures.

D. Vertical Load. Hofelt (6) concluded from the results of stopping - distance tests of automobiles and commercial vehicles that the vehicles showed higher friction coefficients when unloaded than when loaded. He did feel, however, that brake efficiencies were effected by the added load, so brakes in this respect had to be considered also as contributing effects.

E. Temperature. Hample (5) indicated that from the results of tests the apparent friction coefficient decreased with an increase in temperature.

Pavement Factors

A. Types of Pavement. White and Thompson (24) measured the dry and wet friction coefficients of all the major types of highway surfaces in Mississippi by the stopping distance method. Tests were conducted at two hundred project sites and two thousand skid measurements taken. In only twenty-eight of the two hundred projects were coefficients of less than 0.4 found for the wet condition. And at the twenty-eight sites tested, where friction values proved inadequate, the predominate surface condition of the pavement was an excess of bitumen or polished aggregates.

With regard to gradation, Moyer (13) reported that for roadways constructed with dense-graded sand, the friction coefficients were consistently lower than those for surfaces with coarse crushed aggregate. Conversely, however, Virginia test results showed that fine grained, dense-graded Kentucky-rock asphalt gave higher friction coefficients for all types of surfaces.

B. Aggregates and Pavement Surface Texture.

1. Aggregate Size - On the basis of test results of Michael and Gruman (12), the effect of size has not been felt to appear to be a governing factor in producing high friction coefficients.

2. Aggregate Shape - Shupe and Goetz (17) showed angular aggregates gave higher friction values than rounded aggregates.

   White and Thompson (24) also showed that in their workings with sealcoats, that the more the crushed aggregate the greater the friction value.

3. Aggregate Hardness - Finney and Brown (3) demonstrated that the harder to polish stones, or the harder stones on Moh's hardness scale, gave the higher friction value.

4. Pavement Surface Texture - Test results by Moyer (13) showed that higher friction coefficients were attained on dense-graded asphalt surfaces rather than on coarse, open-graded asphalt surfaces for the dry test runs. The higher friction coefficients were due essentially to the increased contact area for the dense-graded surface.

   In the wet pavement tests, however, the coarse, open-graded, angular aggregates gave higher friction values than the dense-graded surface. The reversed results were thus felt to be due to the fact that the increased voids provided better drainage thus allowing for increased contact area and consequently increased friction.

Though all these factors are of significance, their importance varies according to the method of friction evaluation used. A brief review of some of the principal field and laboratory methods of the past are presented in Chapter 2.

CHAPTER 2

PREVIOUS FRICTION MEASURING DEVICES

The problem of skid resistence has generally been attacked from both field and laboratory angles. Regardless as to whether the approach has been either field or laboratory, accuracy and feasibility served as the desired objectives. The following paragraphs relate the basic theory behind each of the methods, and discuss the comparative values associated with each.

Field Testing Method

In a report for the United States Naval Civil Engineering Laboratory (USNCEL) Tomita (21) classified field devices into three basic methods: (1) The Stopping Distance Method, (2) Deceleration Method, and (3) Trailer or Friction Cart Method. These methods are outlined below.

Stopping Distance Method

Basically this method was quite simple. The testing vehicle was an automobile which acted as a free body. At a predetermined rate of speed the brakes were applied to lock the wheels and the stopping distance measured from the point of application to the point where the vehicle comes to a halt. In the case of a wet-surface test, a water truck sprayed on the specified amount of water just prior to testing in order to insure relative consistency. Referring to equation [5a] in

Chapter 1 the coefficient of friction could then be determined as such

$$f = \frac{V^2}{30S} \qquad [5a]$$

where

S = the average stopping distance in feet

V = initial speed in mph at application of brakes

f = average coefficient of friction

Essentially all tests were run on grades of practically zero. Occasionally, when locations of this sort could not be found, tests were made on grades and a correction was made to account for the grade effects. Where the grade was significant, the following modified formula used by Nickols, Dillard, and Alwood (14) was

$$f \pm \frac{\text{Percent Grade}}{100} = \frac{V^2}{30S}$$

The plus or minus was determined by whether the tests were made upgrade (negative) or downgrade (positive).

According to Tomita (21) some of the primary advantages and disadvantages associated with this method are as follows:

Advantages:

1. This method is quite realistic in evaluating friction coefficients between pavement and tires.
2. The results obtained are more consistent than those of the Trailer Method.

Disadvantages:

1. With the replacement of testing vehicles it is difficult to compare old and new test data.
2. Tests are more time consuming and costly than the Trailer Method.
3. Grades and curves affect testing locations.
4. Tests require water truck and special traffic control devices.

Deceleration Method

Decelerometers, when used in conjunction with the stopping - distance method, are mounted on the floor of the auto and are used to measure friction coefficients. Originally designed for testing brakes, the Tapley Decelerometer has fast become the most popular. Used by Dillard (2), Marshall and Gartner (10), and others the decelerometer functioned on the principle of a damped pendulum which swung forward in an arc from its normally level position. The angle of arc produced was proportional to the rate of deceleration. The ratio of the rate of deceleration at any given speed in the test to the deceleration of gravity was the friction coefficient.

Some of the basic advantages and disadvantages cited by Tomita's report are:

Advantages:

1. The method itself is quite simple.
2. More consistent results are obtained than in the Trailer Method.

3. A decelerometer can easily be added in the stopping - distance method.

Disadvantages:

1. Since the decelerometer is mounted in the vehicle tester in stopping - distance method, the disadvantages will be the same for both.

A number of other significant limitations were also discovered and brought to light. Nickolas, Dillard, and Alwood (14) reported that, at below 25 mph, as the deceleration rate increased the dial readings gradually increased, while between 25 mph and 40 mph, constant readings were obtained. Also, in 1962, Dillard pointed out that the "dive" of the test vehicle upon braking was a potential source of error. He felt the "dive" meant the pendulum could not be perpendicular to the vehicle, thus the actual deceleration would be less than the apparent deceleration by the amount of the angle of the "dive" of the vehicle.

Trailer or Friction Cart Method

In this method the testing equipment consisted mainly of a towing vehicle, usually a truck, and a trailer or cart. The trailer was towed with locked wheels over the pavement surface. The braking force or pull on the draw-bar was then measured by a dynamometer. This value, when divided by the vertical load on the wheels, gave the friction coefficient.

In calibrating the trailer, Skeels (19) pointed out that the weight transfer from the trailer wheels to the truck hitch (caused by the application of brakes to the trailer wheels) must be considered. In analysing this problem he explained that when the braking torque developed,

it applied a downward pressure on the truck hitch. With the weight of the trailer constant, this downward force would then cause a decrease in the effective load on the wheels. A graphical illustration and derivation of the friction coefficient analysis is presented in Figure 2.

Some of the notable advantages and disadvantages as seen by Tomita are as follows:

Advantages:

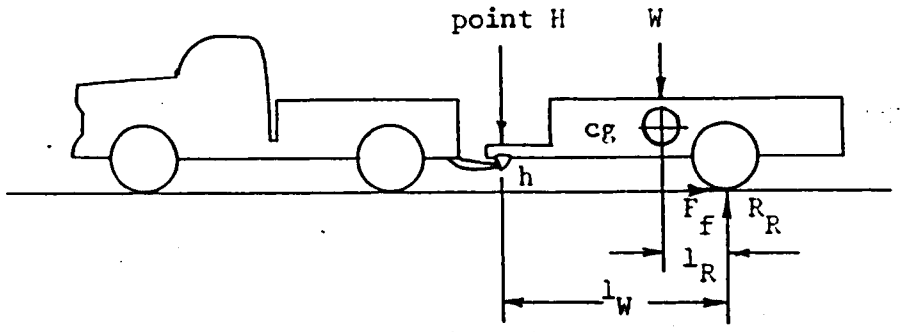
1. Tests can be made quickly with minimum traffic interference.
2. Tests can be made on entire sections at relatively low cost.
3. There is little danger involved in the testing procedure.
4. No auxiliary water truck is needed for testing.

Disadvantages:

1. Heavy sidesway on some trailers affect results.
2. High initial cost is incurred.

Laboratory Testing Devices

Laboratory testers have essentially approached the problem of skid resistance from either of two directions. They have either simulated the desired tire-pavement interaction or actually produced the wanted effect. In a laboratory method by Whitehurst and Goodwin (23), an actual automobile tire was used to develop the tire-pavement interaction. Shupe and Goetz (18) created the simulated version by means of a rubber shoe or disk representing the tire element. The methods are briefly described in the following paragraphs.



1. $M = \frac{F_f}{R_R}$

2. $\Sigma M_H = W(l_W - l_R) - R_R l_W - hF_f = 0$

3. $R_R = \frac{W(l_W - l_R)}{l_W} - \frac{h}{l_W} F_f$

4. $M = \frac{F_f}{W(1 - \frac{l_R}{l_W}) - \frac{h}{l_W} F_f}$

With no braking

5. $F_f = 0$ and the total trailer wheel reaction force, R_R, becomes:

6. $R_R = W(1 - \frac{l_R}{l_W})$ = static weight on trailer wheels.

Therefore

7. $M = \frac{F_f}{W_S - \frac{h}{l_W} F_f}$

Where:

M = Friction Coefficient
F_f = Friction Force
W_S = Static Weight on Trailer Wheels
h = Trailer Hitch Height
l_W = Trailer Hitch to Axle Distance

[After Skeels (19)]

Figure 2. Determination of Friction Coefficient for Towed Trailer

Whitehurst and Goodwin

In short, this method (2) was based on the amount of power needed, or relative power demand, to keep a tire spinning at a constant speed against a fixed continually watered pavement specimen.

The speed of the tire was regulated by a drive motor which produced a range of tire speeds from 7 to 345 rpm. Air pressure introduced into a cylinder was used to vary the wheel load from dead weight to 1200 lb.

A tachometer was used to show the rotational speed of the wheel at any time. The (rotational) speed and air pressure were continually recorded.

The drive motor was powered by a 220-volt three phase circuit. The amount of power needed to keep the tire spinning varied directly with the pavement slipperiness. The relative power demand was thus a relative measure of the pavement slipperiness.

Due to considerable instrumentation, tests could be made without constant supervision for extended periods of time, in some cases, 72 hours.

Some of the basic advantages and disadvantages of this method are:

Advantages:

1. Minimum costs are incurred in testing.
2. The device is able to detect variations in aggregate blend to as little degree of change as 10 percent.

Disadvantages:

1. Results are considerably affected by tire wear, thus causing inequities in a frictional evaluation.

Shupe and Goetz (18)

The method basically consisted of the action of a rotating pavement core against a fixed rubber testing head. A 6" pavement core was placed in a mold affixed to a lower variable speed shaft. A 40 hp drive motor provided enough power to rotate the shaft at an angular velocity of 2500 rpm. A rubber testing head, attached to an upper shaft, was forced against the rotating test specimen at a pressure of 28 psi. The upper shaft was attached to a stationary cantilever beam on which two electrical strain guages were located.

The torque developed in the upper shaft as a result of head-pavement interaction, produced a bending moment in the cantilever beam. The induced moment consequently caused changes in the resistance in the strain guages. The variation of resistance would then be detected by a strain analyzer, resulting in deflection variations in the automatic recorder.

The deflections recorded for each specimen were used in determining a numerical relative resistance value (RRV) in order to rate the different pavement surfaces on a relative scale. No coefficient of friction was determined as such.

The following advantages and disadvantages associated with this method are:

Advantages:

1. Operational costs are minimal.
2. Excellent reproducibility of test results can be obtained.
3. The machine shows good correlation with the stopping-distance method.

Disadvantages:

1. The testing procedure yields only a relative value by simulation.
2. A grooved rubber disk or head can only partially assume tire characteristics (tire wear, tread design, contact configuration).

The preceding laboratory and field testing methods represent some of the typical approaches to friction measurement. They varied not only in cost, but also in testing accuracy and limitations. Their advantages and disadvantages served as a basis for selection of one method over another.

A similar evaluation, but far more detailed and extensive, was made of the Arizona Laboratory Friction Tester (ALFT) and is presented in the following chapters.

CHAPTER 3

ARIZONA LABORATORY FRICTION TESTER

The friction tester to be analyzed in this paper, the Arizona Laboratory Friction Tester, was designed and constructed by D. S. Welker and R. A. Jimenez (22). It is located in the Highway Materials Laboratory at The University of Arizona, Civil Engineering Department. It is now presently being used for skid resistance analysis by Jimenez (7) for the Arizona State Highway Department.

Advantages and Disadvantages

This laboratory tester possesses certain features which exemplify the qualities desired in a laboratory tester, or any tester for that matter. Greater consistency in testing through controlled laboratory conditions poses as a primary attribute. The resulting data becomes relatively more significant in meaning and is far more readily obtained. The extraction, transportation, and preparation of the sample cores for testing represent the only real time involved, thus, valuable time is saved. Though time does represent a substantial saving, it is not the most meaningful. Costs, whether initial, operational, or maintenance, have proven to be minimum.

Despite the obvious advantages of this method, a number of shortcomings exist. For one thing, it is not entirely realistic. The lab tester only simulates the tire-pavement interaction, it does not possess

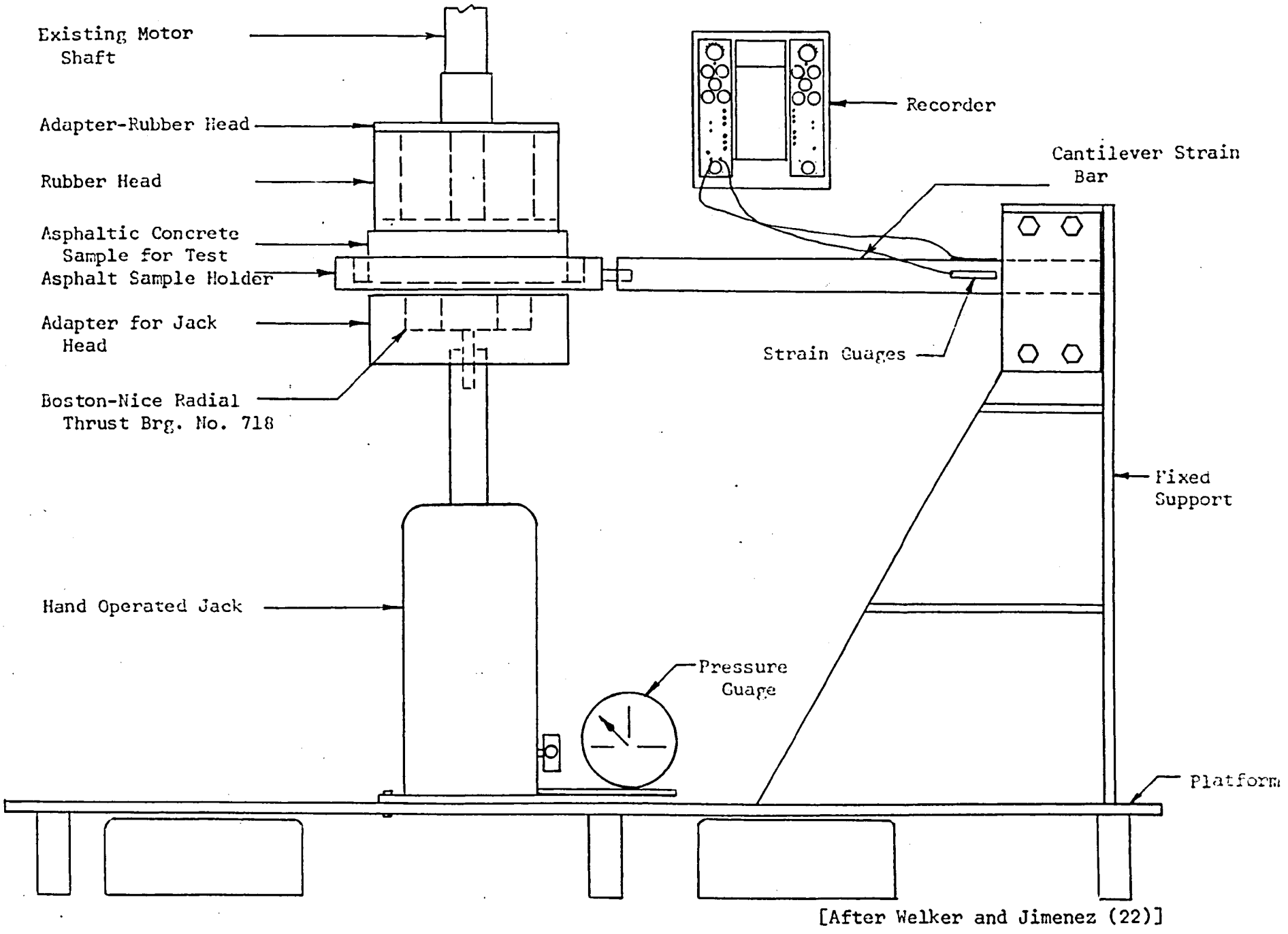
true reality in the strictest sense. Even the values obtained are not true friction values, but rather, just relative values, values based on a laboratory standard. Since the machine is manually operated, it is subject to inconsistences due to the human element involved. Numerous operational limitations increase the number of variables thus jeopardizing the credibility of the results. In order to give grater meaning to these limitations, however, an understanding of the actual testing apparatus and its functions is needed.

Test Apparatus

The equipment used for testing consists of two primary pieces; the friction tester and a Sanborn Recorder. In short, the test consists of the action of a rotating rubber head against a fixed specimen. The specimen holder in which the sample is placed transfers a frictional force to a strain bar from which the recorder receives a strain reading or an indirect friction value. A schematic diagram of the testing setup is shown in Figure 3.

The friction is developed by means of a rubber disk at the end of a rotating shaft. The drive motor, a Blakeslee C-50 mixer, has variable speeds capable of rotating the shaft through a range of 10-125 rpm. Once the chosen speed for testing has been selected, it remains constant throughout the test.

An hydraulic jack is used to raise the test cylinder and holder into position and apply the appropriate pressure. Through the center of the rubber head, a flow of water at the rate of 0.15 GPM is used to lubricate the specimen. The specimen lubrication simulates "field"



[After Welker and Jimenez (22)]

Figure 3. Arizona Laboratory Friction Tester

pavement wetness. A seven gallon head tank is used to provide the needed flow rate for testing. This flow rate can be adjusted by means of the pinch clamp on the rubber hose connecting the head tank and rotating head, (see Figure 4).

As the specimen tries to rotate with the driving head, a lever arm affixed to the holder transfers this rotational force to a stationary steel bar. Using half-bridge electric strain guage connections, the strain incurred by the bar is registered by the Sanborn Recorder. A direct conversion can be made from the deflection of the beam to a friction value.

Design Assumptions

In the design of the Surface Friction Tester several assumptions were made in order to facilitate design practicallity. They can be stated briefly as follows:

1. By use of a radial thrust bearing plate a frictionless surface for the sample holder to rotate on was assumed to be provided.
2. By following certain procedures, a uniform loading between the rubber head and the asphaltic concrete sample was assumed to be affected.
3. By use of electric strain guages, a sensitivity of $\pm$ 0.05 for the friction coefficient was assumed to be attained.

Design Considerations

In order to achieve the intended simulation of tire-pavement interaction, a number of controllable variables were introduced. The

Figure 4. Testing Apparatus Setup

objective was to parallel as closely as possible the real factors involved in the development of friction. The essential factors involved have previously been categorized into three groups; (1) Vehicle or Machine Operation Factors, (2) Tire Factors, and (3) Pavement Factors.

Since actual pavement samples are used in testing, the pavement factors exist as previously mentioned in Chapter 1. With regard to vehicle or machine operation factors the desired reproduction of the realistic or field situation was accomplished. The effective duplication of speed as a variable factor was achieved by means of a rotating head. Angular velocities of 10-125 rpm were easily attainable, more than enough to effectively demonstrate the effect of speed.

In simulating the tire factors, an effective representation was developed. In the case of tread design, variations of the design of the contact area and head strength can be made if desired. For purposes of this study Devcon "Flexence 60" was used as the head material. "Flexane 60" has a Shore A hardness of 60 durometers. With a contact area of 12.8 square inches, the testing head had a surface design as illustrated in Figure 5. By means of raising and lowering the specimen under the action of the rotating head, variations in pressure were created, thus simulating the effects of load and tire inflation (pressure).

Testing temperatures were held constant but were adjustable by means of a room thermostat.

Potential Sources of Error

Though the above variables do represent the desired factors, there are certain sources of error which can enter the process and thus

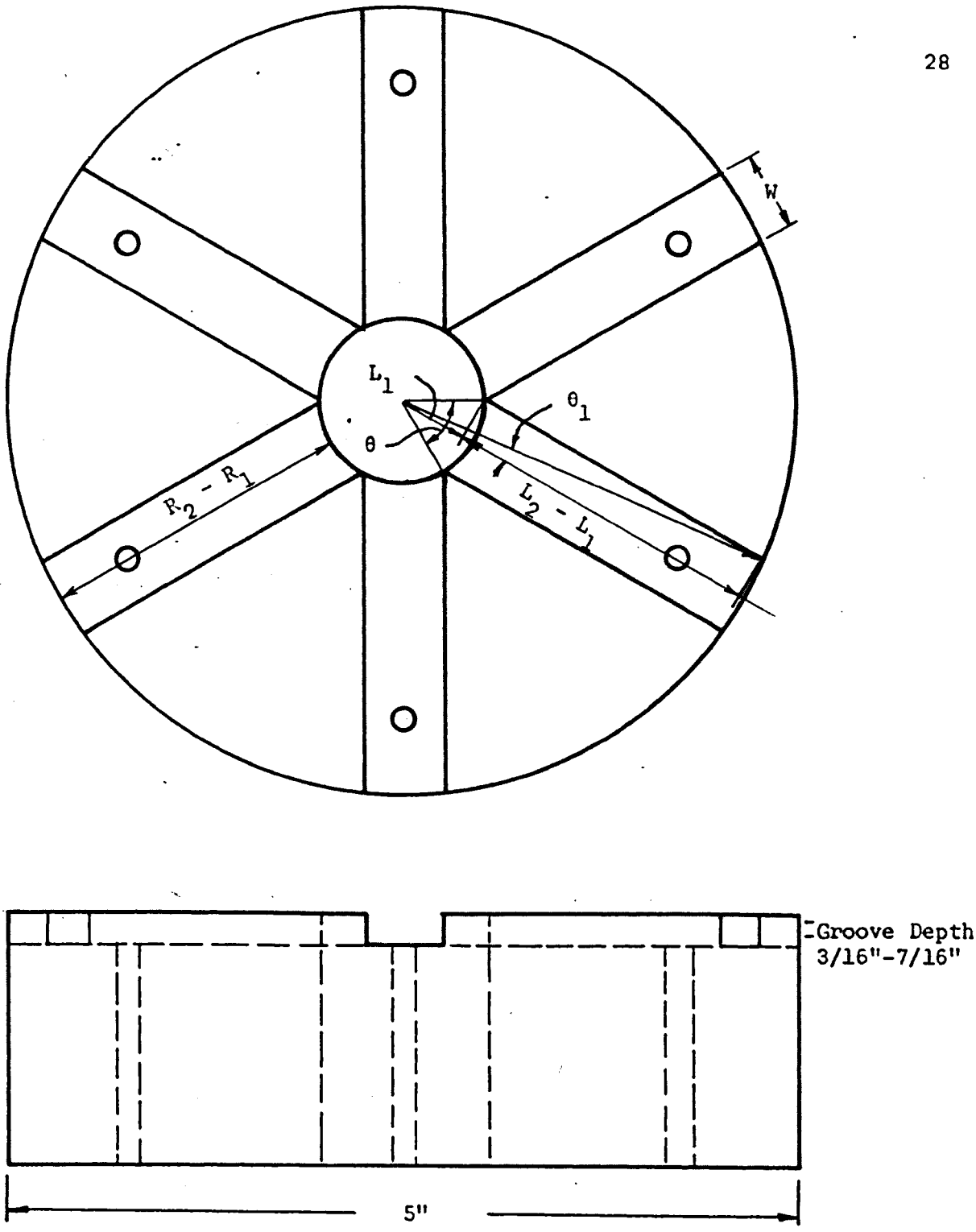


Figure 5. Rubber Testing Head Used in the Laboratory Method

affect results. All of these, however, can be eliminated by careful testing procedures. Some of the more likely sources of error are as follows:

1. Failure to standardize the friction head before each test set,
2. Improper molding and nonuniform head strengths,
3. Variation in flow rate of water throughout the test,
4. Specimen loose in holder,
5. Specimen not level, and
6. Improper application of pressure (pressure must be applied evenly).

Design Theory

In considering the plausibility of the laboratory tester, only physical limitations have been considered up to this point. But, in order to fully comprehend the real extent of the machine's capabilities, a theoretical analysis must be made.

As previously mentioned the primary concept is that of the simulation of the tire-pavement interaction by the tester. Therefore, the analysis must begin with the theoretical aspects of this interaction.

As the rubber of the rotating head tries to cling to the pavement sample, a rotational force (couple) or moment is applied to the sample. Using the same notation as in Figure 5, the moment ultimately developed is

$$M = p\mu R_2^2(2/3\pi R_2 - 3W) - p\mu R_1^2(2/3\pi R_1 - 3W) \qquad [9]$$

or in terms of μ:

$$\mu = \frac{M}{p[R_2^2(2/3\pi R_2 - 3W) - R_1^2(2/3\pi R_1 - 3W)]} \qquad [10]$$

The moment incurred by the steel bar as a result of the transfer of force from the specimen holder to the bar is:

$$M_s = \frac{E\epsilon_s I}{c} \qquad [11]$$

or in terms of the moment of the head:

$$M_s = \frac{ML_2}{L_1} \qquad [12]$$

where

L_1 = distance from the center of the specimen holder to the point of load transfer on the steel bar, in inches.

L_2 = distance from the point of load transfer on the steel bar to the center of the strain guages, in inches.

M = moment of the head.

M_s = moment of the steel bar.

By substituting equations [11] and [12] into [10], the coefficient of friction can be determined as follows:

$$\mu = \frac{\epsilon_s}{p}\left[\frac{EIL_1}{L_2 c[R_2^2(2/3\pi R_2 - 3W) - R_1^2(2/3\pi R_1 - 3W)]}\right] \qquad [13]$$

or

$$\mu = \frac{\epsilon_s}{p}\kappa, \text{ where } \kappa \text{ has been calculated to be } 2.66(10^4).$$

On the Sanborn Recorder, ε_s, at an attenuator setting of "2" and a sensitivity of "10^{-4}", becomes the following:

$$\varepsilon_s = 2 \times 10^{-5} \text{ (Recorder Deflections)}$$

if p = 26 psi, then equation [13] can be written as

$$\mu = \frac{\varepsilon_s}{p}(2.66)(10^{-4}) \text{ or } \mu = 2.03\ (10^{-2}) \text{ (Recorder Deflections)}$$

A more complete derivation of the design theory can be found in Reference 22.

To further evaluate the operational characteristics and principal variables of the testing process a statistical experiment was initiated to determine the significance of the friction values obtained. The experimental design is reviewed in detail in Chapter 4.

CHAPTER 4

THE EXPERIMENT

The friction values obtained from the laboratory tester relied on three primary variables; the speed at which the testing head was rotated, the pressure imposed on the specimen, and the surface treatment utilized. All precautions were taken to eliminate procedural error, and thus increase the significance of the test. Accurate estimation of the inherent error which could not be removed was made by the statistical model.

Statistical Model

A model of three-way classification with interaction was selected for the experiment. The three basic variables--treatment, pressure, and speed--were identified as fixed effects. The friction coefficients were evaluated for every possible combination of the three variables. The estimate of the error was determined by means of twin sampling in each cell block for each of the different combinations.

The following model was chosen to statistically represent the experiment conducted.

$$F_{ijkm} = U + T_i + P_j + S_k + (TP)_{ij} + (TS)_{ik} + (PS)_{jk} + (TPS)_{ijk} + E_{ijk}$$

where, F_{ijkm} = friction coefficient determined from the m^{th} observation of the k^{th} speed at the j^{th} pressure for the i^{th} treatment.

U = population mean

T_i = the i^{th} treatment effect

P_j = the j^{th} pressure effect

S_k = the k^{th} speed effect

$(TP)_{ij}$ = the combined effect of the j^{th} pressure and i^{th} treatment

$(TS)_{ik}$ = the combined effect of the i^{th} treatment and k^{th} speed

$(PS)_{jk}$ = the combined effect of the j^{th} pressure and k^{th} speed

$(TPS)_{ijk}$ = the combined effect of the i^{th} treatment, j^{th} pressure, and k^{th} speed

E_{ijkm} = the error component associated with the m^{th} observation of the $(ijk)^{th}$ set of conditions

The following values of the subscripts were used:

$i = 1, 2, 3$

$j = 1, 2, 3$

$k = 1, 2, 3$

$m = 1, 2$

A total of 54 (3 X 3 X 3 X 2) observations were made for the model analysis.

Statistical Tests

After the data was secured from testing, it was then subjected to various statistical tests. An analysis of variance was initiated in

order to determine the effects of each model component on the friction coefficient. By use of the "F Statistic" (4) the significance of the different variables and interactions were determined. When the results proved significant, Fisher's Least Significant Difference (LSD) Test (4) was applied to discover pertinent relationships within the population means of the various components.

Plots of the 2-factor interaction components were then made to illustrate the effects of the principal variables on the friction coefficient. Variables were isolated to demonstrate individual characteristics and then averaged to show basic combined trends.

Finally, relationships were established, evaluations made and subsequent conclusions drawn.

Treatments

A total of three asphaltic surfaces, or "surface treatments" for the purposes of this paper, were used in the analysis. Two of the treatments were asphaltic concrete with mix designs as shown in Table 1. The third surface treatment was a slurry seal.

Table 1. Mix Designs for Asphaltic Concrete Treatments - Percent by Weight of the Total Mix

Aggregate Range	T_1 - 3/4" AC	T_3 - 5/8" AC
Course	31.42	21.70
Intermediate	23.82	23.45
Fines	40.01	49.10
Asphalt (60-70 pen grade)	4.75	5.75

The mixes for the two asphaltic concretes were obtained from the Number 2 asphalt mixing plant of the Sundt Construction Company located in Tucson. The SS-1H emulsion used in preparing the slurry seal was purchased from the Chevron Oil Company plant also located in Tucson.

Treatment 1, 3/4" asphaltic concrete with approximately 32% course aggregate by weight (3/4" - 3/8") was selected to demonstrate the frictional contributions of a high percentage of course aggregate in a mix design (Figure 6). A total of 4.75 percent 60-70 penetration grade asphalt was used in the mixture.

Conversely, Treatment 3, 5/8" asphaltic concrete with nearly 50% fines by weight was chosen to illustrate the effects of this percentage of fines in the development of friction (Figure 8). A total of 5.75 percent 60-70 penetration grade asphalt was used in the mixture. The increase in asphalt was probably due to increased surface area of the mix as a result of the added fines.

Before compaction into 6" diameter specimens, the mixtures were placed in ovens to 240°F. The samples were then deposited into preheated molds and compacted by a vibratory kneading compactor. A minimum of three days expired before any tests were preformed on the prepared specimens.

Treatment 2, a slurry seal, consisted of 12.3 percent SS-1H emulsion, 81.6 percent crushed sand, and 6.1 percent water. The seal was rolled into place atop eighteen prepared 6" diameter asphaltic concrete specimens by means of a steel rod. Care was taken in placment in order to insure uniform texture of the testing surface (Figure 7). A

Figure 6. Treatment 1 - 3/4" Asphaltic Concrete

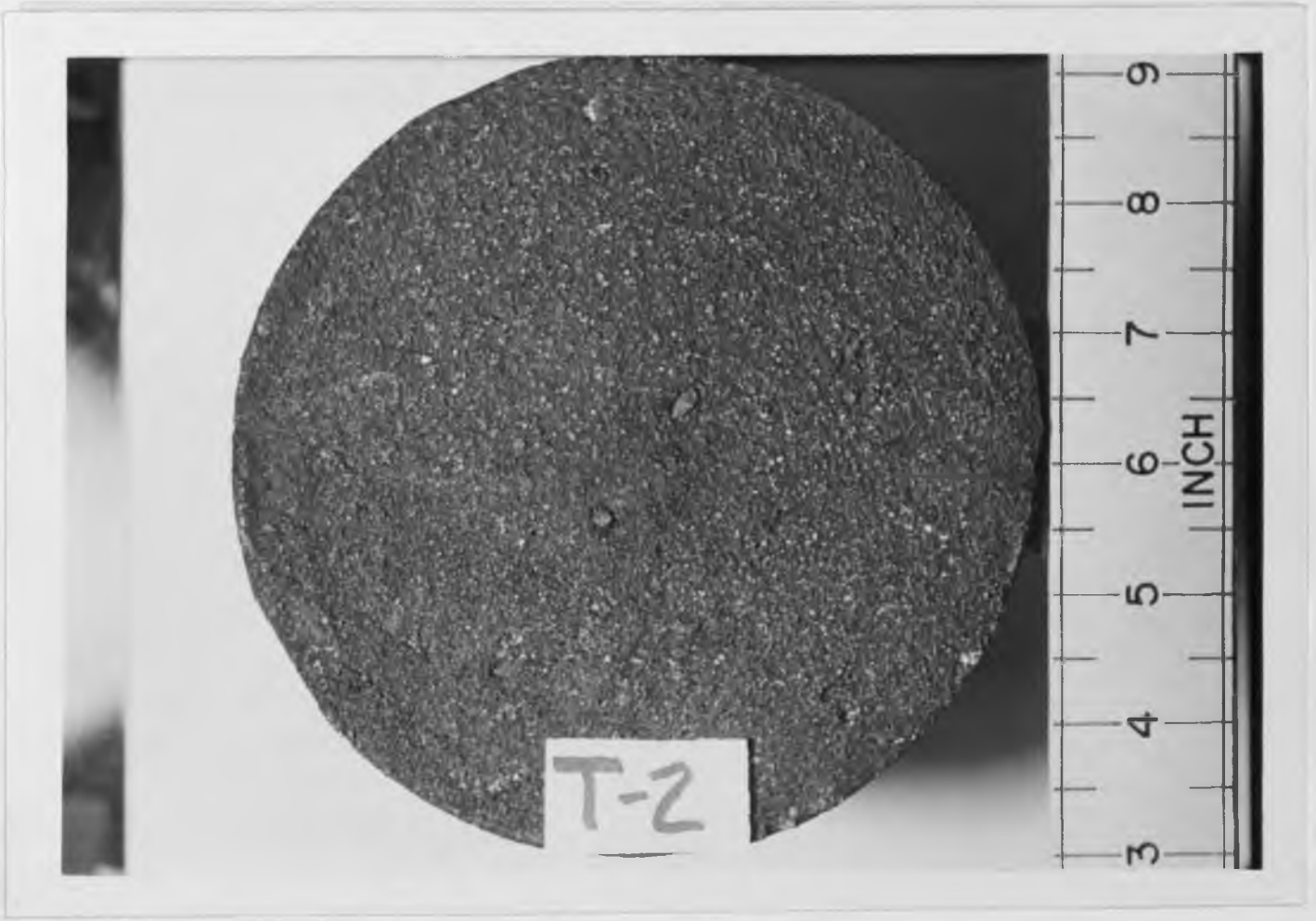


Figure 7. Treatment 2 - Slurry Seal

Figure 8. Treatment 3 - 5/8" Asphaltic Concrete

minimum of three days was also observed before any tests were made. Final verification of the desired surface uniformity was made before and after each test.

Pressures

Linearly related testing pressures of 20, 23, and 26 psi were selected for a number of reasons. Tests conducted in the spring of 1968 indicated that pressures above 26 psi caused rapid head deterioration and irregular test results. Pressures below 20 psi were diagnosed as ineffectual in producing desired pavement wear. Consequently, in order to insure the accuracy of test results, the following pressures were chosen and designated as such:

P_1 = 20 psi

P_2 = 23 psi

P_3 = 26 psi

Speeds

The choices of speeds were arrived at in much the same manner as those of the pressures. Speeds below 40 rpm proved inconsequential to affecting friction values while speeds above 100 rpm proved detremental to the testing head. To facilitate the analysis, a linear relationship between the speeds was established. Speeds were designated as follows:

S_1 = 48 rpm

S_2 = 72 rpm

S_3 = 96 rpm

Testing Procedures

In order to assure consistency and validity of test results, standard procedures for testing were established. The format adopted was strictly adhered to and is outlined in the following step by step procedure.

1. The Sanborn Recorder was activated and allowed to warmup for a minimum of 5 minutes before testing.
2. The cooled specimen was then placed in the sample holder and adjusted until properly centered.
3. The friction tester was then started and the appropriate speed set. Note: If the speed was set first, and then the tester started, a different angular velocity of the testing head would result.
4. The water was released and allowed to flow over the entire specimen surface before application of the pressure.
5. The desired pressure was then applied and held for the specified time of 15 seconds.
6. After the testing time elapsed, the specimen was released from pressure, and the water flow terminated.
7. The testing head was standardized after every other specimen in preparation for the next testing set.
8. The deflection readings obtained from the tests were then tabulated and the friction values determined and recorded.

Experiment Synopsis

Three treatments, 3/4" AC, 5/8" AC, and a slurry seal, were prepared and tested for each proposed combination of pressure and speed. Two samples of each treatment were tested at each combination. The average value for the two specimens was then regarded as the friction coefficient for that treatment in that particular cell. The results were recorded for each of the three treatments and are presented in tabular form in Appendix A. A thorough discussion of the results and conclusions is presented in Chapter 5.

CHAPTER 5

RESULTS OF EXPERIMENT

Results

As previously cited in Chapter 4, the statistical data obtained was analyzed in three consecutive phases; the analysis of variance, Fisher's Least Significant Difference (LSD) tests of the population means, and graphical illustrations of the interaction components. All pertinent results were extracted and then studied for possible conclusions. The tabulated data and results can be found in Appendix A.

Analysis of Variance (ANOVA)

In the analysis of variance, a concise statistical representation of the testing variables was formed. The various components were numerically evaluated and subsequently related to one another.

Pressure was established as the predominant factor affecting friction by a substantial margin. Speed and surface treatment were also established as controlling effects, but of far less significance than that of pressure.

With respect to the interactions, all with the exception of the treatment-pressure interaction, were proven to be significant in developing friction. In comparison to the first level variables--treatment, pressure, and speed--the interactions were found to represent only a minority of the contributing effects. The estimation of the

experimental error was determined to be less than one-half of one percent of the total combined effects.

Fisher's LSD Tests

Fisher's Least Significant Difference tests were conducted on all significant components of the statistical model with the lone exception of the three-factor interaction component (treatment-pressure-speed). The results obtained gave further support and emphasis to the findings of the analysis of variance. The results were essentially, as outlined below:

1. The average friction coefficient obtained at all combinations of speed and pressure for the 3/4" and 5/8" asphaltic concrete treatments, T_1 and T_3 respectively, were determined to be essentially the same.
2. The average friction coefficient for the slurry seal (T_2) proved dissimilar to the friction value of the two asphaltic concrete treatments.
3. The average friction coefficient obtained for each pressure, 20, 23, and 26 psi (P_1, P_2, and P_3) proved to be dissimilar but definitely linearly related to pressure.
4. The average friction coefficient obtained for each speed, 48, 72, and 96 rpm (S_1, S_2, and S_3) proved to be dissimilar but definitely linearly related to speed.
5. The average friction coefficient for each speed--pressure interaction component (i.e., S_1P_1, S_1P_2. . . S_3P_3) proved to be distinct.

6. The average friction coefficient for the treatment-speed interaction, in the case of the 3/4" AC (T_1) and the slurry seal (T_2) at 48 rpm (S_1) and also at 72 rpm (S_2) were determined to be essentially the same.

Graphical Results

The following graphs were plotted to illustrate the extent of the effects of the component variables in the interactions on the ultimate friction developed. In Figures 9, 11, and 13, one variable was isolated in order to dramatize the effect of the variable in that particular interaction. In order to graphically illustrate the effects of the interaction component as a whole (Figures 10, 12 and 14), average values of the isolated variable were calculated and then plotted for the corresponding interaction.

From Figure 9 where speed was the isolated variable, high speeds were determined to yield the higher friction values for each treatment at all pressures, with the possible exception of pressure 3, 26 psi. In the case of the slurry seal (T_2) and the 5/8" asphaltic concrete (T_3), results appeared to indicate that the effect of speed diminished at high pressures. The 3/4" asphaltic concrete (T_1) exhibited the converse relationship, however, the effect of speed somewhat increased with increasing pressure.

From Figure 10, the graphic portrayal of the average friction value for all speeds, the variations of treatment at different pressures were shown to have no consequential effect. The slopes of 0.0294/psi

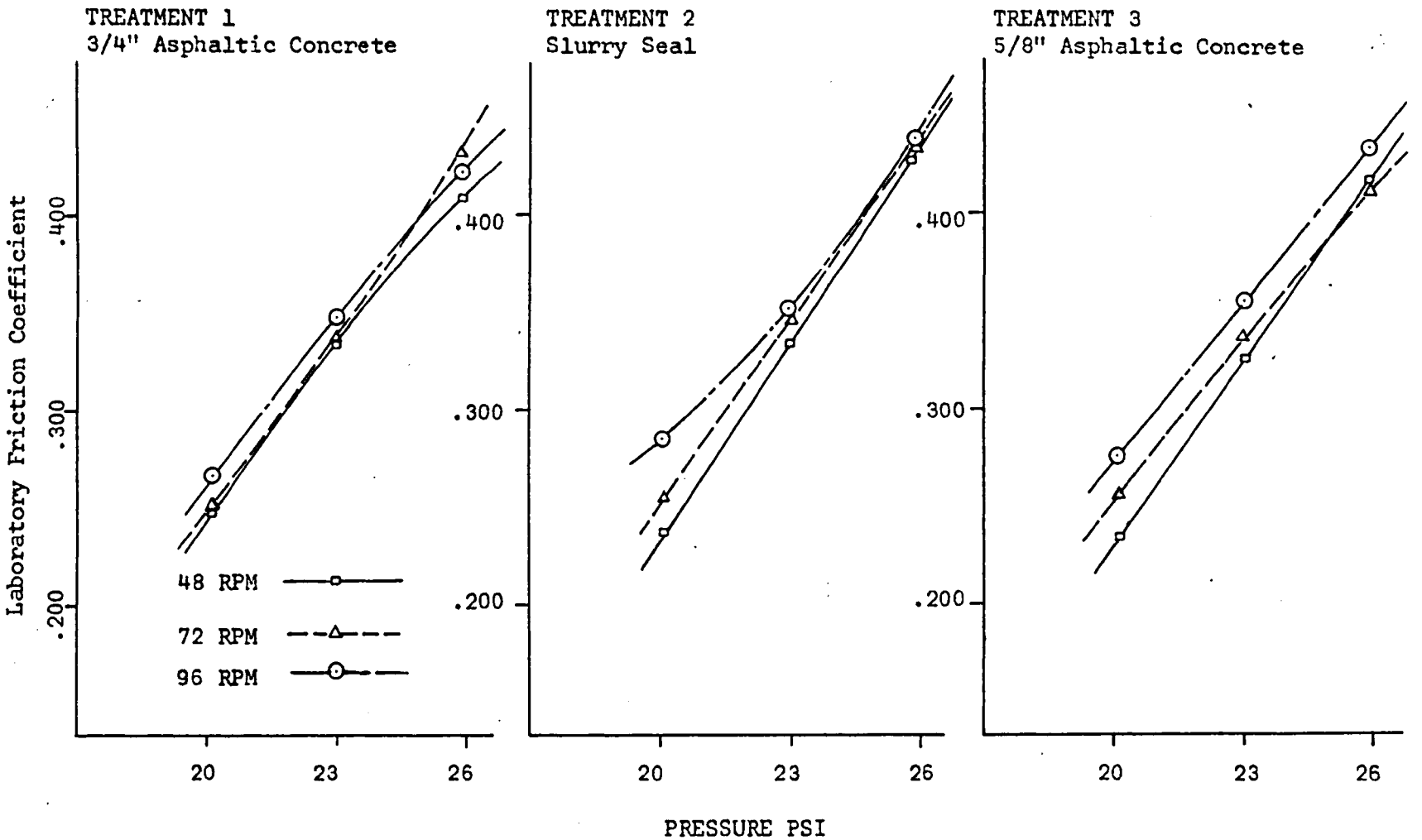


Figure 9. Treatment vs. Pressure - (Speed is the Isolated Variable)

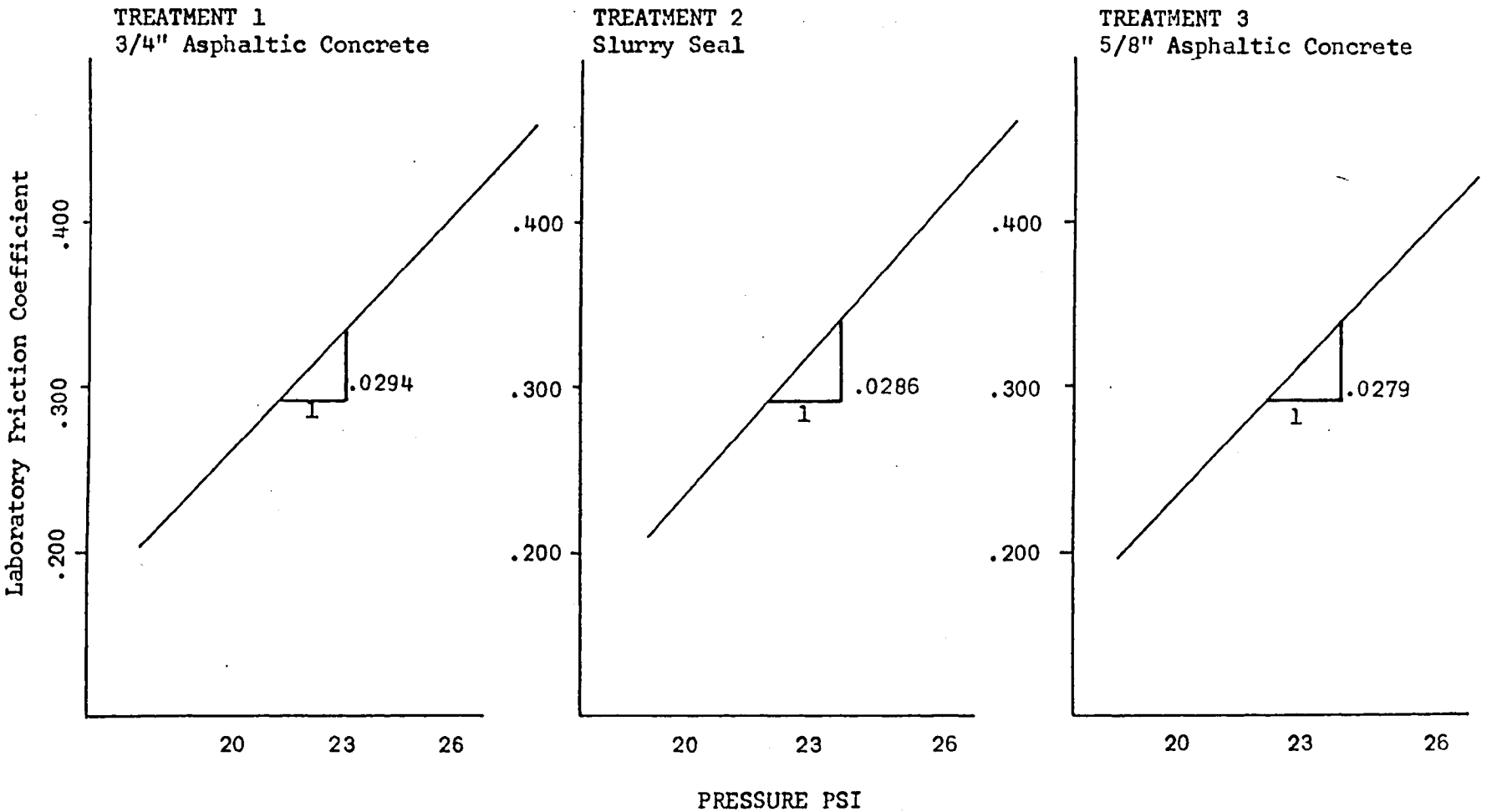


Figure 10. Treatment vs. Pressure - (Average Friction for all Speeds)

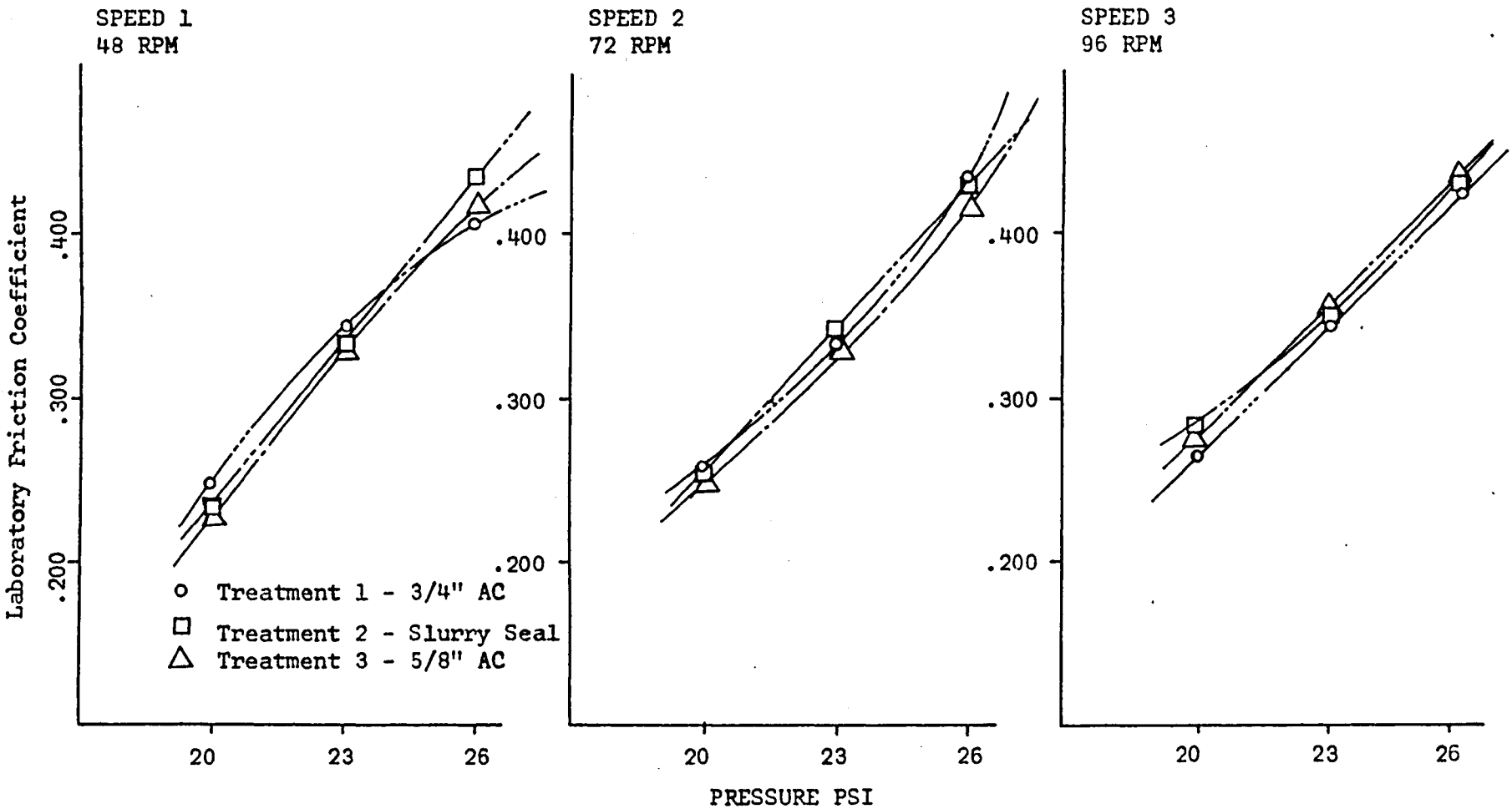


Figure 11. Speed vs. Pressure - (Treatment is the Isolated Variable)

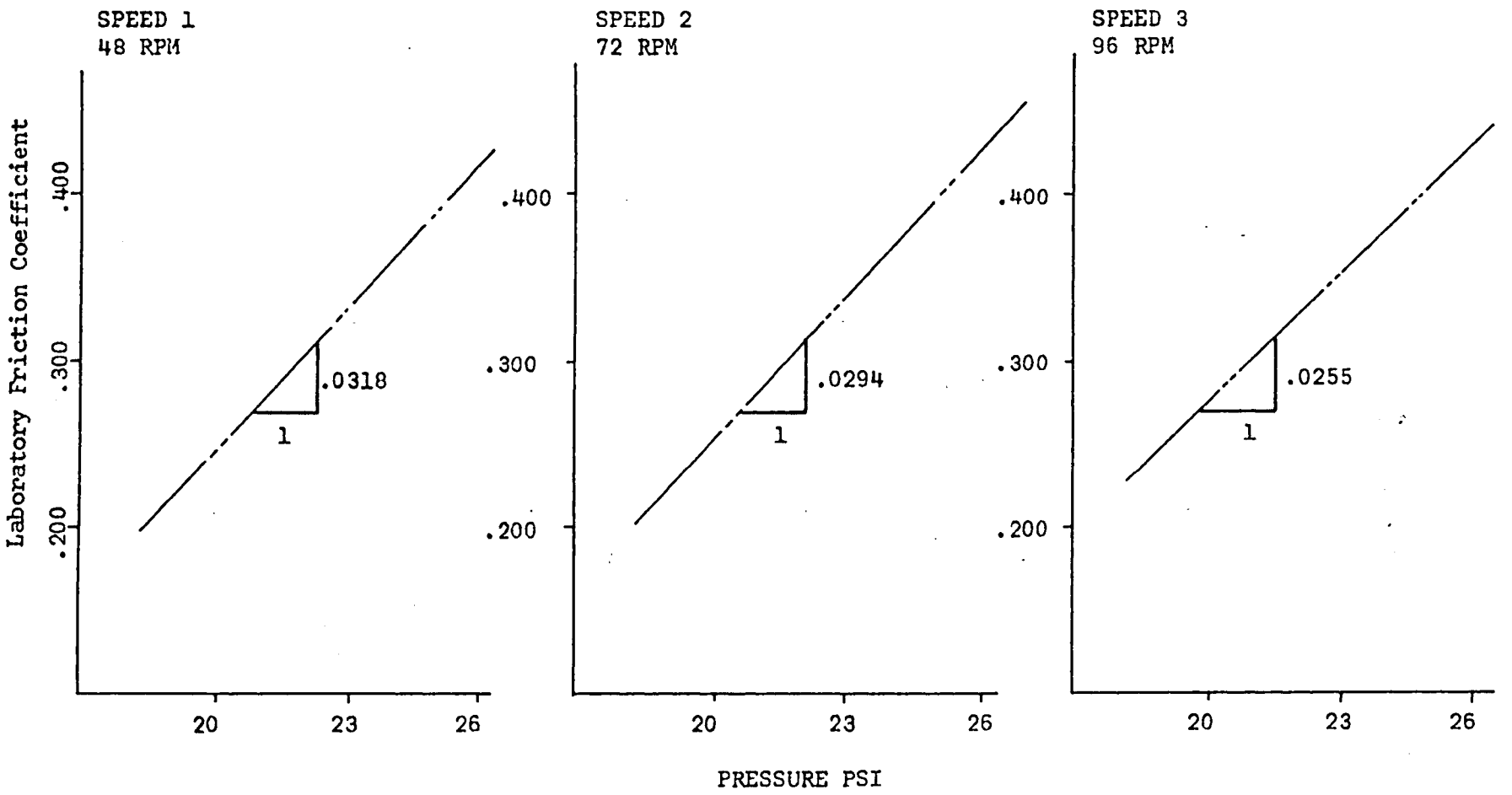


Figure 12. Speed vs. Pressure - (Average Friction for all Treatments)

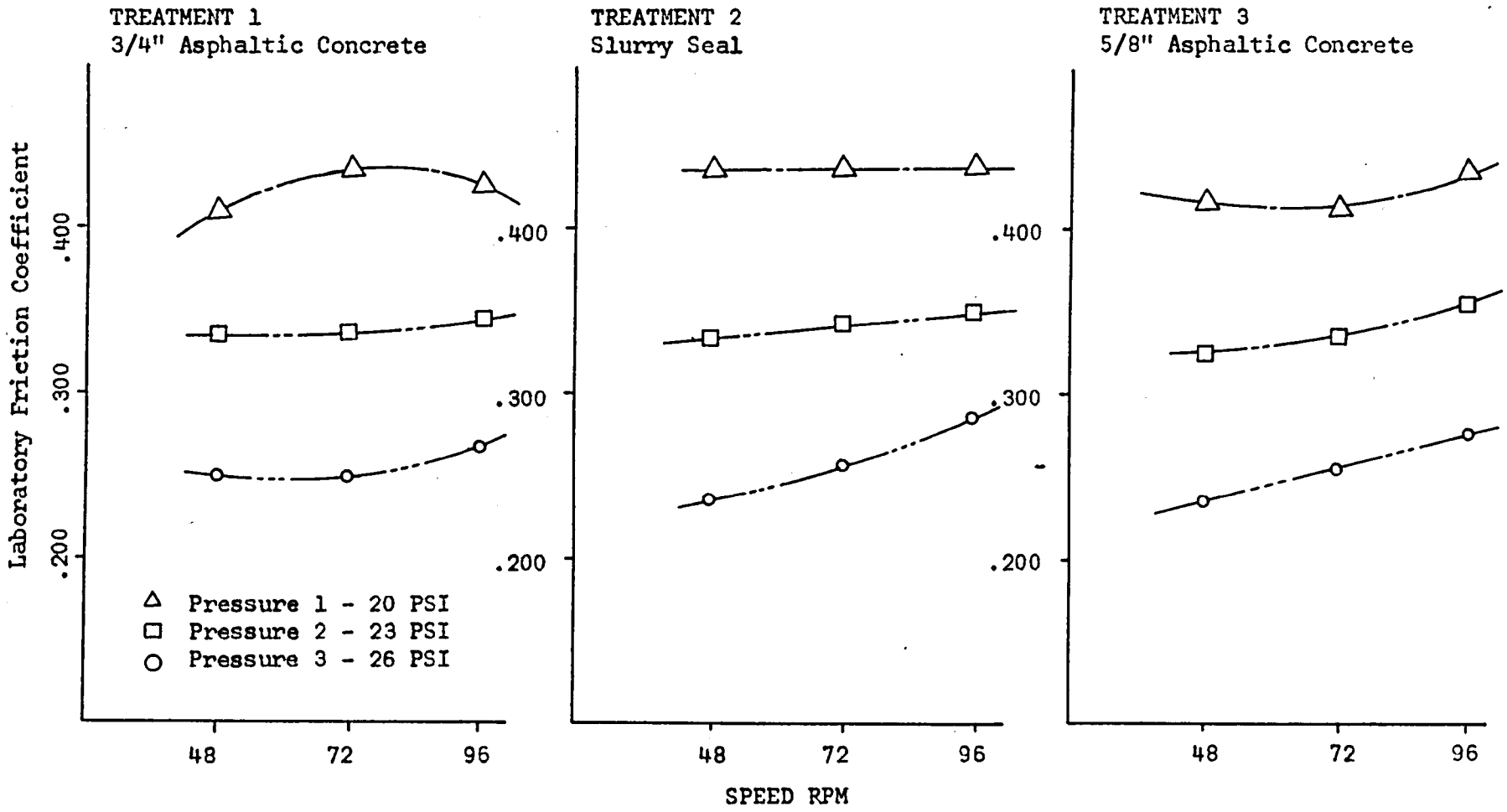


Figure 13. Treatment vs. Speed - (Pressure is the Isolated Variable)

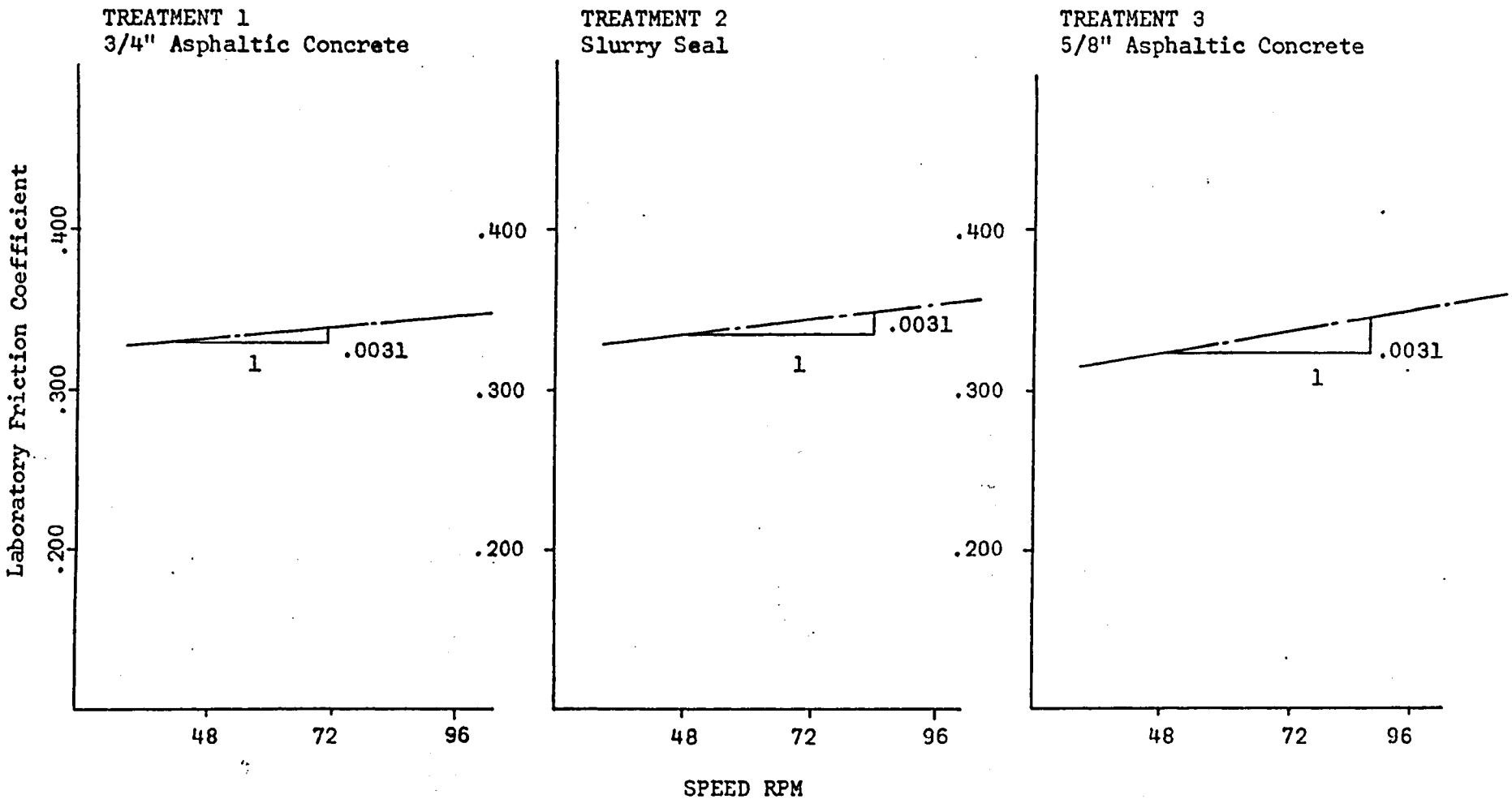


Figure 14. Treatment vs. Speed - (Average Friction for all Pressures)

(T_1), 0.0286/psi (T_2), and 0.0279/psi (T_3) validated the insignificance of the treatment-pressure interaction on the friction value.

In Figure 11, treatment served as the isolated variable. Despite the absence of a distinct variation among the treatment friction values, a definite similiarity between the slurry seal and the 5/8" asphaltic concrete was noted over all the speeds.

In viewing the overall effects of the interaction, Figure 12, the speed-pressure combination was shown to have a noticeable effect on the friction value. This is substantiated by the analysis of variance where the speed-pressure interaction represented the fourth most significant contributing effect to the development of friction. The gradual reduction of slope from 0.0318/psi to 0.0255/psi denoted the following interesting point. As the slopes decreased with an increase in speed, the friction values increased at corresponding constant pressures. Thus, it gave evidence to the fact that as speeds increased, pressure began to lose effect.

In Figure 13, pressure was isolated and effectively illustrated its obvious importance. But probably the most interesting aspect of this interaction, however, is the striking similarity of the slurry seal (T_2) and 5/8" asphaltic concrete (T_3). The effect of increasing speed at each pressure produced identical trends for both treatments. Whereas, in the case of the 3/4" asphaltic concrete (T_1), increasing speed had varying effects at different pressures. At low pressures, an increase in speed caused an increase in friction, while only at high pressures, an increase in speed resulted in initially an increase and eventually a

decrease in friction. Oddly enough, however, in inspecting the treatment as a whole, Figure 14, identical slopes for each treatment reconfirmed the insignificance of the interaction in reference to the whole model, as was true in the case of each preceding interaction.

Despite this lack of influence, however, the interactions did aid in evaluating the prominent variables and arriving at the following conclusions.

Conclusions

On the basis of the statistical model selected, the following conclusions were drawn.

ANOVA

From the analysis of variance, three fundamental conclusions were made and listed as follows:

1. Pressure, with a magnitude of effect sixty times that of speed, was the primary governing factor.
2. Speed and treatment were statistically significant, however, the presence of pressure remained eminent.
3. The treatment-pressure interaction proved insignificant, while all other interactions, though statistically significant, were dwarfed by the effects of the three first level variables--treatment, pressure, and speed.

Fisher's LSD Tests

The following conclusions were drawn on the basis of the combined results of all the model components:

1. The laboratory tester was unable to detect any difference in the two asphaltic concrete mixes. It did, however, note the differences between the slurry seal and the two asphaltic concretes.
2. Effects due to the variations in pressure and speed applied were readily decernible, and had a direct bearing on the friction coefficient produced.
3. No direct relationship between speed and pressure was evident.

Graphical Results

The author's interpretation of the preceding plots of the two-factor interaction components warranted the following conclusions:

1. Higher speeds were shown to yield higher friction coefficients at constant pressure.
2. Speed was shown to suffer some loss of effect at higher testing pressures.
3. The effect of pressure decreased at higher speeds.
4. Treatments 2 and 3, the slurry seal and 5/8" AC, were shown to have similar and sometimes identical friction coefficients at constant pressure or pressure levels, with the exception of pressure 3, 26 psi.
5. The combination of 72 rpm (S_2) and 23 psi (P_2) was selected as the testing standard for future work. The setting was chosen on the basis of statistical tests showing that the

average or mean friction coefficients for all the speed-pressure combinations was that approximated by the (S_2, P_2) setting. The same (S_2, P_2) setting also represented the median value for all average setting combinations.

Overall Conclusions

From a statistical standpoint, the tester failed to numerically detect any variation between the mean friction coefficients determined for each of the two asphaltic concrete treatments. This failure was attributed to a number of possible causes; (1) improper statistical model, (2) insufficient variation between the gradations of the two mixes, and (3) failure to completely eliminate procedural error.

From a qualitative stand-point, however, the tester demonstrated similar trends for the slurry seal and the 5/8" asphaltic concrete. These similarities were accredited to the high percentage of fines in both treatments.

Conversely, however, despite the fact that the mean friction coefficient for both asphaltic concretes were statistically the same, both mixes acted appreciably different under the same direct influences. Since the chief variables in the two mix designs were the percentages of fine and coarse aggregrates the higher percentage of coarse aggregate in T_1 was presumed to be (or the lower percentage of fine aggregate) the cause of variation in the results.

Therefore, generally speaking, the tester showed limited potential under the experimental design. However, its ineptness to

clearly decifer between surface treatments posed as the principal drawback. The friction values yielded by the testing process were of such close proximity that in some cases, no clear cut distinction could be made between the surface treatments with respect to friction.

A correlation study was then made in order to rate the machine's relative effectiveness to the stopping distance method.

CHAPTER 6

CORRELATION STUDY

The second objective of this paper was to search for statistical correlation of the laboratory tester with the stopping distance method. Data obtained by the stopping distance method, or "field data", was furnished by the results of tests conducted by Jimenez (7) in the summer of 1968. The laboratory data used in the analysis was acquired from test results of pavement cores extracted from the same test sites used in the Jimenez study.

Investigation

A total of nine test sites throughout the state of Arizona were utilized for the comparison. The surface treatments for each test site are shown in Table 2. Results from test site 3 (TS-3) a portland cement concrete surface, were not used in the analysis in order to keep the study restricted to asphaltic concrete or asphalt treated surfaces.

Field Data

To form a basis for comparison, friction components had to be acquired at a constant speed and tire pressure. In the Jimenez study, normal procedure called for a testing speed of 40 mph and a tire pressure of 24 psi, the ASTM standard. These values were then chosen as the

Table 2. Test Site Surface Treatments

Test Site	Surface Treatment
TS-1	3/8" Dense graded AC
TS-2	Open graded hot seal
TS-3	PCC - portland cement concrete
TS-4	Slurry seal
TS-5	Type D chip seal
TS-6	Type B chip seal
TS-7	Type D chip seal
TS-8	Type D chip seal
TS-9	Type F chip seal
TS-10	3/4" Dense graded AC

testing standards to give the representative friction coefficient for each test site. Since an exact testing speed of 40 mph was infrequently attainable, a procedure was devised to estimate the probable friction coefficient at a projected 40 mph speed.

For each test site a plot of friction versus speed was constructed. The slope between the 40-50 mph speed interval was calculated and established as the slope factor used for friction projection. Wherever tests failed to produce the required 40 mph speed, "theoretical" friction coefficients were determined by interpolation. The "theoretical" friction thus became the 40 mph friction and was used as such in the analysis. All slope determinations were tabulated and placed in Appendix B.

Laboratory Data

In keeping with the statistical format, laboratory tests were performed at a constant speed and pressure. Based on the previous evaluation of the tester, specimens were subjected to a speed of 72 rpm and a pressure of 23 psi.

A total of 26 specimens were tested for the laboratory part of the analysis. Three pavement cores were taken from each test site with the exception of TS-6 where two were taken. The average friction coefficient for each test site was then termed the friction coefficient for that particular test site. The results were then paired against those of the field data (Table 3) and a correlation analysis begun.

Table 3. Friction Coefficients - Paired Data

Test Site	Laboratory Method	Stopping-distance Method
TS-1	.392	.687
TS-2	.416	.551
TS-3	----	----
TS-4	.355	.620
TS-5	.331	.652
TS-6	.360	.552
TS-7	.332	.696
TS-8	.369	.564
TS-9	.267	.566
TS-10	.325	.586

Before the data was paired, statistical tests were performed to determine if the means and variances of the field and laboratory data were equivalent. The data was then paired as shown in Table 6.3 and the Spearman-Rank Correlation Coefficient was determined for each of three cases.

Case 1. In this case, results from all test sites were used in the analysis. Regardless to question or doubt as to the validity of the data, the correlation coefficient was calculated and general relationships were noted.

Case 2. In the second case, data from TS-4 and TS-5 were eliminated. The absence of data from the 50 mph test runs prevented slope factor determinations, thus allowing for only estimation of the friction coefficient. In the demand for greater accuracy the results from the two test sites were discounted.

Case 3. In the final case, TS-6 was discounted along with TS-4 and TS-5 due to insufficient data also. Here, however, only two cores were tested and the results revealed such a large variance that they were subject to question.

The results from all three approaches were analyzed separately and then collectively in order to obtain the most fruitful results. The corresponding correlation tables are presented in Appendix B.

Results

In the analysis of the paired data assuming normal distribution, tests indicated that while the means of the laboratory and field data

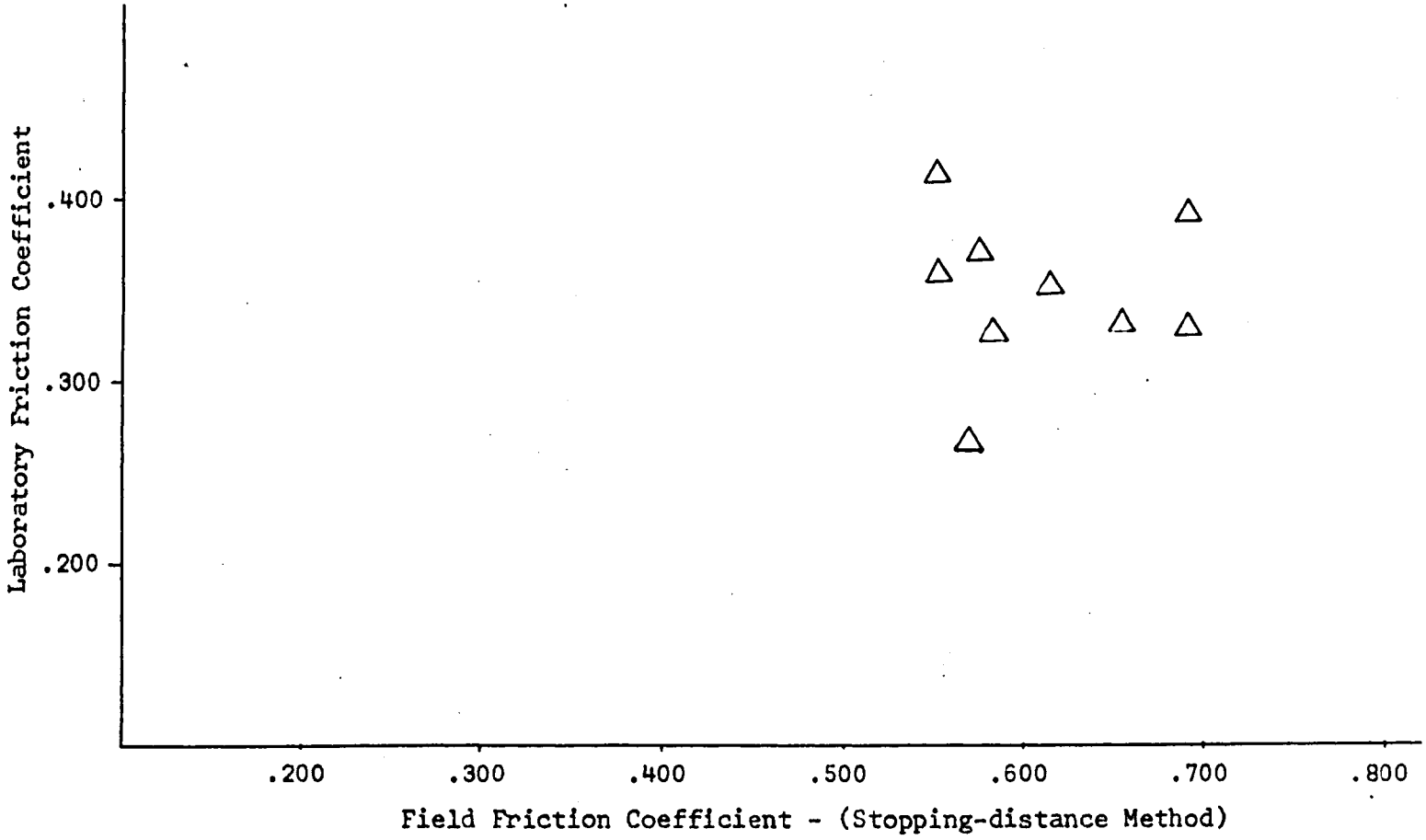


Figure 15. Correlation of Field and Laboratory Methods

proved unequal as expected, the variances displayed statistical equality.

Results from all cases indicated that at a 10 percent level of significance, the correlation coefficient (Rs) was not significantly differently from zero. The effect of increased accuracy through reduced uncertainty failed to materialize anything important. A plot (Figure 15) of the friction coefficients of the laboratory and field methods further manifested the lack of any direct relationship. Therefore, the methods appeared unrelated.

In viewing the situation from a physical standpoint, the close grouping of data gave cause for further investigation. Since the results were so close, rank of the various test sites could be altered quite easily by the slightest change in the friction coefficient. One inferior pavement core could easily affect such a change.

Improper testing criteria was also considered to be another possible cause for the absence of a relationship. Perhaps, some combination of pressure and speed not tested would possibly better suit the analysis.

On the basis of the above information, the following conclusions were made.

Conclusions

The primary conclusion of the entire correlation analysis was that the two methods, laboratory and stopping-distance, were unrelated. Neither of the two methods revealed any similar tendencies under the

same regulated conditions. Possible causes for various discrepencies were cited as follows:

1. The questionable validity of the results of certain samples tested,
2. Improper testing criteria of the laboratory tester used in the analysis,
3. The comparison of a steady-state device (laboratory) to a non-steady state device (field) - the most probable cause, and
4. Insufficient data gathered for the analysis.

It was further concluded that due to the great amount of uncertainty surrounding the test results, further investigation was necessary before final judgement of the tester could be made.

Final conclusions of the overall analysis are presented in the following chapter.

CHAPTER 7

SUMMARY AND CONCLUSIONS

Summary

The statistical model components of treatment, pressure, and speed were shown to be significant in affecting friction values. All interactions, with the exception of the treatment-pressure interaction, were also proven to be significant contributions.

Variations in aggregate blend of the two asphaltic concretes were detected by the tester. The high percentage of fines in the 5/8" asphaltic concrete and the slurry seal caused similar friction trends at high speeds for all pressures. The average friction coefficient developed at each pressure, proved to be dissimilar but linearly related to pressure. The average friction coefficient obtained at each speed was also distinct but linearly dependent on speed.

The minimal effect of the interactions on the total friction developed was then demonstrated through a series of related graphs. Each variable was isolated to illustrate its effects on the friction coefficient. The effects of the interaction combinations as a whole were cited and appropriate conclusions drawn.

A correlation study was then conducted between the stopping-distance and laboratory methods. Results indicated that at a ten percent level of significance the two methods had a correlation coefficient equivalent to zero. The fact that the laboratory method employed a

steady-state device and the field (stopping-distance) method a non-steady state instrument, was noted as the most likely reason for the absence of correlation. Insufficient and questionable validity of data were also cited as possible sources of variation.

Conclusions

The pressure imposed on the test specimen was concluded to be the governing factor of all the model componants in developing friction. The greater the pressure applied on the specimen, the higher the friction coefficient sustained. The rotational speed of the testing head was acknowledged as the second most important variable, with the greater speeds generating the higher friction coefficients. Treatment, on the basis of the statistical model chosen and the asphaltic treatments utilized in the analysis, was shown to be of the same magnitude of importance as speed, but of far less significance than pressure.

The two-and three-factor interactions demonstrated statistical significance, but failed to exhibit any substantial contribution to the development of friction. Thus, on this basis, the friction coefficient obtained was essentially a function of the applied pressure, with speed and treatment only minor contributions.

It was thus concluded that more data had to be gathered on a greater variety of surface treatments in order to determine whether the effect of treatment in the friction process was actually more significant than evidenced in the previous analysis.

If the new data was to display the same imbalance of contributing effects, then certain adjustments to the machine would have to be made in order to make "treatment" more of a controlling factor.

In addition to this, a number of other recommendations for future study were made. These were deemed not only desirable but also necessary for the final evaluation of the tester. They are outlined below.

Recommendations for Future Study

1. A further investigation of the direct effects of pressure should be made. Various pressures between 23 and 26 psi (and higher if possible) should be thoroughly examined.
2. The effect of the higher speeds in combination with the higher pressures should also be the subject of more scrutiny.
3. A correlation study should be made similar to the one conducted, however, field data should be obtained during the winter months. In this way, the effect of pavement temperature on road tests can be noted, and hence, a more complete analysis made.
4. A correlation study between the stopping-distance, Tapley decelerometer, and the laboratory tester should be made, with a minimum of three observations at fifteen test sites, in an attempt to fully relate the various methods.

APPENDICES

APPENDIX A

TESTS FOR STATISTICAL SIGNIFICANCE

Table A-1. Friction Coefficients for each Treatment-Pressure-Speed Combination

	Treatment 1 - 3/4" Asphaltic Concrete					
	P1=20 psi		P2=23 psi		P3-26 psi	
	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
S1=48 rpm	.254	.244	.328	.345	.410	.406
S2=72 rpm	.244	.254	.325	.345	.436	.436
S3=96 rpm	.268	.264	.345	.345	.426	.426

	Treatment 2 - Slurry Seal					
	P1=20 psi		P2=23 psi		P3=26 psi	
	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
S1=48 rpm	.226	.246	.325	.341	.436	.430
S2=72 rpm	.254	.254	.328	.355	.446	.426
S3=96 rpm	.286	.284	.345	.349	.436	.436

	Treatment 3 - 5/8" Asphaltic Concrete					
	P1=20 psi		P2=23 psi		P3=26 psi	
	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
S1=48 rpm	.233	.233	.325	.325	.416	.416
S2=72 rpm	.254	.254	.335	.335	.406	.416
S3=96 rpm	.274	.274	.355	.355	.430	.437

Table A-2. Analysis of Variance

Source	D.F.	Sum of Sq.	Mean Sq.	"F" Statistic
Total	54	6.52541		
Mean U	1	6.25396		
Corr. Total	53	0.27145		
T	2	0.00061	0.00031	7.625
P	2	0.26202	0.13101	3,275.250
S	2	0.00447	0.00223	55.750
(TP)	4	0.00030	0.00007	1.750
(TS)	4	0.00049	0.00012	3.000
(PS)	4	0.00102	0.00025	6.250
(TPS)	8	0.00130	0.00016	4.000
Error	27	0.00124	0.00004	

At the 5% level of significance the following F(numerator, denominator) were determined :

$F(2,27) = 3.35$

$F(4,27) = 2.73$

$F(8,27) = 2.31$

As can be seen, only the treatment-pressure interaction indicates insignificance (2.73>1.75).

Table A-3. Results of LSD Testing for all First Level Variables

Average friction coefficient obtained for each treatment over all speed-pressure combinations.

T1 = .339 T2 = .345 T3 = .337 LSD_x = 0.004

Average friction coefficient obtained for each pressure over all treatment-speed combinations.

P1 = .255 P2 = .339 P3 = .426 LSD_x = 0.004

Average friction coefficient obtained for each speed over all treatment-pressure combination.

S1 = .329 S2 = .339 S3 = .351 LSD_x = 0.004

Table A-4. Results of LSD Testing for all Two-Factor Interaction Components

(Friction Coefficients)

Speed-Pressure Interaction

	S1=48 rpm	S2=72 rpm	S3=96 rpm
P1=20 psi	.239	.252	.275
P2=23 psi	.331	.337	.349
P3-26 psi	.419	.428	.431

Treatment-Speed Interaction

	T1=3/4" AC	T2=S.S.	T3=5/8" A.C.
S1=48 rpm	.331	.334	.324
S2=72 rpm	.340	.343	.333
S3=96 rpm	.345	.346	.354

The Least Significant Difference value used in testing was 0.003.

Note: The Treatment-Pressure Interaction was shown to be insignificant, so LSD testing was unnecessary.

APPENDIX B

TESTS FOR CORRELATION WITH STOPPING-DISTANCE METHOD

Table B-1. Laboratory Friction Coefficients for Field Core Specimens

Test Site	Sample 1	Sample 2	Sample 3	Average Friction
TS-1	.365	.406	.406	.392
TS-2	.416	.416	.416	.416
TS-3	PCC	PCC	PCC	PCC
TS-4	.325	.335	.406	.355
TS-5	.325	.304	.365	.331
TS-6	.426	.294	---	.360*
TS-7	.325	.335	.335	.332
TS-8	.386	.345	.376	.369
TS-9	.284	.223	.294	.267
TS-10	.315	.335	.325	.325

*See Chapter 6 for explanation of useage in the correlation analysis.

Table B-2. Slope Factors Based 40-50 MPH Speed Interval

Test Site	Slope Factor (SF)(Friction/MPH)
TS-1	0.00317
TS-2	0.00390
TS-3	PCC
TS-4	Tests conducted only at 40 mph
TS-5	Tests conducted only at 40 mph
TS-6	0.00430
TS-7	0.00965
TS-8	0.000375
TS-9	0.00327
TS-10	0.00662

Note: Slope was either positive or negative depending on whether the actual test speed was above or below the designated 40 mph testing speed.

Table B-3. Spearman's Rank Correlation Coefficient Case 1. Nine Test Sites Used in the Correlation Study

Test Site	Lab Friction Values Laboratory Method	Rank	Field Friction Values Stopping-Distance M.	Rank	dr	dr^2
TS-1	.392	8	.687	8	0	0
TS-2	.416	9	.551	1	8	64
TS-3	---	-	---	-	-	-
TS-4	.355	5	.620	6	-1	1
TS-5	.331	3	.652	7	-4	16
TS-6	.360	6	.552	2	4	16
TS-7	.332	4	.696	9	-5	25
TS-8	.369	7	.564	3	4	16
TS-9	.267	1	.566	4	-3	9
TS-10	.325	2	.586	5	-3	9
						$\Sigma dr^2 = 156$

Correlation Coefficient = Rs

$$Rs = 1 \frac{-6\Sigma(dr^2)}{n(n^2 - 1)} = 1 \frac{-6(15b)}{9(80)} = 1 - 1.3 = - .300$$

Table B-4. Spearman's Rank Correlation Coefficient Case 2. Seven Test Sites Used in the Correlation Study

Test Site	Lab Friction Values Laboratory Method	Rank	Field Friction Values Stopping Distance M.	Rank	dr	dr^2
TS-1	.392	6	.687	6	0	0
TS-2	.416	7	.551	1	6	36
TS-6	.360	4	.552	2	2	4
TS-7	.332	3	.696	7	-4	16
TS-8	.369	5	.564	3	2	4
TS-9	.267	1	.566	4	-3	9
TS-10	.325	2	.586	5	-3	9
						$\Sigma dr^2 = 78$

$$Rs = 1 \frac{-6\Sigma(dr^2)}{n(n^2 - 1)} = 1 \frac{-6(78)}{7(48)} = 1 - 1.392 = -.392$$

Table B-5. Spearman's Rank Correlation Coefficient Case 3. Six Test Sites used in the Correlation Study

Test Site	Lab Friction Values Laboratory Method	Rank	Field Friction Values Stopping-Distance M.	Rank	dr	dr^2
TS-1	.392	5	.687	5	0	0
TS-2	.416	6	.551	1	5	25
TS-7	.332	3	.696	6	-3	9
TS-8	.369	4	.564	2	2	4
TS-9	.267	1	.566	3	-2	4
TS-10	.325	2	.586	4	-2	4
						$\Sigma dr^2 = 46$

$$Rs = 1 \frac{-6\Sigma(dr^2)}{n(n^2-1)} = 1 \frac{-6(46)}{6(35)} = 1 - 1.314 = - .314$$

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