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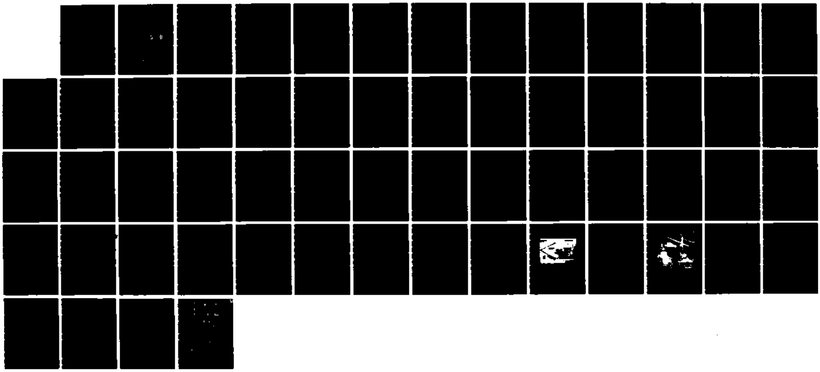

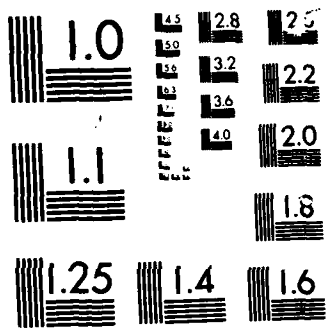

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Runway Rubber Removal Specification Development: Final Report

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October 1985

Final Report

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16. Abstract

The phenomenon of runway touchdown-zone rubber buildup is a potentially hazardous problem. Rubber buildup covers the runway surface and occludes the surface texture. This results in a reduced wet friction coefficient between the runway pavement and aircraft tires.

Methods and equipment are available for evaluating the wet friction coefficient; however, these methods are expensive and require highly trained personnel. Currently no guidelines have been established for determining the need and effectiveness of rubber removal. Therefore, most airport and airbase managers rely exclusively on visual impressions of rubber buildup in lieu of quantitative measurements.

Quantitative evaluation techniques are desirable for evaluating rubber buildup. An extensive literature review suggested that pavement surface texture measurement techniques are indicative of rubber buildup and resultant reduction in wet friction coefficients. A statistically designed field experiment determined that surface texture measurements were indicative of pavement friction levels; however, these relationships lacked the precision necessary for inclusion in performance specifications.

Discussed herein is a summary of previous work in developing a rubber removal specification, supporting evidence for the frictional performance criteria proposed in developing a coherent specification for rubber removal contracts, and proposed contract specification criteria for runway rubber removal.

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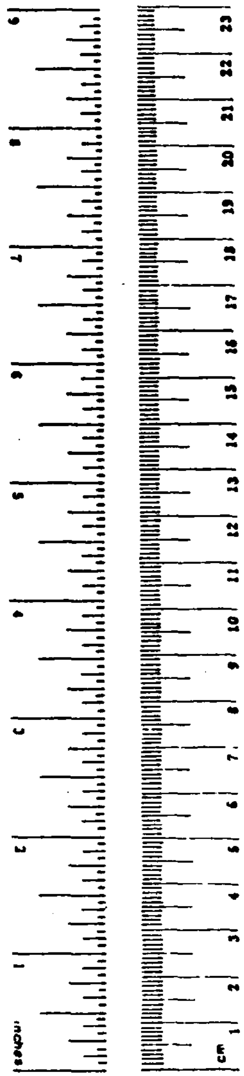
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

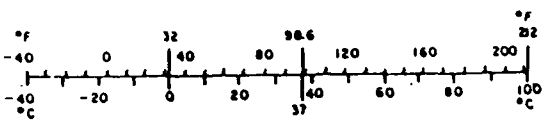
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



SECTION I
INTRODUCTION

OBJECTIVE

The objective of this effort was to develop a procedure for evaluating the frictional performance of runway rubber removal contracts. This procedure should be economical, easily implementable, and sensitive to changes in runway friction. From this procedure, criteria were developed for determining when runway rubber deposits should be removed and when these deposits have been effectively removed.

BACKGROUND

The higher operational speeds and heavier gross weights of modern aircraft require high shear forces generated at the tire-pavement interface for safe operation. These shear forces are dependent upon the available tire-pavement friction. Dry friction between the tire and clean pavement does not present a problem, because of the chemical and physical properties of tire rubber and the mechanical properties of the tire structure. However, once a lubricant, most commonly water from rainfall, is introduced at this interface, a serious loss of friction can occur. This loss of friction can be slight, as on damp pavement when the operator must reduce frictional demand during maneuvering to maintain directional control, or significant, as in the case of hydroplaning where the operator loses directional control of the vehicle.

Once a contaminant other than rainwater is placed on the pavement, the operational characteristics of the pavement change. Specifically, on a runway, rubber deposits formed by landing aircraft can dramatically reduce the wet frictional performance of the runway touchdown zone pavement. Since the touchdown zone is subjected to impact of the tires during landing, a certain amount of rubber is transferred from the tire to the pavement as a result of heat and abrasion produced when the aircraft tires spin-up. This rubber is deposited on the pavement surface in thin layers that adhere to the pavement materials. As subsequent rubber deposits increase to build up a significant layer thickness, several problems occur. They are (1) obliteration of pavement markings, (2) accumulation of loose debris on the runway surface, and (3) reduced wet frictional levels. Maintenance action is required to eliminate or reduce these problems to an acceptable level. Painting of pavement markings is a regular activity at all active airports; periodic sweeping of runway removes the loose debris; and rubber removal may restore the pavement's frictional properties.

The United States Air Force (USAF) and the Federal Aviation Administration (FAA) recommend periodic removal of runway touchdown-zone rubber deposits. Presently, the airport pavement engineer must rely heavily upon limited visual impressions and/or experience to determine when rubber removal is required and when it has adequately improved the pavement's frictional characteristics. Unfortunately, test results obtained by the USAF indicate that this visual/experience method of inspecting rubber deposits does not correlate well with the results obtained with a Mu-Meter (Reference 1). Since the Mu-Meter or other tire-pavement measurement equipment is expensive, requires highly trained personnel, and has limited usage, it is unavailable at many airfields. As a result, a cost-effective rubber removal program is needed, with guidelines indicating when rubber buildup is sufficient to warrant removal.

SCOPE

The New Mexico Engineering Research Institute (NMERI) was tasked to develop an alternate procedure to quantify the amount of rubber buildup and its effect on the frictional characteristics of runway pavement. This project was subdivided into the following five phases.

Rubber Removal Techniques and Equipment Review

This phase consisted of a review and research of existing rubber removal techniques. Effectiveness, cost, simplicity, safety, and environmental effects of the existing techniques were evaluated. The reviewed techniques were applied solely to Porous Friction Surfaces (PFS).

Permeability Equipment Evaluation for Porous Friction Surfaces

This phase required a review of existing techniques for evaluating permeability of Porous Friction Surfaces. During this review, the application of these techniques was evaluated, and measurement techniques were recommended.

Rubber Buildup Criteria and Evaluation Procedure Development

This first phase of the specification development consisted of a review of the existing techniques for evaluating pavement surface friction. Based upon this review, an evaluation procedure was developed which requires little special training, is insensitive to operator change, and is cost effective (less than $10,000 per installation to implement).

Rubber Buildup Parameters Development

This phase required the field testing of the evaluation procedure developed above. This evaluation was conducted before and after rubber removal at selected airports and airbases. Friction measurements using a self-watering Mu-Meter, along with five other candidate procedures, were obtained for future analysis and correlation. The field testing was conducted on various surface types including Portland Cement Concrete (PCC), Asphalt Concrete (AC), and PFS pavements.

Rubber Removal Specification Criteria Development

This final phase resulted in concise criteria for rubber removal contracts based on the self-watering Mu-Meter. The intent of this final product was to eliminate the undesirable attributes of existing visual/experience methods for determining rubber removal quality. Thus an efficient rubber removal program can be initiated.

All of the aforementioned topics have been completed and, except for the specification critria, are reported upon elsewhere (References 2, 3, 4, and 5).

This report summarizes the findings of the previous reports with primary emphasis on the results of the specification critria; the evolution of rubber removal performance criteria based upon the frictional characteristics of the pavement.

SECTION II
OVERVIEW OF PREVIOUS WORK

This section discusses the results from previous reports (References 2, 3, 4, and 5,). Since References 2 and 3 were concerned solely with Porous Friction Surfaces, they will be discussed first, with the discussion of References 4 and 5, developing the background for the rubber removal criteria development, presented in Section III.

RUBBER REMOVAL TECHNIQUES AND EQUIPMENT

This phase was interested in the question of rubber removal from Porous Friction Surfaces. The National Runway Friction Measurement Program (NRFMP) (Reference 6) indicated that 38 test sections had significant rubber buildup which reduced the mean Mu value from 77.5 to 67.5. This reduction yields a friction coefficient well above the accepted minimum. Furthermore, only 3 PFS test sections were below the generally accepted minimum of 50. This clearly indicates that PFS pavements retain acceptable friction characteristics. They also indicated that during the course of their survey, no rubber was removed from PFS pavements.

From this information, three questions were formulated:

1. Is it necessary to remove rubber from PFS?

2. Is it possible to remove rubber from PFS?

3. If so, what is the best method for doing so?

Beginning with the first question, rubber deposits are cumulative. Each layer of rubber occludes or clogs more of the drainage capacity of PFS. Thus, a 30 percent rubber accumulation, as indicated by NRFMP, may not cause the critical blockage of bulk water drainage paths necessary to cause a drastic reduction in friction. However, continued rubber buildup would eventually cause this blockage to occur. Aggravating this problem is chemical and/or physical changes that occur when rubber is allowed to age on the runway. This aging process may cause stronger adhesional bonds between the rubber and pavement materials. The result is the rubber deposits are much harder to remove, increasing the possibility of damage to the runway during cleaning. Therefore, if traffic loadings are such that rubber buildup occurs, excess rubber should be periodically removed from the PFS.

Secondly, it is possible to remove rubber from a PFS pavement. The only method that has been used is the high pressure water method. No other available method was found in an earlier investigation that offers a significant advantage (Reference 2). However, the PFS pavement must be in good repair, properly constructed, and rubber must be removed regularly. If any of the following three conditions are not satisfied, damage to the surface can result:

1. The PFS must be in good repair. The high water pressures used in rubber removal can aggravate the problems of raveling, patches, and reflective cracking.

2. The PFS must be properly constructed. Inadequate bonding between aggregate and asphalt, delamination of the overlay, and improper sealing of the base pavement are aggravated by the high pressures of the water.

3. Rubber deposits must be removed regularly. Long term physical and/or chemical interactions between the rubber and the paving materials make rubber removal extremely difficult.

Finally, of the rubber removal methods investigated, only high pressure water techniques were found to be viable methods for removal.

PERMEABILITY EQUIPMENT FOR POROUS FRICTION SURFACES

The previous paragraphs discussed the possibility of removing rubber from PFS pavement. It was found that a moderately heavy deposit of rubber did not decrease the frictional characteristics of the runway pavement below the generally accepted minimum of 50 MuN. A literature review was initiated to determine methods of measuring the bulk water drainage capacity of PFS pavement. Since this report (Reference 3) was intended to identify and recommend methods to measure the apparent permeability of PFS, no correlation of friction levels to permeability was performed.

This earlier report reviewed existing literature to determine devices currently used to evaluate the bulk water drainage capacity of PFS pavement. Also included in this report is a review of various studies on PFS which investigated various aspects of the serviceability as they are affected by construction, mix design, traffic loading, weather, maintenance, construction, and contaminants. This section places emphasis on devices used to determine the drainage capacity of PFS pavements, and the methods employed in measuring this drainage.

Bulk water drainage of PFS pavement is derived from two sources; pavement permeability and outflow through the pavements macrotexture. Permeability is based on an experiment by Darcy in the 1900s. In this experiment, he discovered a one-dimensional relationship between flow rates and area, pressure drop, and length of the water flow path. In the laboratory, all these parameters can be measured, thus a constant permeability (k) can be determined. However, in field testing, the area of flow must be assumed as the discharge area of the measuring device and the length of flow must also be assumed, therefore the stated permeability constant (k) is dependent upon the device used and the assumptions made. Since no standard method of assuming either of these quantities was found in the literature, comparisons between test results were difficult. Complicating this problem, the bulk drainage of PFS is derived from two sources; the permeability of the thin overlay, and the drainage channels formed by its high macrotexture. Therefore, an applicable permeability device should be of an outflow configuration, that is, the device should measure the rate at which water can escape from under a device through both the surface voids and the pervious overlay. Details of this selection are given in a previous report (Reference 3), with the most appropriate device being the WES permeability testing device described in Appendix A of this report.

RUBBER BUILDUP CRITERIA AND EVALUATION PROCEDURE DEVELOPMENT

This work developed the theoretical background and a review of the existing friction measuring techniques currently used. The earlier report (Reference 4) determined that the theoretical basis of determining friction levels as measured by the pavement's textural characteristics, warranted investigation. Thus, an experiment was statistically designed to determine which texture measurement techniques could predict friction levels as determined by the Mu-Meter. Included in this section is a short discussion of texture measurements, how they relate to friction, the design constraints of the experiment, and the designed experiment.

Tire-pavement friction is a complex phenomenon that can be measured directly by any one of a variety of friction test devices which use standard test tires, or may be estimated by measurement of the pavement's textural characteristics. Reference 4 discusses the various friction test modes and related devices and indicates the general relationships between them. This study was asked to design an experiment that would economically define the differences in friction caused by both rubber buildup and its subsequent removal. The use of texture measurements was believed to be the only economical method to accomplish this task. An experiment was designed that would define the pavements textural characteristics that would characterize the frictional response measured by a yawed tire test device (Mu-Meter) and develop performance specifications for rubber removal contracts.

The pavement's textural characteristics are believed to govern the tire-pavement's response to roughness, noise generation, and friction. This texture is subdivided into two frequency bands by Moore (Reference 7). These are: macrotexture and microtexture. The pavement macrotexture is the individual asperities or stones that protrude above the pavement surface. The microtexture is the finer asperities or grit on the larger asperities. Figure 1 illustrates the difference between microtexture and macrotexture. According to Moore (Reference 7), typical wavelengths (λ) associated with macrotexture are 6 to 20 mm (0.25 to 0.80 inch), and for microtexture are 10 to 100 μm (0.0004 to 0.004 inch).

It is generally believed that measurements of these two texture bands will estimate the pavement's frictional levels. Therefore, from a review of the of the currently used texture measurement techniques, five candidate procedures were selected. These procedures were subjected to the following constraints:

1. Economic; costing less than $10,000 to implement.

2. Simple; tests and techniques must be easy to understand and use by typical airport personnel.

3. Reliable and sensitive; must be able to predict friction and differences in friction levels due to rubber removal.

4. Readily accepted; tests that are currently available and do not require excessive research and development to substantiate.

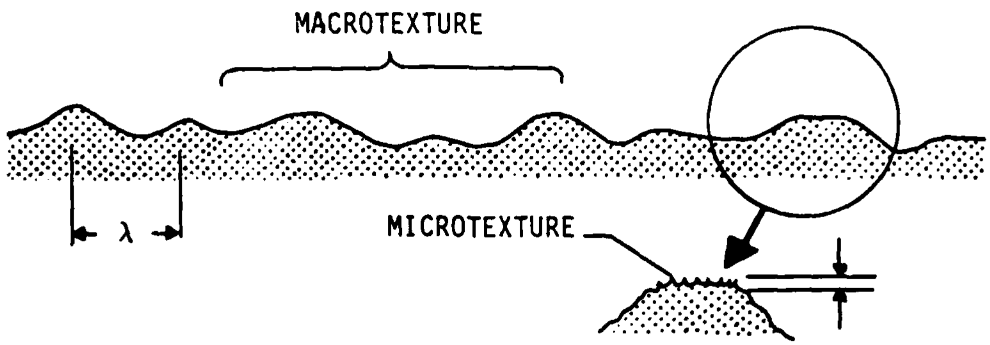


FIGURE 1. PAVEMENT ROUGHNESS INDICATING MACROTEXTURE AND MICROTEXTURE (REFERENCE 7).

The following test techniques, summarized in Table 1, were selected for use in the field experiment. The Mu-Meter was used for determining the direct tire-pavement friction levels. The sand patch and silicone putty volumetric procedures were used to measure the average texture depth indicative of macrotexture. The Penn State drag tester and chalk wear tester were used to quantify microtexture. Stereophotography was used to quantify both micro- and macrotexture.

TABLE 1. SELECTED FIELD PROCEDURES (REFERENCE 4)

Tire-pavement Friction	Mu-Meter (ASTM E-670)
Macrotexture	Sand Patch Volumetric Technique (ASTM E-965) Silicone Putty Volumetric Procedure
Microtexture	Penn State Drag Tester Chalk Wear Tester
Combined Micro/Macro	Stereophotography

Since the intent of this experiment was both to evaluate runway touchdown zone friction levels before and after rubber removal, and to correlate the pavement's textural properties to friction levels as measured by the Mu-Meter, various theoretical concepts were considered. First, rubber removal is not always 100 percent effective in increasing the friction levels of the pavement. Therefore, two control sections were included which would determine the effects of both weathering and traffic polish, and indicate the maximum obtainable friction level on any particular pavement. This concept is further illustrated in Figure 2. In this figure there are three theoretical friction curves. The lowest curve is the rubber-contaminated zone before removal. It has the smallest intercept and the largest negative slope due to the rubber deposits coating the microtexture and occluding the macrotexture. The middle curve is representative of the rubber zone after removal. This curve has a

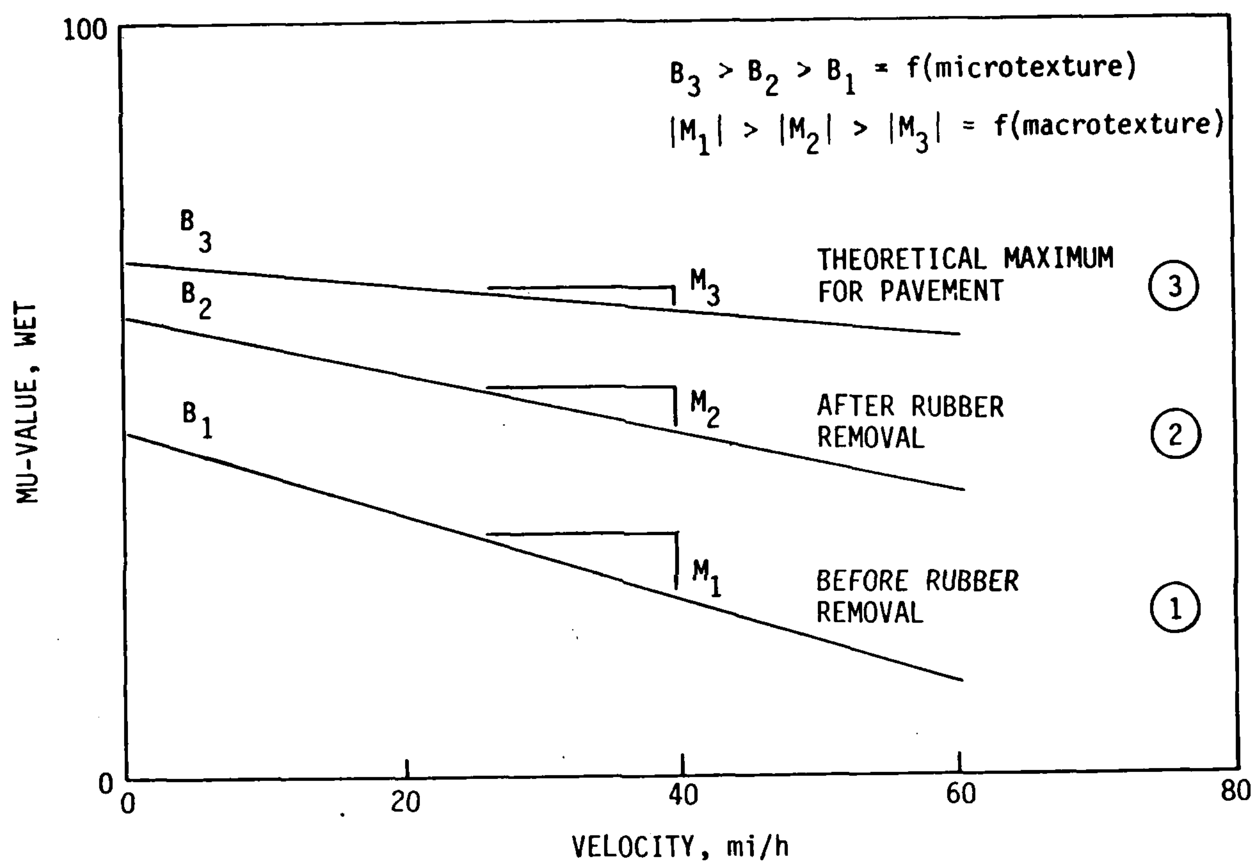


FIGURE 2. THEORETICAL FRICTION CURVES (REFERENCE 4)

larger intercept due to increased microtexture and a decreased negative gradient due to the increase of the pavement's macrotexture. The upper curve is indicative of the control sections. The clean pavement's microtexture allows large adhesional friction forces to form and, since the pavement's macrotexture provides good bulk water drainage, the frictional decline with speed is less.

The test matrix (Figure 3) collected both wet and dry Mu-Meter values at 32, 48, and 96 km/h (20, 40, and 60 mi/h), pavement temperatures corresponding to each Mu-Meter run, sand patch average texture depth, silicone putty average texture depth, both wet and dry Penn State drag test numbers (DTN) in both the longitudinal and transverse directions, chalk wear coefficients as measured by the chalk wear tester in the longitudinal and transverse directions, and two sets of stereophoto pairs for each repetition. The various wet Mu-Meter test speeds [32, 48, and 96 km/h (20, 40, and 60 mi/h)] were used to develop friction speed curves as discussed previously. In addition, dry Mu-Meter testing was performed to determine an ultimate friction value.

Since the Mu-Meter provides an analog output of friction over a given test section, a point-by-point comparison of Mu-Meter testing with the five candidate procedures was performed. This comparison was performed by using a standard test section as shown in Figure 4. Three distinct sections were analyzed. These included a centerline rubber section, tested before and after rubber removal, a centerline non-rubber section, and a pavement edge non-rubber section. Within each section, three locations, placed at the quarter points of the section, approximately 120 feet apart, were tested in a random sequence with two repetitions per location. Since analysis of the effect of both rubber buildup and removal of this buildup on any specific pavement required control sections to gauge its effectiveness, two control sections were used. The centerline nonrubber control section was tested to judge the possible effects of traffic polish. The pavement edge nonrubber section was included to determine the possible effects of weathering and the maximum friction level for any given pavement texture. Each of the selections was tested on pavement of the same material and surface texture as the rubber buildup area, enabling comparisons to be valid.

The statistical approach described above was used in collecting a data base to find meaningful relationships between the friction levels measured by the Mu-Meter and texture measurements. Since runway access time for testing was limited, two replicative measurements were taken at each location to analyze test variability.

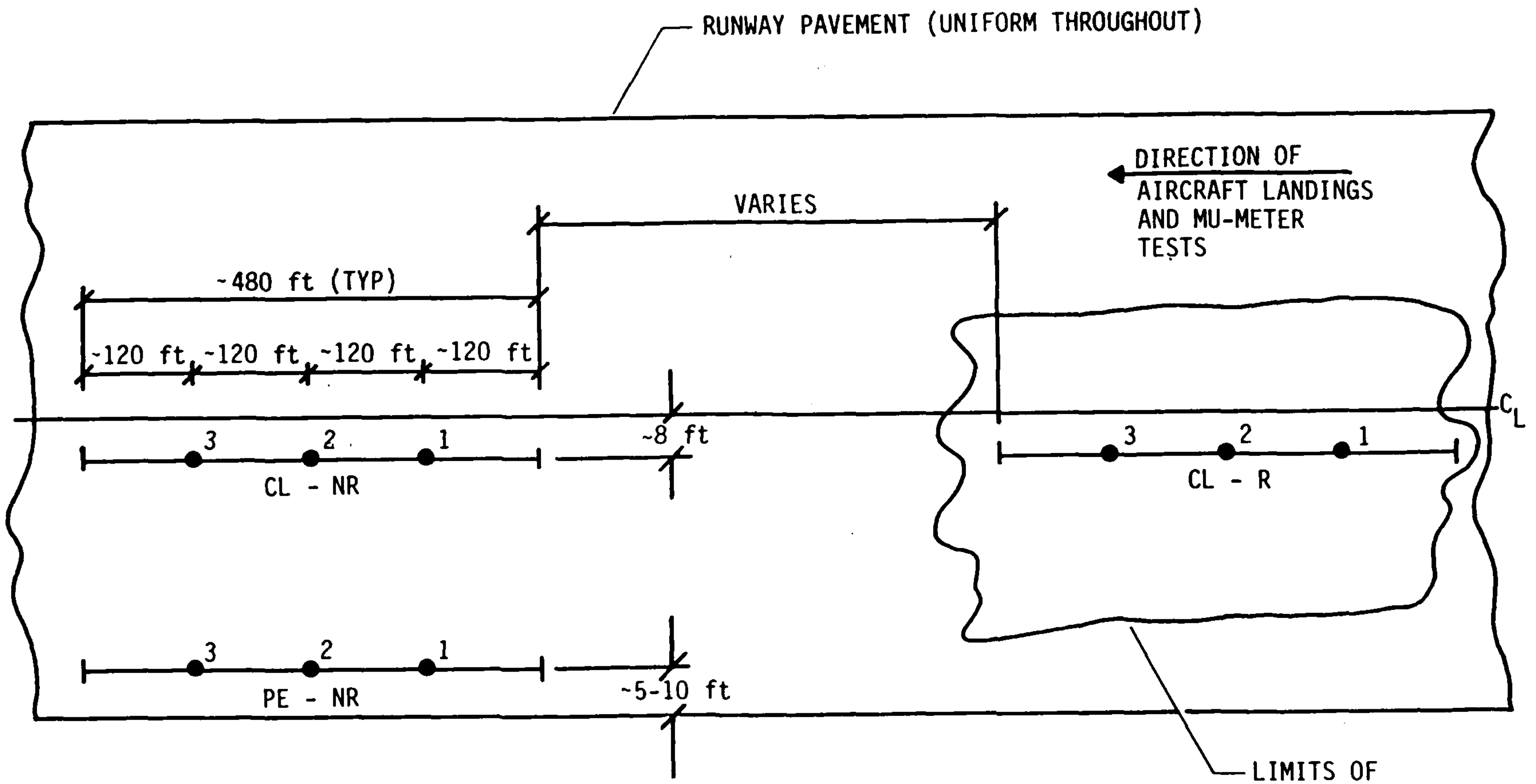
Reference 4 includes a test series on the repeatability of the volumetric average texture depth techniques. This experiment analyzed the variability of three test techniques (sand patch, silicone putty, and NASA grease smear) on two control surfaces. Based upon the results of this experiment, the two macrotexture tests (sand patch and silicone putty) were selected for use. Also included in this report is the analysis and design of both the Mu-Meter self-watering system and the Mu-Meter nozzle. Appendix B shows a detailed drawing of this nozzle.

Summarizing this section, the various candidate procedures, the two macrotexture (sand patch and silicone putty average texture depth procedures) and two microtexture (chalk wear tester and the Penn State drag tester), along with the combined micro/macrotexture test (stereophotography) were thought

TEST SECTION		Test Location	TEST PROCEDURES																						
			Mu-Meter (Mu values and temperatures)												Candidate Procedures										
			20 mi/h				40 mi/h				60 mi/h				Sand Patch, x.0001 in	Silicone Putty, x.0001 in	Penn State Drag Test (Drag test number and temp.)						Chalk Test Chalk Wear, x.0001 in		Stereo Photography
																	Dry			Wet					
			Dry	Temp.	Wet	Temp.	Dry	Temp.	Wet	Temp.	Dry	Temp.	Wet	Temp.			Long	Trans.	Temp.	Long	Trans.	Temp.	Long.	Trans.	
Center Line - Rubber Area	Before Rubber Removal	1																							
		2																							
		3																							
	After Rubber Removal	1																							
		2																							
		3																							
Center Line Nonrubber Area		1																							
		2																							
		3																							
Pavement Edge Nonrubber Area		1																							
		2																							
		3																							

Notes "Temp." is pavement temperature in degrees Fahrenheit.
Two repetitions per cell (four for stereophotography).
"Long." is longitudinal direction of runway.
"Trans." is transverse direction of runway.

FIGURE 3. FIELD EVALUATION TEST MATRIX (REFERENCE 4)



TEST SECTION

CL - R: CENTERLINE - RUBBER AREA

CL - NR: CENTERLINE - NON-RUBBER AREA

PE - NR: PAVEMENT EDGE - NON-RUBBER AREA

TEST LOCATIONS

1, 2, and 3 PER TEST SECTION

FIGURE 4. TYPICAL TEST SECTION LAYOUT (REFERENCE 4)

capable of predicting pavement friction levels as measured by the Mu-Meter. A statistical experiment was designed to evaluate this hypothesis. The empirical and theoretical basis for this experiment is explained in detail in an earlier report (Reference 4).

RUBBER BUILDUP PARAMETERS DEVELOPMENT

This phase discussed the results of the field experiment described previously using texture measurements to predict friction levels. In an earlier report (Reference 5), the theoretical background of pavement friction is developed in detail and the data collected from the field experiment (excluding stereophotography) was analyzed and used to statistically investigate various hypotheses on how texture measurements can predict friction levels. The stereophoto pairs obtained during the field experiment were not analyzed during this effort because the desired source, which was to reduce the data from the stereophoto pairs, was unable to perform the work within the time constraints of this project. Also included is a discussion of the practical value of these friction prediction models with the strong and weak points outlined.

Tire-pavement friction is a very complex phenomenon. It is commonly thought to be a combination of two mechanisms: adhesional and hysteretic friction. Adhesional friction is energy dissipated at the surface of the rubber surface interface caused by the making and breaking of bonds. This phenomenon has been studied by many researchers who have attempted to explain the adhesional nature of rubber compounds. However, to date only approximate relationships have been determined. Thus, the physical laws governing this phenomenon have yet to be discovered. Likewise, hysteretic friction, which is energy dissipated within the rubber bulk due to the stress relaxation, is not fully understood. Thus the determination of rubber friction without the added complexities of lubrication, tire stiffness, inflation pressure, and tread patterns is difficult. The use of a standard frictional test device using standard test tires, such as the Mu-Meter, holds many of these confounding variables constant. Through the use of such devices, the influence of other surface or pavement parameters can be investigated.

Pavement texture, as previously stated, is generally thought to be able to predict pavement friction levels as determined by a standard tire-pavement friction device. In this experiment, various texture and corresponding friction measurements were collected in an attempt to predict friction levels from texture measurements. Since the statistical inferences of using one or more variables to predict the levels of another are based upon the variability of the predicting variables, or the confidence of knowing the predictor variable, a short discussion of the test variability is given.

The variables used in this experiment were stated previously and are summarized in Table 1. For brevity, only the significant variables are discussed herein. These variables are the response variable (Mu-Meter friction levels, MuN) and the following predictor or candidate procedures: SAP (sand patch average texture depth measured in 10^{-4} inch) and CTL and CTT (chalk wear coefficients expressed in 10^{-4} in./ft, measured in the longitudinal and transverse directions respectively).

The Mu-Meter test results, expressed in MuN, were found to have a low standard deviation of approximately 2 MuN. This low standard deviation is in agreement with earlier published results (Reference 8) and indicates the high repeatability of this measurement.

The various candidate procedures did not fair as well. This is evidenced by their higher variation. Therefore, the true measured value is more difficult to determine. For example, the sand patch average texture depth had a standard deviation of approximately 4 milliinches or 4×10^{-3} inch. Thus, on low-textured pavements, where the measured average texture depth was 10 milliinches or 10×10^{-3} inch, the standard deviation approached one half of the mean value, making the determination of a true measured value difficult. Likewise, the standard deviation of the chalk wear coefficients (CTL and CTT) was approximately 15×10^{-4} in./ft. This high standard deviation presented a similar problem to that of the sand patch average texture depth. Therefore, the high variability of these tests has a strong influence in determining the reliability of the regression or prediction equations given later. Detailed descriptions of the sand patch volumetric technique and chalk wear tester procedures are given in Appendix C.

The collected field data were also used to investigate four methods of predicting friction from texture measurements. These were:

1. Predicting the friction value of the pavement by a combination of a microtexture term times a macrotexture term as first proposed by D. Burk (Reference 9) and reported upon by the authors in an earlier report (Reference 10).

2. Predicting the slope and intercept of a linear wet friction speed curve analogous to the exponential curve presented by Leu and Henry (Reference 11) for locked wheel correlations, with macrotexture predicting the slope and microtexture predicting the intercept.

3. Predicting pavement drainage coefficients C_{mac} and C_{mic} as proposed by Horne and Buhlmann (Reference 12). Using microtexture to predict C_{mic} and macrotexture to predict C_{mac}, these can be used to compute the friction level of any given pavement.

4. Directly predicting the friction levels of pavement by a linear combination of a microtexture and macrotexture term in the form of:

$$Mu(micro,macro) = \beta_0 + \beta_1(micro) + \beta_2(macro) \qquad (1)$$

Each of these models were capable of estimating friction levels, however, the predictions were not adequate for use in a performance specification. Therefore, only the best model that can be used to estimate friction levels before rubber removal is discussed herein.

The best predictive model found was of the form of the fourth method, namely;

$$MW40 = \beta_0 + \beta_1 LSAP + \beta_2 CTL + \beta_3 CTT \qquad (2)$$

or

$$MW40 = -53 + 16.0\ LSAP + 0.080\ CTL + 0.12\ CTT \qquad (3)$$

$$R = 0.88$$

$$\sqrt{MSE} = 6.43$$

where MW40 is the 40 mi/h wet MuN, β_0, β_1, β_2, and β_3 are the regression coefficients, LSAP is the natural log of the average texture depth as measured by the sand patch volumetric procedure expressed in 10^{-4} inch, CTL and CTT are the chalk wear coefficients expressed in 10^{-4} in./ft measured by the chalk wear tester in the longitudinal and transverse directions respectively, R is the regression coefficient, and $\sqrt{MSE}$ is the root mean square error or the standard error of prediction expressed in MuN. This model may be used to estimate the friction level of a rubber contaminated pavement and used as a basis for determining when this section is approaching a critical value. However, engineering judgment is required in the use of this model and it should be verified by Mu-Meter testing if this value is to be used for the intent of the specification given in the next section. Since confidence intervals of prediction are determined by both the root mean square error and the distance the predictor variable is from the mean on which the regression model was based, confidence intervals for this equation are difficult to determine. However, most values will be within twice the root mean square error of the predicted values. Thus, this equation will determine friction levels within +/- 13 MuN. A plot of MuN values predicted by this equation, versus measured MuN values is given in Appendix D.

The following conclusions can be reached as a result of this field experiment.

The influence of average texture depth on higher friction levels is strongly evident. This is based upon the strong correlations between average texture depth and the wet 64 km/h (40 mi/h) Mu-Meter testing. MacLennan et al. (Reference 6) reached this same conclusion in the National Runway Friction Measurement Program. However, they state that measurement of friction rather than texture is a preferable basis for planning routine runway maintenance. The results of this experiment verify this conclusion for the following four reasons:

1. The measurement of macrotexture by either the sand patch or the silicone putty volumetric procedures is an inexpensive method of quantifying macrotexture. However, important parameters of macrotexture are not measured by these procedures. Average texture depths do not determine the general shape of the pavement asperities; in addition, nonconnected voids measured by these methods do not help in the removal of bulk water. Each of these parameters is deemed important in the friction literature, yet, their influence has not been empirically validated. Furthermore, the techniques necessary to measure these parameters are more expensive and require highly trained personnel, thus defeating the purpose of this experiment. However, the use of more sophisticated techniques may not yield better results.

2. The measurement of microtexture has an elusive quality. The correlations of microtexture measurements to either the intercept of a friction speed curve or to the dry Mu-Meter tests, which is generally believed to correlate, is evidence that microtexture could not be measured by the simple methods used in this experiment. Current technology has not developed an alternate method of measuring this textural band.

3. The Mu-Meter was designed to determine averages in friction over an extended length, usually a 152.4 meter (500 foot) test section. Being designed for such use, the system dampening caused by both the test tires and the hydraulics of the load cell make this device insensitive to all but extreme localized texture variations.

4. The measurement of texture to determine friction levels of a pavement will only give an indication or an approximation of values measured by a friction test device. For this reason, if the need arises to measure friction closely for performance specifications, a friction measuring device on which acceptance levels were previously established should be used.

The following recommendations are stated as a result of the above described experiment and resultant analysis.

1. The use of highly textured pavements or use of grooving systems is essential in retaining high friction levels in rubber contaminated zones. Thus, the use of these highly textured pavements is strongly recommended.

2. The use of texture measurements to determine accurately the friction levels of a pavement cannot be accomplished with present technology. Therefore, the use of texture measurements should only be used as a guide in determining friction levels.

3. Alternate methods of measuring or quantifying the microtexture of pavement is required to predict friction from texture measurements. These methods must be researched to empirically determine microtexture's role in pavement friction.

4. Alternate methods of measuring the pavement's macrotexture should be investigated. Emphasis should be given to nonconnected voids, asperity density, asperity shape, and profiles of the pavement's macrotexture.

5. Investigations into the analysis of stereophoto pairs in determining the density and shape of the asperities, volume of nonconnected voids, and profiles of the pavement's macrotexture should be conducted. These parameters arise often in friction literature, yet detailed analysis of such a procedure has not been reported. This method, if analyzed by a computer algorithm, would be insensitive to operator error and therefore, would be able to determine the true variability of the pavement texture. Furthermore, if the resolution of the stereophoto pairs was fine, the role of microtexture in determining pavement friction may be better defined.

SECTION III
SPECIFICATION CRITERIA DEVELOPMENT

Research findings and technological advances in recent years have helped alleviate (but not eliminate) the hazards associated with adverse-weather aircraft operations. Conversely, better avionics, growth in aircraft fleets, airport/runway congestion, and economics are factors which have increased the frequency of aircraft ground operations during inclement weather. However, pilots still prefer landing into the wind on a long, clean, dry runway, keeping to a minimum the number of challenging situations which can arise during operations on slippery runways with fluctuating crosswinds. Improvement in aircraft braking systems, pilot simulator training programs, and runway surface treatments have tended to increase safety margins, but weather related accidents still occur. Timely removal of touchdown rubber buildups can help reduce skidding accidents during inclement weather by increasing the friction level of the pavement, thereby increasing the pilot control of the aircraft.

Rubber deposits formed by landing aircraft can dramatically reduce the wet frictional performance of the runway touchdown-zone pavement. These rubber deposits are formed by rubber being transferred from the tire to the pavement as a result of heat and abrasion produced when the aircraft tires spin up. These deposits form gradually by one tire footprint overlaying another until a sufficient thickness is present which coats the surface texture. As the rubber becomes thicker, the pavement texture is occluded, resulting in a substantial reduction in friction. Therefore, rubber deposits on high traffic runways is a persistent problem.

The rubber buildup problem is just one aspect of a runway maintenance program. A cost effective solution to this problem is timely removal of rubber deposits. This can be accomplished by a variety of available techniques. Among these techniques are removing rubber by sand blasting, shot blasting, water blasting, milling and chemical washing methods. However, to best utilize these techniques with minimal damage to the runway pavement, rubber should be removed regularly, but only when needed, before its removal becomes difficult. However, a too high rubber removal frequency may cause other maintenance problems, such as accelerated polishing of the pavement texture, or shorter joint sealant life.

The following criteria are required to achieve rational cost-effective maintenance scheduling, while retaining the safety of the pavement:

1. An accepted and widely available friction rating system must be established and used. This system must be capable of rating the frictional properties of the pavement, being sensitive to changes due to rubber buildup.

2. A value, based upon the above rating system, must be set for determining when remedial action is required to improve the frictional safety of the runway.

3. An economical solution to correct the unsafe runway should exist. Specifically, with rubber deposits on the runway, rubber removal may raise the frictional level above the critical limit.

4. A check of the friction should be made to determine if the remedial action corrected the unsafe condition.

In 1968, studies were conducted at Wallops Island, Virginia, jointly by the National Aeronautics and Space Administration (NASA), the FAA, and the British Ministry of Technology to relate the friction value, as determined by a test device, to aircraft braking performance (Reference 13). From these studies, they developed standard values to be used for determining when friction was below a critical level. The generally accepted levels of wet friction value (MuN from the Mu-Meter, and stopping distance ratios (SDR), which are the ratio of the wet stopping distance of a diagonal braked vehicle to stopping distance on dry pavement) and associated hydroplaning potential are shown in Table 2.

TABLE 2. HYDROPLANING POTENTIAL (REFERENCE 1)

MuN (40 mi/h)	SDR (60 mi/h)	Aircraft Braking Response	Hydroplaning Response
>50	1.0 - 2.5	Good	No Hydroplaning Potential
42 - 50	2.5 - 3.2	Fair	Transitional (Not Well Defined)
25 - 41	3.2 - 4.4	Poor	Potential for Hydroplaning
<25	>4.4	Unacceptable	Hydroplaning Potential High

The limited studies performed at Wallops Island serve as a yardstick to relate friction levels to aircraft braking performance. Since the true relationship of how the Mu-Meter relates to aircraft, or whether or not side force friction is the correct or most critical quantity to measure has yet to be determined. Therefore, research by NASA and FAA is continuing in this area to determine both analytically and empirically the relationships between friction test devices and aircraft tire-pavement frictional performance. However, this standard was proposed to equip pavement engineers with some means of deciding when slick is slick. This standard is currently used to rate runway friction and provide guidelines to enhance the safety of modern runways.

Since no other generally accepted standard exists for other types of test equipment, correlations between the Mu-Meter and other friction equipment have been conducted by the FAA as an acceptance criteria for their use and reliability. Correlation studies between various frictional test devices have also been performed by NASA, FAA, USAF, British Ministry of Transport, and other interested agencies with the intent to both understand the general theory of tire-pavement friction, which in many ways is still in its infancy, and to provide better methods to economically and reliably measure friction. As a result of these studies, relative levels of tire-pavement friction can be determined and generally compared to another device. However, the measured friction values sensitivity to the design of both the tire and the measuring system make definitive relationships impracticable. Therefore, when reporting tire pavement friction levels, careful attention must be given to the testing conditions and devices used.

In the United States, both the United States Air Force (USAF) and the Federal Aviation Administration (FAA) use friction values determined by the

Mu-Meter to rate relative runway friction levels. This device is currently being used by the USAF for runway friction surveys and for accident investigations. However, the USAF has only one team that performs this service worldwide, thus limiting its use for routine maintenance checks necessary for rubber removal scheduling and performance checks. Likewise the FAA has set advisory standards for runway friction based upon this device. In 1978, the National Runway Friction Measurement Program (Reference 6) evaluated airports nationally to determine the influence of rubber buildup, the effectiveness of various pavement surface texturing, and where corrective action was necessary. However, this method of runway rating is not used for routine maintenance because of its operating expenses. It is primarily used for further research and for performance specifications of costly corrective action such as new pavements or overlays. The initial cost of the Mu-Meter and tow vehicle, and the cost of training personnel make widespread usage of this device for routine maintenance impractical. Therefore, another method for runway rating is desirable for economical maintenance checks.

Remedial actions used to improve the friction levels of runways have been many and varied. These actions include costly replacements of existing runways with new pavement textural characteristics improving the safety of the runway, installation of pavement grooving systems to reduce the hydroplaning potential of a low textured pavement, use of porous friction overlays, and removal of touchdown zone rubber. Frictional level acceptance criteria are used for most of these projects with the exception of rubber removal where economic constraints prevail. Typically, a larger dollar contract can justify performance specifications which may be expensive to run yet are a small percentage of the total contract. Thus, compliance of the pavements frictional properties can be checked against specifications. This does not hold true for the lower cost rubber removal contracts where testing consumes a fair share of the budget. Therefore, acceptance of adequate rubber removal is still subjectively determined by visual/experience methods. For example, many pavement engineers or airport managers decide to remove rubber when individual tire footprints are no longer distinguishable, and judge acceptance by a subjective visual removal of 90 percent of the builtup rubber.

The field experiment conducted and described in Reference 5 determined that only a 3 MuN increase in average friction levels was noted before and after removal. This slight increase implied that either rubber removal was performed ineffectively, or was not required at many airports and air bases. This increase was not consistent on all runways, therefore the unnecessary removal of rubber at some of the runways may have biased these results. As a result of this, these three questions were raised:

1. Was the runway friction level below a hazardous value?

2. Is removal of the rubber deposits likely to improve the runway friction significantly?

3. Was the removal of rubber effective in increasing the friction of the runway?

The following pages describe the methodology used in answering these three questions.

Utilizing the mean friction levels of three sections, a rubber contaminated section before removal, a rubber contaminated section after removal, and a clean pavement edge control section, Table 3 describes the data used to initiate a procedure answering the preceding questions. Table 3 lists the identity of the runway (A through R), the primary usage of each runway (military or commercial), the mean friction level before rubber removal (Mu_B), the mean friction level after removal (Mu_A), the mean friction level of the pavement edge control section (Mu_C), the difference in the friction levels between the clean control pavement and the rubber contaminated section before removal (Mu_C - Mu_B), the improvement in friction level, or the difference between before and after rubber removal (Mu_A - Mu_B), the ratio of the improvement, which is the improvement noted by removal divided by the maximum attainable friction as determined by the difference between the contaminated zone before removal and the clean pavement [(Mu_A - Mu_B)/(Mu_C-Mu_B)], a judgment whether the removal was effective in increasing the friction level (Y or N), and a code identifying which contractor removed the rubber (A, B, C, or D). This table is ordered by the increasing differences between the control section and the rubber contaminated section before removal. This ordering provided insight in determining whether rubber removal was likely to improve the runway friction. An expected improvement line separating the runways on which improvement is unlikely from those where improvement is likely is shown on this table. This concept is discussed in more detail in the later part of this section. Before continuing with the procedure used to answer the three questions, a discussion of the contents of Table 3 is presented.

The first heading (FAC I.D.) is an identification code for the runways tested. This code is consistent with the coding of the data listing in Reference 5. In this earlier report, each runway is described with a complete listing of the data in Appendix C of that report.

The second heading (FACTYPE) identifies the primary usage of the runway. The three usage codes are: AFB (Air Force Base which is a USAF military runway where the traffic is predominately military aircraft), CAF (commercial air facility where traffic is predominately commercial air traffic), and NAS (Naval Air Station where the traffic is both carrier aircraft and supply planes). Since rubber buildup is a function of the number of landings, the type of aircraft, and the tire tread rubber, the amount of rubber buildup and composition of this buildup may have been different between these groupings. This, coupled with the differences in pavement texturing and maintenance budgets between commercial and military runways, may explain the fact that most of the military runways tested had sufficient rubber buildup to warrant removal. Pavement texture determines the volume of rubber required for a marked reduction in friction, and as stated earlier, is a strong indicator of pavement friction levels. Thus, higher macrotexture values are indicative of higher friction levels and correspondingly, more rubber would be needed to fill these surface voids to cause a reduction in frictional values. MacLennan et al. (Reference 6) in the National Runway Friction Measurement Program, determined that surfaces with higher average texture depths sustained more landings before a critical rubber buildup was reached. Figure 5 illustrates this point with four pavement texture types: asphalt, concrete, grooved concrete, and grooved asphalt. As noted in this graph, comparing rubber buildup versus cumulative landings of aircraft, the two low textured surfaces, asphalt and concrete, have much steeper slopes indicating the necessity of more frequent rubber removal. Whereas the grooved pavements required removal only 1/4 to

TABLE 3. ANALYSIS OF RUNWAY FRICTION DATA

		Friction							
FAC I.D.	FACTYPE	Before Removal Mu_B, MuN	After Removal Mu_A, MuN	Control Section Mu_C, MuN	Mu_C-Mu_B, MuN	Mu_A-Mu_B, MuN	Improvement Ratio, $\frac{Mu_A-Mu_B}{Mu_C-Mu_B}$	EFF	CONT I.D.
I	AFB	40.4	50.4	40.7	0.3	10.0	30.00	Y	A
R	AFB	57.2	53.5	58.0	0.8	-3.7	-4.40	N	D
Q	CAF	69.8	68.3	71.1	1.3	-1.5	-1.13	N	C
P	CAF	75.5	73.8	82.3	6.8	-1.7	-0.24	N	A
L	CAF	65.4	67.1	73.4	8.0	1.7	0.21	N	C
J	CAF	65.3	66.5	73.8	8.5	1.2	0.14	N	B
E	CAF	55.4	51.2	65.4	10.0	-4.2	-0.42	N	D
N	NAS	39.9	40.1	53.6	13.7	0.2	0.01	N	B
B	AFB	62.9	68.2	77.6	14.7	5.3	0.36	Y	B
H	AFB	60.4	67.4	76.1	15.7	7.0	0.45	Y	A
O	NAS	46.1	50.8	61.8	15.7	4.7	0.30	Y	B
F	CAF	47.1	44.1	63.4	16.3	-3.0	-0.18	N	D
M	AFB	34.5	49.3	53.3	18.8	14.8	0.79	Y	A
G	CAF	49.2	48.7	69.5	20.3	-0.5	-0.02	N	D
A	AFB	37.0	46.2	60.3	23.3	9.2	0.39	Y	C
K	CAF	48.2	56.2	71.5	23.3	8.0	0.34	Y	B
D	AFB	35.4	38.4	62.9	27.5	3.0	0.11	N	C
C	CAF	44.6	54.4	80.3	35.7	9.8	0.28	N	C

NOTES:

MuN = Mu Number at 40 mi/h (wet).

FAC I.D. = Runway identity code.

FACTYPE = Facility type, (military or commercial).

CAF = Commercial air facility.

AFB = U.S. Air Force Base.

NAS = U.S. Naval Air Station.

Mu_B = Mean friction level of rubber section before removal.

Mu_A = Mean friction level of rubber section after removal.

Mu_C = Mean friction level of control section.

Mu_C-Mu_B = Difference between Mu_C and Mu_B.

Mu_A-Mu_B = Difference between Mu_A and Mu_B.

Improvement Ratio = Ratio of $(Mu_A - Mu_B)/(Mu_C - Mu_B)$.

EFF = Effective, Y (Yes) or N (No) (Y if Ratio > 0.30).

CONT I.D. = Code identifying rubber removal contractor.

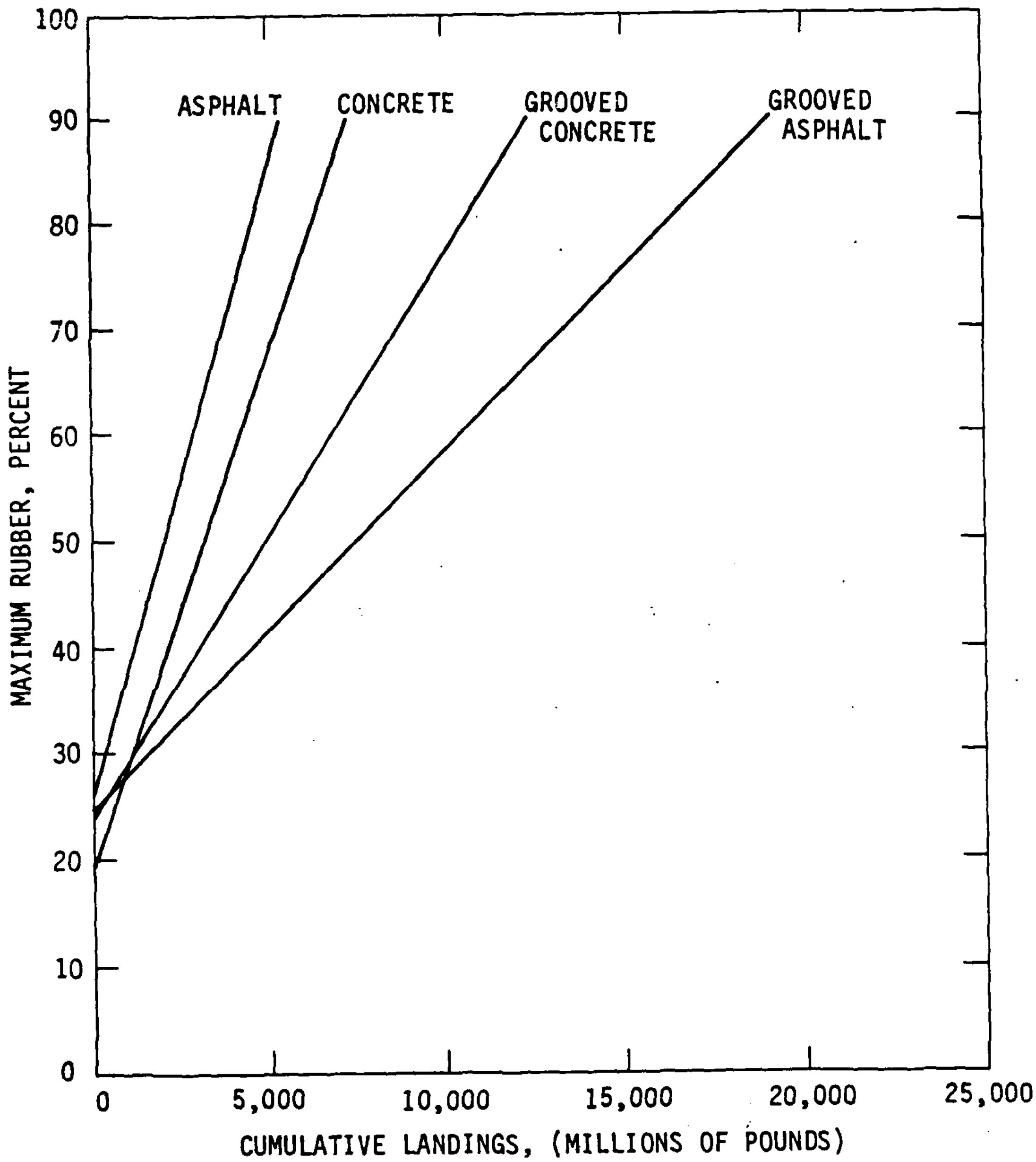


FIGURE 5. RELATIONSHIP OF MAXIMUM RUBBER (500-FOOT SEGMENT) TO CUMULATIVE LANDINGS SINCE RUBBER REMOVAL (REFERENCE 6)

1/2 of the frequency of the ungrooved systems. This relationship strongly determined the necessity of the military runways tested for removing rubber, since the military runways tested typically had less average texture depth than their commercial counterparts. Economic factors also determine the frequency of rubber removal. Since pavement friction is only one part of a pavement maintenance program, rubber removal contracts must compete with other pressing needs resulting in a reduced frequency of rubber removal. Commonly, rubber removal contracts are coupled with paint removal contracts. This provides an economical solution to two maintenance needs, since the same contractor typically performs both tasks.

Availability of maintenance funds and different liability obligations either enable or force the commercial runways to provide higher frictional safety factors. Thus, commercial runways typically have higher average texture depths to ensure this factor of safety and possibly remove rubber at a greater frequency than required. The differences in tire tread compounds, aircraft type, and cumulative weight of landings since last removal between commercial and military bases could also cause this difference. Therefore, valid reasons exist explaining the higher necessity for removing rubber on military runways than their commercial counterparts.

The next two columns in Table 3 are average friction values before (Mu_B) and after (Mu_A) rubber removal. A study of these columns reveals that all the runways that lie above the line of expected improvement are above the generally accepted friction value of 50 MuN (with the exclusion of one that is an obvious exception of ranking). These runways did not significantly increase in friction after rubber removal operations. A significant increase in friction is an increase of 3 or more MuN. This increase is the smallest value that can be determined confidently by the Mu-Meter which has a standard deviation of 2 MuN. The placement of this runway (I) was caused by the control pavement having much lower texture depth and not being representative of the rubber contaminated pavement. This trend indicates that if the friction level of the pavement is high to begin with, little chance of improvement is possible. Therefore, if the pavement's frictional level is considered safe, rubber removal is not warranted. However, if a potential of improvement exists as explained later, rubber removal conducted on these higher friction surfaces will increase their friction.

The fifth column is the mean friction level of the control section (MU_C). Seven of the nine commercial runways have friction levels greater than or equal to 70 MuN, while with their military counterparts only two of the nine are at this same high level. Additionally, three military runways have marginal friction levels (MuN < 55) on the clean pavement edge control sections. As mentioned earlier, differences in available funds and liability obligations may be the prime reason for this dramatic difference in runway friction levels. Other reasons for this are the relative ages of the runways, and the lack of pavement grooving systems on the military runways investigated. Military runways are typically much older than their commercial counterparts, therefore recent advances in pavement texturing could not be incorporated into the design of these runways. Also, the initiation of pavement grooving systems into the military maintenance programs may have been delayed due to possible tread wear and damage to tires in use in the late 1960s when grooving was introduced (Reference 14). The current use of the tire performance specifications and the use of fabric reinforced tire treads may have reduced the problems of chevron cuts and stripping observed in this earlier report.

The sixth column in Table 3 is the average difference in friction levels between the rubber contaminated pavement before rubber removal and the clean pavement edge control section (MU_C - Mu_B). This column, as stated earlier, is ordered in increasing differences between the two pavement sections. Since the friction in the rubber contaminated pavement has decreased because of the presence of rubber and the clean control pavement has retained its higher friction value, the difference is indicative of the maximum increase in friction possible by removing the rubber deposits. Increases of this magnitude are unlikely since the removal of rubber is not 100 percent effective and average texture depth and microtexture of the rubber pavement is likely to be reduced because of wear and traffic polishing. However, this difference can be used to determine whether rubber removal is likely to be effective in increasing the friction level and the relative efficiency of the rubber removal operation.

The seventh column is the measured difference in friction caused by rubber removal (Mu_A - Mu_B). This column is used later to determine an efficiency ratio that relates the friction difference obtained by rubber removal with the maximum obtainable friction difference. The varied differences in frictional increase strongly suggest that other variables (other than the amount of obtainable friction) determine the frictional change caused by rubber removal. Two possible variables that may complicate this relationship are the pavement condition and the techniques of the rubber removal contractor. These variables are qualitatively analyzed to provide insight to exceptions to the efficiency ratings given later.

The eighth column is the improvement ratio; which is the ratio of the difference in friction levels obtained by rubber removal to the maximum obtainable friction indicated by the difference between the rubber contaminated zone to the clean pavement zone [(Mu_A - Mu_B)/(Mu_C - Mu_B)]. This ratio is used as a basis for determining the effectiveness of rubber removal. Removal of rubber which has increased the friction level of the pavement 30 percent of its potential increase was judged to be effective. As seen in Table 3, six of the runways tested show a negative ratio. Since these runways decreased in friction, they were obviously not effective in increasing friction. Four of these runways showed insignificant improvement (less than 3 MuN difference in friction between before and after removal). This slight increase cannot be determined accurately with the Mu-Meter which has a standard deviation of 2 MuN; therefore, they were also deemed ineffective. This leaves less than half, or eight runways on which rubber removal was effective.

The ninth column states whether rubber removal was effective in increasing the friction level of the runway. The criteria used were developed in the preceding paragraph, that is, was the increase in friction level obtained 30 percent of that which is possible? Thus this column simply identifies the runways where rubber removal was considered effective by the symbol Y (Yes) and those where rubber removal was ineffective by the symbol N (No).

The last column lists which contractor did the removal. During this field experiment, high-pressure water was the only technique used in the removal of rubber. Since the effectiveness of rubber removal is a function of the amount of energy delivered to the pavement, it depends on such variables as dwell time, height of spray bar, and water pressure. Therefore, the various contractors, each with varying levels of experience, equipment, and proprietary techniques, determined to a large extent, whether or not the removal was effective. Therefore, patterns among the contractors will be used to explain the exceptions to the procedure given later.

Since the contents of Table 3 have been presented, the data trends answering the three previous questions should follow. However, since field observations indicated that inadequate rubber removal was performed at four runways (E, F, G, and N), and the collected data was suspect at two others (D and I), these runways were deleted from Table 3. On runways E, F, and G, the rubber was removed by the same contractor with none of the runways increasing in friction values. Conversely, these runways experienced a reduced friction level after rubber removal. After testing average texture depths of the centerline rubber section before rubber removal by the silicone putty procedure, some silicone putty was still adhering to the pavement surface. After the contractor removed the rubber, the silicone putty was still adhering to the pavement surface and the impression left by the original test remained visible. Therefore, the contractors rubber removal technique was suspect. The rubber removal job started on runway N and was aborted because the high pressure water was damaging the runway surface. On runway D, the centerline rubber section was both highly polished and sufficiently rough to affect the Mu-Meter traces. Pavement roughness was noted by the Mu-Meter operator during the 40 mi/h test runs. This roughness caused the Mu-Meter to bounce along the pavement resulting in an uneven normal load on the Mu-Meter tires. This produced Mu-Meter traces that were highly variable and difficult to read. Therefore, the friction levels determined at this base are suspect. On runway I, the pavement edge control section was not representative of the centerline rubber section. This section was lower in average texture depth, and had a different surface texture. Thus, it was also suspect.

Once these six runways were eliminated from Table 3, data trends became more evident. The data from Table 3, less the above six runways, are shown in Table 4.

Observing the average friction values in Table 4, the three concerns of rubber removal can be addressed.

1. The average friction level before rubber removal determines the relative safety of the runway. If this value is above the generally accepted level of 50 MuN, the runway is considered safe, thus, rubber removal is not necessary. However, rubber removal may be conducted to increase the friction and safety level of the runway.

2. Secondly, the removal of rubber is likely to improve the friction of the runway only if the current friction has declined sufficiently for the possibility of improvement to exist. Theoretically, the clean pavement section should retain the highest friction levels of a homogeneous pavement. This control section has not been subjected to any decline in friction caused by either traffic or rubber buildup, therefore to determine the available friction increase of any given pavement, the difference between the lower

TABLE 4. ANALYSIS OF RUNWAY FRICTION DATA (MODIFIED)

FAC I.D.	FACTYPE	Friction: Before Removal Mu_B, MuN	Friction: After Removal Mu_A, MuN	Friction: Control Section Mu_C, MuN	Mu_C-Mu_B, MuN	Mu_A-Mu_B, MuN	Improvement Ratio, $\frac{Mu_A - Mu_B}{Mu_C - Mu_B}$	EFF	CONT I.D.
R	AFB	57.2	53.5	58.0	0.8	-3.7	-4.40	N	D
Q	CAF	69.8	68.3	71.1	1.3	-1.5	-1.13	N	C
P	CAF	75.5	73.8	82.3	6.8	-1.7	-0.24	N	A
L	CAF	65.4	67.1	73.4	8.0	1.7	0.21	N	C
J	CAF	65.3	66.5	73.8	8.5	1.2	0.14	N	B
B	AFB	62.9	68.2	77.6	14.7	5.3	0.36	Y	B
H	AFB	60.4	67.4	76.1	15.7	7.0	0.45	Y	A
O	NAS	46.1	50.8	61.8	15.7	4.7	0.30	Y	B
M	AFB	34.5	49.3	53.3	18.8	14.8	0.79	Y	A
A	AFB	37.0	46.2	60.3	23.3	9.2	0.39	Y	C
K	CAF	48.2	56.2	71.5	23.3	8.0	0.34	Y	B
C	CAF	44.6	54.4	80.3	35.7	9.8	0.28	N	C

NOTES:

MuN = Mu Number at 40 mi/h (wet).

FAC I.D. = Runway identity code.

FACTYPE = Facility type, (military or commercial).

CAF = Commercial air facility.

AFB = U.S. Air Force Base.

NAS = U.S. Naval Air Station.

Mu_B = Mean friction level of rubber section before removal.

Mu_A = Mean friction level of rubber section after removal.

Mu_C = Mean friction level of control section.

Mu_C-Mu_B = Difference between Mu_C and Mu_B.

Mu_A-Mu_B = Difference between Mu_A and Mu_B.

Improvement Ratio = Ratio of $(Mu_A - Mu_B)/(Mu_C - Mu_B)$.

EFF = Effective, Y (Yes) or N (No) indicator (Y if Ratio > 0.30).

CONT = Code identifying rubber removal contractor.

friction in the rubber contaminated section and the control section is computed. As seen in Table 4, when this difference is less than 8.5 MuN, rubber removal did not increase the friction levels of any of the pavements tested. Conversely, once this difference was greater than 14.7 MuN, the runway friction after rubber removal increased. Therefore, a value between 8.5 and 14.7 MuN exists that can determine when rubber removal is likely to be effective, that is when pavement friction will increase 3 MuN after rubber removal. This value was selected as 10 MuN. Thus, the friction level in the rubber contaminated section is likely to improve if the difference between the control pavement and the rubber section is greater than 10 MuN.

3. A value determining when the contractor has adequately or successfully removed the rubber must be set. Since the difference between the rubber section and the control section determined the available increase, a percentage of this value was thought to be a representative performance requirement. Table 4 demonstrates that a value of 30 percent of this difference is an achievable level of improvement. This value was selected as a conservative level to be used as an interim performance requirement until such time as a larger data base justifies the adoption of another value. Shown in Table 4 is one runway (C) that did not meet this performance criteria. However, this particular runway was tested 10 days after rubber removal due to weather constraints. Therefore, immediately after removal, this runway may have met the above criteria.

Figure 6 shows a rational decision flow chart to guide the airport or air base manager as to when rubber should be removed, when it is likely to improve the pavement's frictional level, and to determine when the contractor has adequately increased the frictional properties of the pavement. Beginning at the top, a decision whether or not to remove rubber is based upon the generally accepted critical friction level of 50 MuN. At this point the flow chart divides into two paths. Following the right half of the flow chart, that is, the friction level in the rubber-contaminated section is still greater than 50 MuN, rubber removal may still increase the pavement's friction. At this point, a second determination is required. Is the difference in friction between the pavement edge control section and the rubber contaminated section greater than 10 MuN? If the answer is no, removal of the runway rubber is unlikely to improve the friction, therefore rubber removal is unwarranted, ending the decision process. However, if the answer is yes, rubber removal is likely to increase friction and rubber removal could be considered to further increase the friction of the runway. Since the critical friction value of 50 MuN was only proposed as a guideline for ranking the pavement friction, higher friction levels are both possible and desired. For example, a runway with a friction of 70 MuN is considered safer than a runway with a friction value of only 55 MuN. These higher friction levels ensure the increased safety of the runway. Another reason for removing rubber at this point is it is easier to remove. Once the rubber is allowed to age on the runway, long term chemical and/or physical changes occur. These cause the rubber to bond to the pavement materials making its removal difficult. Removal of this aged rubber may require additional energy to debond this rubber, possibly causing accelerated pavement wear and polish, and increased maintenance costs due to shorter joint sealant life. Therefore, regular removal of rubber is beneficial in preserving the pavement's serviceability. If it is decided to remove rubber, the contractors performance can be evaluated. If the increase in friction due to rubber removal is greater than or equal to 30 percent of the difference between the control section and the rubber section before removal

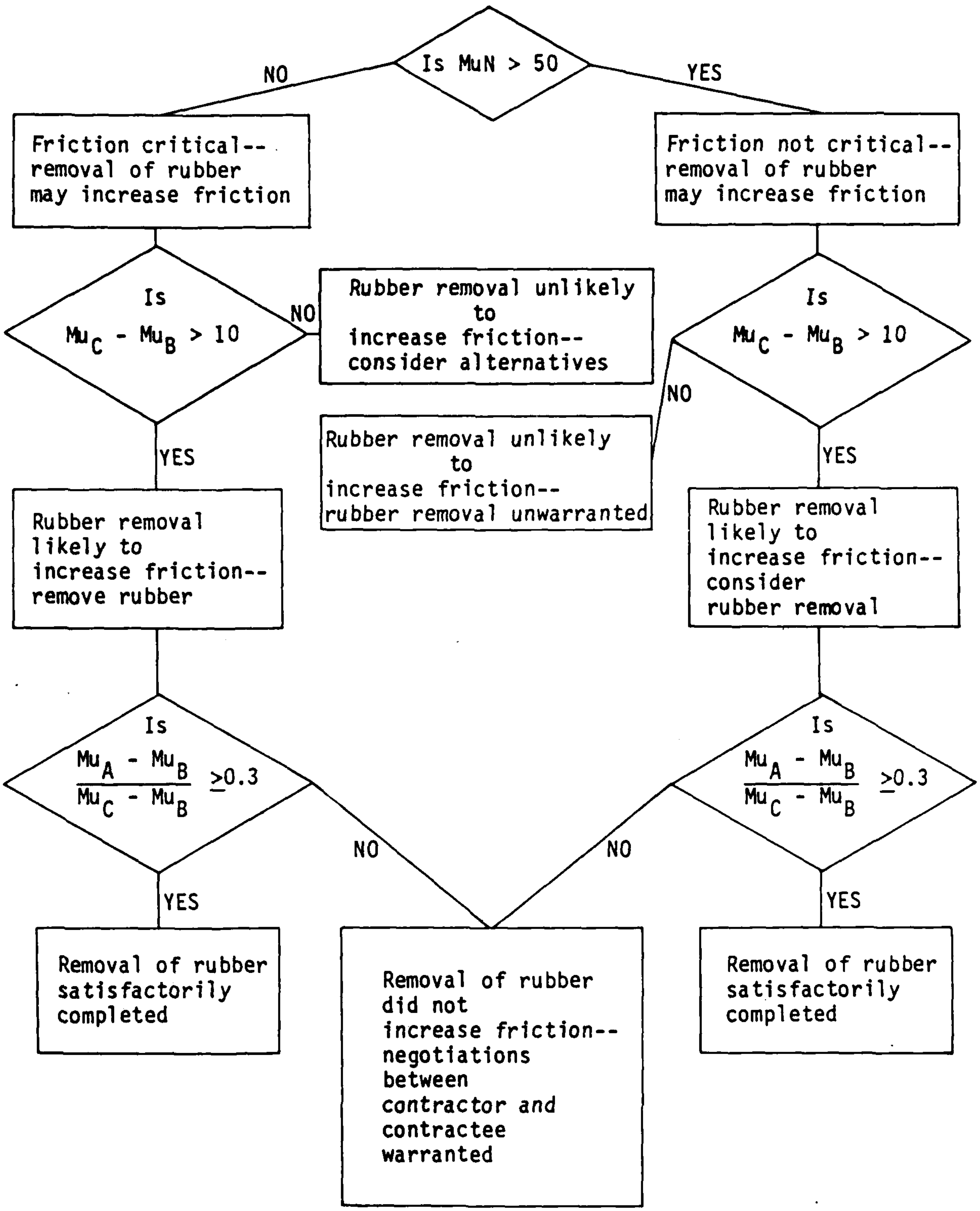


FIGURE 6. RUBBER REMOVAL FLOW CHART

$[(Mu_A - Mu_B)/(Mu_C - Mu_B) > 0.30]$, the contractor has adequately removed the rubber. If this increase did not occur, then negotiations between the contractor and the contracting officer are in order.

Following the left side of the flow chart, the friction level is critical, therefore, some action should be taken to remedy this possibly unsafe condition. Rubber removal may be considered as a solution if the difference in friction between the control section and the rubber contaminated section is greater than 10 MuN. If this difference is less than 10 MuN, rubber removal is unlikely to improve the friction and other alternates, such as installation of a grooving system or possibly an overlay should be considered. However, if this difference is greater than 10 MuN, rubber should be removed to increase friction. Once the rubber is removed, the performance of the contractor can be evaluated by determining if the increase in friction was greater than or equal to 30 percent of the difference between the control and rubber covered sections $[(Mu_A - Mu_B)/(Mu_C - Mu_B) > 0.30]$. If this criteria has been satisfied, the contractor has adequately removed the rubber. If not, negotiations between the contractor and contracting officer are in order.

Rubber removal may solve the problem of low friction runways in many cases; however, rubber removal will not solve all cases of low friction. For example, Runways C, K, and O were still below the critical level of 50 MuN; even though the friction of these runways was increased by satisfactory or near satisfactory rubber removal. Thus, if rubber removal does not cure the pavement friction problem, alternate methods of improving the friction should be investigated.

Also note the possibility of the contractor damaging the pavement surface. The high water pressures of the waterblasting rubber removal equipment may etch the pavement surface. While this etching may satisfy the friction performance requirements of the rubber removal contract by increasing both the macrotexture with grooves and the microtexture by newly fractured aggregate, the damage sustained by the pavement exceeds any potential benefits of the increased friction. Damage to the runway may also occur with other removal techniques. The techniques of shot blasting and sand blasting may also damage the pavement. Similarly, too high a concentration of removal chemicals may deteriorate the hydrocarbon bonding of both asphalt pavements and joint sealants. Therefore, care must be exercised in the application of any of the existing rubber removal methods.

SECTION IV
CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

In this section the conclusions of the various phases of this project are restated for emphasis. Since each of these phases fulfilled a specific purpose, a review of each and their conclusions are given in this section.

Rubber Removal Techniques and Equipment

Existing rubber removal techniques were reviewed. An evaluation of effectiveness, cost, simplicity, safety, and environmental effects were ascertained when the reviewed techniques are applied solely to Porous Friction Surfaces (PFS). This review determined the following:

1. Rubber removal from PFS pavement is necessary if traffic loadings are heavy.

2. Rubber can be removed from a PFS without damage if the pavement is in good serviceable condition, and the rubber is removed regularly before its removal becomes difficult.

3. High pressure water removal techniques were the only suggested method of removal.

Permeability Equipment for Porous Friction Surfaces

This phase reviewed existing techniques for evaluating permeability of PFS. This report concluded that of the present methods of measuring the permeability of PFS, the most appropriate method was measuring the outflow of water from an outflow device. The WES pavement permeability device shown in Appendix A was deemed best suited for this purpose.

Rubber Buildup Criteria and Evaluation Procedure Development

The existing techniques for evaluatin surface friction were reviewed. It was desired to evaluate the friction on a runway surface and develop a procedure capable of predicting friction which requires little special training, is insensitive to operator change, and is cost effective (less than $10,000 per installation to implement). This phase determined the following:

1. An extensive literature review suggested that the measurement of the pavement's textural properties was able to predict the pavement's friction levels.

2. To evaluate this concept, a statistical test matrix was designed to determine whether five selected techniques of measuring pavement texture could predict friction. The use of these simple texture measurements were to be correlated with pavement friction as measured by the Mu-Meter.

3. A design of the Mu-Meter self watering system was performed with the introduction of a new nozzle. A detailed drawing of this nozzle, model GSL, is presented in Appendix B.

Rubber Buildup Parameters Development

The field testing of the developed evaluation procedures was performed. This evaluation was conducted before and after rubber removal at selected airports and airbases. Friction and texture measurements were obtained on various pavement surfaces [portland cement concrete (PCC), asphalt concrete (AC), and porous friction surfaces (PFS)] according to the experimental procedures developed. The subsequent analysis revealed the following.

The influence of average texture depth on higher friction levels is strongly evident. This is based upon the strong correlations between average texture depth and the wet 64 km/h (40 mi/h) Mu-Meter testing. MacLennan et al. (Reference 6) reached this same conclusion in the National Runway Friction Measurement Program. However, they state that measurement of friction rather than texture is a preferable basis for planning routine runway maintenance. The results of this experiment and subsequent analysis verify this conclusion for the following reasons:

1. The measurement of macrotexture by either the sand patch or silicone putty volumetric procedures is an inexpensive method of quantifying macrotexture. However, important parameters of macrotexture are not measured by these procedures. Average texture depths do not determine the general shape of the pavement asperities; in addition, nonconnected voids measured by these methods do not help in the removal of bulk water. Each of these parameters is deemed important in friction literature, yet their influence has not been empirically validated. The techniques necessary to measure these parameters are more expensive and require highly trained personnel, thus defeating the purpose of this experiment. Furthermore, the results of these techniques may not provide better results.

2. The measurement of microtexture has an elusive quality. The correlations of microtexture measurements to either the intercept of a friction speed curve or to the dry Mu-Meter tests with which it is generally believed to correlate is evidence that microtexture could not be measured by the simple methods employed in this experiment. Current technology has not developed an alternate method of measuring this textural band.

3. The Mu-Meter was designed to determine averages in friction over an extended length; usually a 152.4-meter (500-foot) test section. Being designed for such use, the system dampening caused by both the test tires and the hydraulics of the load cell make this device insensitive to all but extreme localized texture variations.

4. The measurement of texture to determine friction levels of a pavement will only give an indication or an approximation of values measured by a friction test device. For this reason, if need arises to measure friction more accurately for performance specifications, a friction measuring device on which acceptance levels were previously established should be used.

5. The difference in friction between before and after rubber removal is slight. This slight difference indicates that rubber is being removed at many runways needlessly, therefore, the need for a frictional performance specification is evident for cost-effective rubber removal.

Rubber Removal Specification Criteria

The intent of these specification criteria are to eliminate the undesirable attributes of the existing visual/experience methods for determining rubber removal quality. This phase developed a rational procedure for determining when to remove rubber deposits, when rubber removal is likely to improve the friction levels of the pavement, and when the contractor has performed an adequate job of removing the rubber. This procedure is outlined in a flow chart (see Figure 6) and is stated in the following three criteria:

Q_1--When should rubber be removed?

A_1--When the friction level of the rubber contaminated pavement is less than the critical value of 50 MuN, rubber removal should be considered as one method of increasing the pavement friction. Otherwise, rubber removal may be considered but is not necessary.

Q_2--Is the removal of rubber likely to improve the frictional performance of the pavement?

A_2--If the difference in friction levels (MuN) between the rubber contaminated pavement and the clean pavement edge control section is greater than 10 MuN, rubber removal is likely to increase the friction level of the pavement. If this difference is less than 10, improvement is unlikely and decreases in the friction level may occur as a result of pavement polishing caused by the rubber removal.

Q_3--Did the contractor successfully remove the rubber and increase the friction level of the pavement?

A_3--If the friction level of the pavement increased 30 percent of the difference between the rubber contaminated pavement and the clean control pavement, the contractor successfully removed the rubber. As previously stated in the body of this report, this 30 percent increase in friction may well be a conservative value. However, its use is suggested until such a time as a larger data base is available which indicates the adoption of another value.

These criteria are based on frictional performance. Their adoption is strongly recommended. However, the expense of Mu-Meter testing may cause costly implementation of these criteria. No rational method could be developed using less costly texture measurement techniques.

RECOMMENDATIONS

The following recommendations are presented as a result of this project.

1. The use of highly textured pavements or grooving systems is essential in retaining high friction levels in rubber contaminated zones.

2. The use of texture measurements to accurately determine the friction levels of pavement cannot be accomplished with present technology. Therefore, texture measurements should only be used as a guide in determining friction levels with a standard friction test device used for precisely determining friction.

3. Alternate methods of measuring or quantifying the microtexture of the pavement are required for the prediction of friction from texture measurements. These methods must be researched to empirically determine microtexture's role in pavement friction.

4. Alternate methods of measuring the pavement's macrotexture should be investigated. Emphasis should be given to nonconnected voids, asperity density, asperity shape, and profiles of the pavement's macrotexture.

5. The analysis of the stereophotographs obtained during this research may determine the parameters described in the preceding paragraph. In addition, if the resolution of the stereophoto pairs is fine, this method may be helpful in measuring microtexture and therefore enable researchers to better define its role in tire-pavement friction.

6. This report presents a concise specification criteria for rubber removal contracts. The implementation of this specification criteria is recommended to eliminate the subjective visual/experience methods of present rubber removal contracts. The use of this specification criteria could also reduce current costs and improve runway safety by guiding airport and airbase managers in determining when to remove rubber, and when it has been effectively removed.

7. The best economical method of removing rubber from PFS was the use of high pressure water techniques. These techniques will present the least damage to the pavement and environment.

8. The WES permeability device, shown in Appendix A, was the most appropriate method of determining the permeability of PFS. Therefore, investigations of permeability as it relates to friction, and studies determining the long term effects of traffic loading, weather, rubber buildup, and construction should be initiated using this device.

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APPENDIX A
WES PERMEABILITY TEST DEVICE

The WES permeability test device consists of a clear plastic standpipe [2-inch (5.08 cm) ID and 2 1/2-inch (6.35 cm) OD] with a height of 13 inches (33 cm). The device has a 1/2-inch (12.7 mm) thick, 4-inch (10.16 cm) OD collar on the bottom with a 1/4-inch (6.35 mm) thick sponge-rubber gasket [2-inch (5.08 cm) ID and 4-inch (10.16 cm) OD] to prevent surface leakage (Figure A-1).

The results of the permeability tests are affected by the surcharge load applied to ensure contact of the standpipe and pavement surface. A surcharge load of 100 pounds (444.8 N) has been satisfactorily used to ensure that the condition of the tests are reasonably constant in this respect. Any method of supplying this surcharge is applicable, provided it is constant and is applied perpendicular to the pavement surface.

Once the standpipe is positioned and loaded, water is introduced into the standpipe to a level above the 10-inch (25.4 cm) mark on the side of the standpipe. The addition of water is then stopped, and the time to fall from the 10- to 5-inch (25.4 to 12.7 cm) level is measured with a stopwatch. This test is repeated three times and the average of the values is computed. The flow rate is determined from the relation $Q = VA$. Thus, for a 5-inch (12.7 cm) falling head, Q in ml/min is equal to 15,436.8 divided by the time to fall in seconds. A wide range in permeability measurements can be expected, but a reasonable lower limit of permeability for newly constructed PFS pavement is 1000 ml/min.

FIELD TESTS

In the field, an open truck door or bumper-mounted bracket can be used for the reaction weight with an extension screw used to apply the load. The load system should include a ball bearing or universal mechanism for self-alignment. When a truck is used to react against, the truck should not be parked broadside to the wind. Wind rocking the truck will cause the load to vary and adversely affect the results.

LABORATORY TESTS

In the laboratory, good results have been obtained by conducting the test on 6-inch (15.24 cm)-diameter specimens.

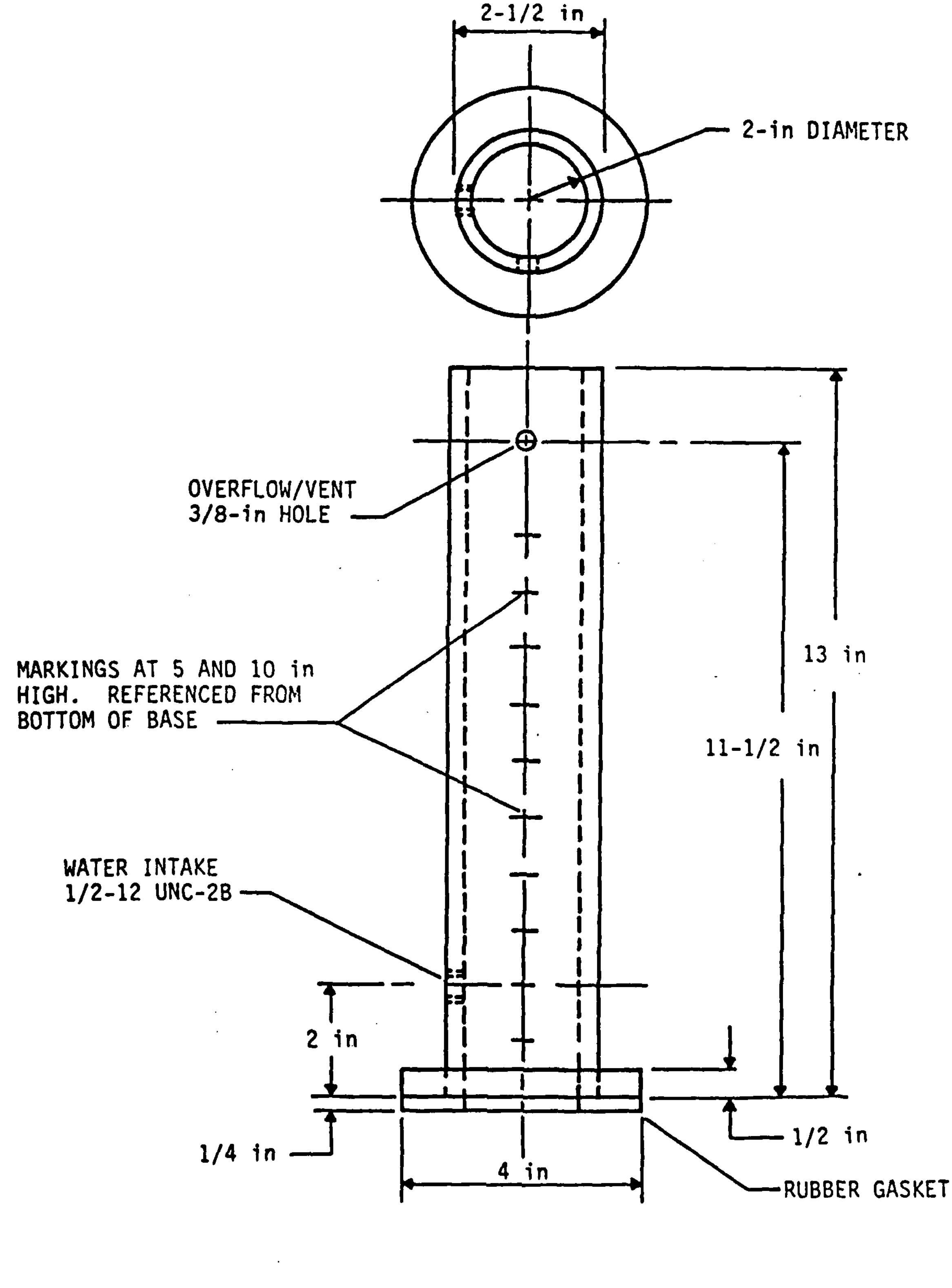

FIGURE A-1. WES PERMEABILITY DEVICE (1 in. = 24.4 mm)

APPENDIX B
MU-METER NOZZLE, MODEL GSL

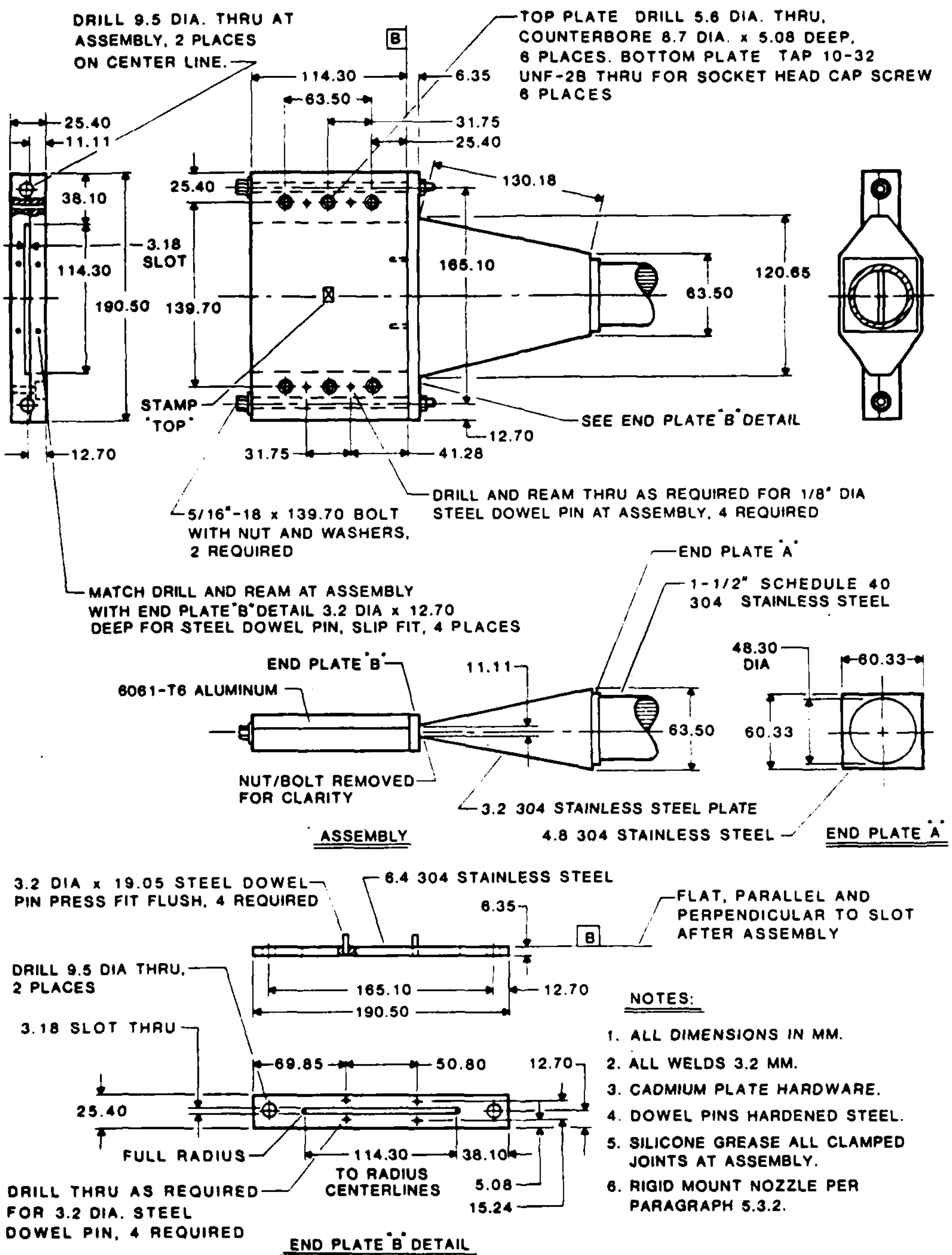

FIGURE B-1. MU-METER NOZZLE, MODEL GSL

APPENDIX C
TEXTURE MEASUREMENT PROCEDURES

*This description was obtained from the 1984 Annual Book of ASTM Standards, Section 4 Construction, Volume 04.03 Road and Paving Materials; Traveled Surface Characteristics pp. 803-806. Reprinted with permission from ASTM, 1916 Race Street, Philadelphia, PA 19103.

Designation: E 965 - 83

Standard Test Method for
MEASURING SURFACE MACROTEXTURE DEPTH USING A SAND VOLUMETRIC TECHNIQUE[1]

This standard is issued under the fixed designation E 965; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method describes a procedure for determining the average depth of pavement surface macrotexture (**1**)[2] by careful application of a known volume of sand on the surface and subsequent measurement of the total area covered. The technique is designed to provide an average depth value of only the pavement macrotexture and is considered insensitive to pavement microtexture characteristics.

1.2 The results obtained using this procedure to determine average pavement macrotexture depths do not necessarily agree or correlate directly with those obtained by other pavement macrotexture measuring methods (**1 through 6**).

1.3 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of whoever uses this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Applicable Documents

2.1 *ASTM Standards:*

C 778 Specification for Standard Sand[3]

E 178 Recommended Practice for Dealing with Outlying Observations[4]

3. Summary of Test Method

3.1 The standard materials and test apparatus consist of a quantity of uniform sand, a container of known volume, a suitable wind screen or shield, brushes for cleaning the surface, a flat disk for spreading the sand on the surface, and a ruler or other measuring device for determining the area covered by the sand patch. A standard laboratory balance is also recommended for further ensuring consistently equal sand amounts for each measurement sample.

3.2 The test procedure involves spreading a known volume of sand on a clean and dry pavement surface, measuring the area covered, and subsequently calculating the average depth between the bottom of the pavement surface voids and the tops of surface aggregate particles. This measurement of pavement surface texture depth reflects primarily the surface macrotexture characteristics (**1, 5**).

NOTE 1—In spreading the sand specified in this test method, the surface voids are completely filled flush to the tips of the surrounding aggregate particles. This test method is not considered suitable for use on grooved surfaces or pavements with large (≥1.0 in. (25 mm)) surface voids.

4. Significance and Use

4.1 This test method is suitable for field tests to determine the average macrotexture depth of a pavement surface. The knowledge of pavement macrotexture depth serves as an additional tool in characterizing the pavement surface texture. When used in conjunction with other physical

[1] This test method is under the jurisdiction of ASTM Committee E-17 on Traveled Surface Characteristics and is the direct responsibility of Subcommittee E17.23 on Surface Characteristics Related to Tire-Pavement Friction.

Current edition approved Sept. 30, 1983. Published December 1983.

[2] The boldface numbers in parentheses refer to the list of references at the end of this standard.

[3] *Annual Book of ASTM Standards*, Vol 04.01.

[4] *Annual Book of ASTM Standards*, Vol 14.02.

tests, the macrotexture depth values derived from this test method may be used to determine the pavement skid resistance capability and the suitability of paving materials or finishing techniques. Improvements in pavement finishing practices and maintenance schedules may result from use of this test method.

4.2 The texture depth measurements produced using this test method are influenced primarily by surface macrotexture characteristics and not significantly affected by surface microtexture. Pavement aggregate particle shape, size, and distribution are surface texture features not addressed in this procedure. This test method is not meant to provide a complete assessment of pavement surface texture characteristics.

4.3 The pavement surface macrotexture depth values measured by this test method, with the equipment and procedures stated herein, do not necessarily agree or correlate directly with other techniques of surface texture measurements. This test method is also suitable for research and development purposes, where direct comparisons between pavement surfaces are to be made within the same test program.

NOTE 2—The pavement surface to be measured using this test method must be dry and free of any construction residue, surface debris, and loose aggregate particles which would be displaced or removed during normal environmental and traffic conditions.

5. Materials and Apparatus

5.1 The essential elements of the apparatus, shown in Fig. 1, consist of the following material and equipment:

5.1.1 *Sand*—A natural silica sand from Ottawa, IL conforming to Specification C 778 shall be used. The clean, dry sand shall be graded to pass a No. 50 sieve and retained on a No. 100 sieve.

5.1.2 *Sand Sample Container*—A metal or plastic cylinder closed at one end and containing a predetermined internal volume of at least 1.5 cubic in. (25 000 mm^3) shall be used to determine the volume of sand spread.

5.1.3 *Sand Spreader Tool*—A flat, hard disk approximately 1 in. (25 mm) thick and 2.5 to 3.0 in. (60 to 75 mm) in diameter shall be used to spread the sand. The bottom surface or face of the disc shall be covered with a hard rubber material and a suitable handle may be attached to the top surface of the disc.

NOTE 3—An ice hockey puck is considered suitable for use as the hard rubber material in this test method.

5.1.4 *Brushes*—A stiff wire brush and a soft bristle brush shall be used to clean thoroughly the pavement surface prior to application of the sand sample.

5.1.5 *Wind Screen*—A small, portable screen or shield shall be mounted on the pavement surface for protection of the sand sample from the wind during spreading and obtaining measurements.

5.1.6 *Scale*—A standard scale 12 in. (305-mm) or greater in length and having 0.1-in. (2.5-mm) or 1-mm (0.04-in.) divisions should be used.

5.2 Use of a standard laboratory-type balance, sensitive to 0.1 g, is recommended with this test method to provide additional control and to ensure that the amount of sand used for each surface macrotexture depth measurement is equal in both mass and volume.

6. Procedure

6.1 *Test Surface*—Inspect the pavement surface to be measured and select a dry, homogeneous area that contains no unique, localized features such as cracks and joints. Thoroughly clean the surface using the stiff wire brush first and subsequently the soft bristle brush to remove any residue, debris, or loosely bonded aggregate particles from the surface. Position the portable wind screen around the surface test area.

6.2 *Sand Sample*—Fill the cylinder of known volume with dry sand and gently tap the base of the cylinder several times on a rigid surface. Add more sand to fill the cylinder to the top, and level with a straightedge. If a laboratory balance is available, determine the mass of sand in the cylinder and use this mass of sand sample for each measurement.

6.3 *Test Measurement*—Pour the measured volume or weight of sand onto the cleaned test surface within the area protected by the wind screen. Carefully spread the sand into a circular patch with the disk tool, rubber-covered side down, filling the surface voids flush with the aggregate particle tips. Measure and record the diameter of the sand patch at a minimum of four equally spaced locations around the sample circumference. Compute and record the average diameter of the sand patch.

NOTE 4—For very smooth pavement surfaces where the patch diameters are greater than 12 in. (305 mm), it is recommended that half the normal volume of sand be used.

6.4 *Number of Test Measurements*—The same operator should perform at least four, randomly-spaced measurements of average macrotexture depth on a given test pavement surface type. The arithmetic average of the individual macrotexture depth values shall be considered to be the average macrotexture depth of the test pavement surface.

7. Calculations

7.1 *Cylinder Volume*—Calculate the internal volume of the sand sample cylinder as follows:

$$V = \frac{\pi d^2 h}{4}$$

where:
V = internal cylinder volume, in.^{3} (mm^3),
d = internal cylinder diameter, in. (mm), and
h = cylinder height, in. (mm).

7.2 *Average Surface Macrotexture Depth*—Calculate the average surface macrotexture depth using the following equation:

$$MATX_d = \frac{4V}{\pi D^2}$$

where:
$MATX_d$ = average surface macrotexture depth, inches (mm),
V = sand sample volume, in.^{3} (mm^3), and
D = average sand patch diameter, in. (mm).

8. Faulty Tests

8.1 Tests that are manifestly faulty or that give average surface macrotexture depth values differing by more than 0.005 in. (0.13 mm) from the average of all tests on the same pavement surface shall be treated in accordance with Recommended Practice E 178.

9. Report

9.1 The report for each pavement test surface shall contain data on the following items:

9.1.1 Location and identification of test pavement surface,

9.1.2 Date,

9.1.3 Volume of sand used for each test measurement, in.^{3} (mm^3),

9.1.4 Number of test measurements,

9.1.5 Average sand patch diameter, in. (mm), for each test,

9.1.6 Average surface macrotexture depth, in. (mm), for each test, and

9.1.7 Average macrotexture depth, in. (mm), for total pavement test surface.

10. Precision and Bias

10.1 Analysis of sand patch data collected during extensively controlled tests **(6)** produced estimates of the repeatability (method precision) and reproducibility (applied precision) of the sand patch method, as well as sampling errors that can be expected in measuring the average texture depths of a pavement section by the method. The sand patch precision estimates are expressed as a percentage, such as the ratio of the standard deviation of the texture measurements to the mean texture depth times 100.

10.2 The standard deviation of the repeated measurements by the same operator on the same surface can be as low as 3.3 % of the average texture depth.

10.3 The standard deviation of the repeated measurements by different operators on the surface can be as low as 4.7 % of the average texture depth.

NOTE 5—The standard deviation of the site-to-site measurements may be as large as 27 % of the average texture depth. Here site defines a randomly selected location within a nominally homogeneous pavement section. This means that a sizeable number of measurement observations would be necessary to estimate the average texture depth reliably for a given pavement type, despite the fact that the method is highly repeatable and not subject to large operational influences.

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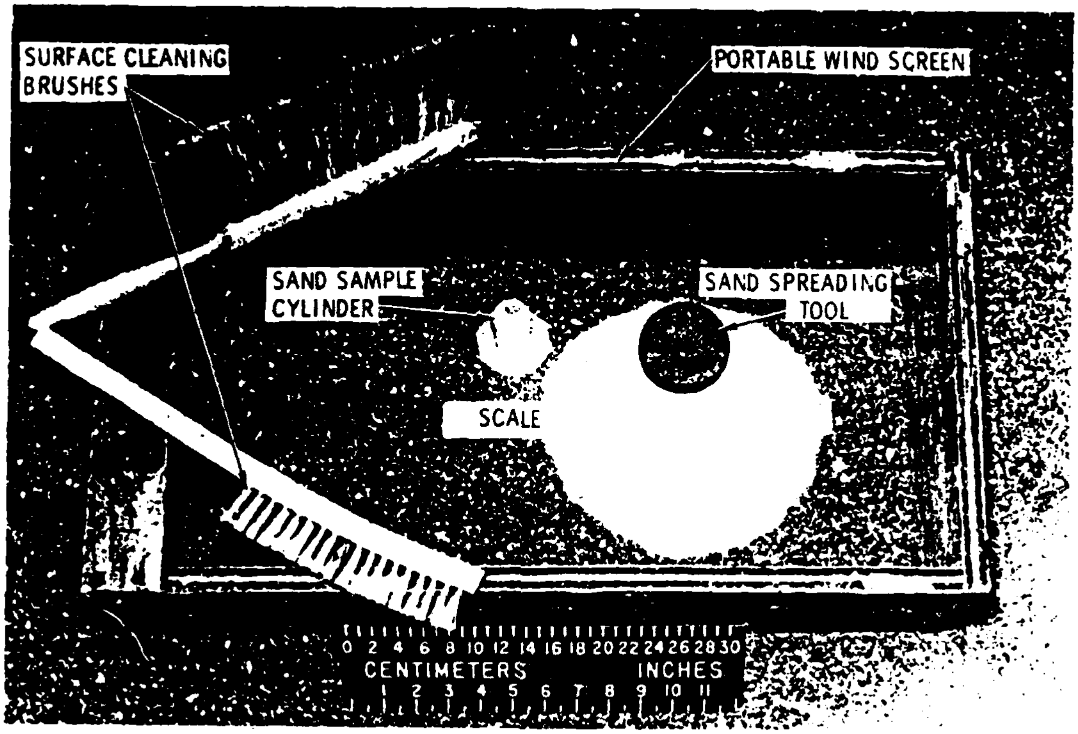

FIG. 1 Apparatus for Measuring Surface Macrotexture Depth

CHALK WEAR TESTER

TEST FUNCTION

The tester measures the wear of a piece of chalk per unit length while traveling at low sliding speeds on pavement. Since microtexture plays an important role in pavement friction, the tester ranks pavements by abrasion due to pavement microtexture.

While the tester can be used on any surface with a hardness greater than the chalk, pavements with low microtexture due to polish may be difficult to test.

PRINCIPLE OF OPERATION

The tester is pushed by the operator at a slow and uniform pace over a clean dry pavement. The normal load on the chalk produces contact pressures and corresponding shear forces that wear the bottom edge of the chalk. To ensure consistent results of wear, a commerically available railroad chalk is used for all tests.

TESTER DESCRIPTION

The tester consists of eight parts:

1. Cart: This furnishes both a convenient handle and an axle to mount the tester. (Harper fold-a-truck, Model No. FT-80EN).

2. Axle weight: This two-piece arrangement attaches the chalk tester to the cart axle and provides a hinged connection to the rest of the unit.

3. Vertical hinge: This eliminates any lateral force on the chalk.

4. Connecting bracket: Connects hinge with alignment bars.

5. Alignment bars: These two bars and the chalk guide form a triangular truss which provides vertical stability of the unit. Connecting the alignment bars to the connecting bracket with a limited rotational fitting also eliminates any torsional bias of the test.

6. Chalk guide: This holds the chalk in place during testing. The chalk is held in place by a friction fit.

7. Extruder screw: This pushes the chalk out of the chalk guide enabling the operator to reset the height of the chalk.

8. Balancing counterweight: This weight is used to balance the axle weight at the cart axle. This ensures proper weight distribution upon the chalk. Balancing is accomplished with only one alignment bar attached to the connecting bracket. The unconnected end of this alignment bar is unsupported during balancing.

The tester is shown in Figure C-1. Detailed fabrication drawings are shown in Figures C-2 and C-3.

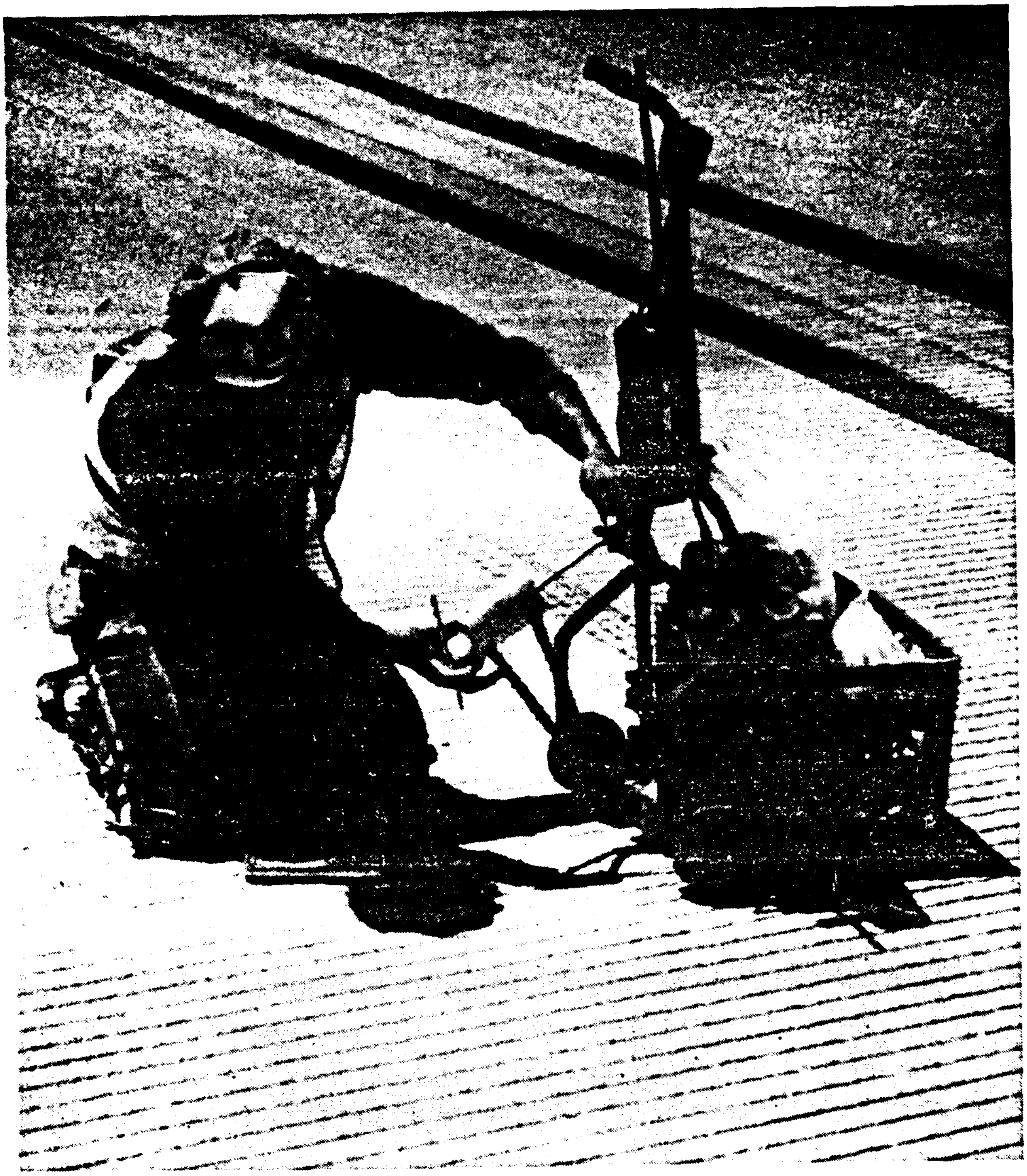

FIGURE C-1. CHALK WEAR TESTER

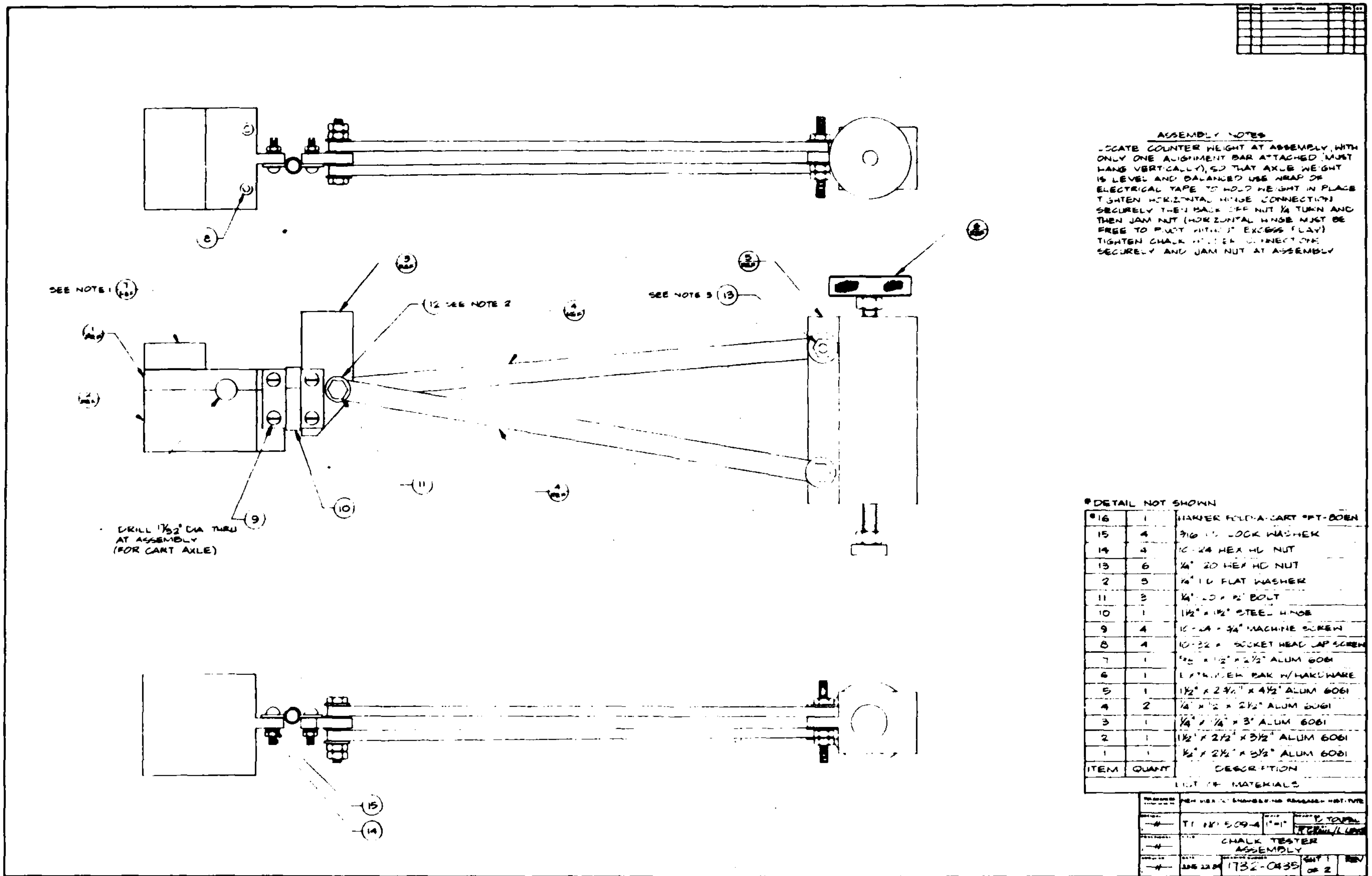

FIGURE C-2. CHALK WEAR TESTER ASSEMBLY

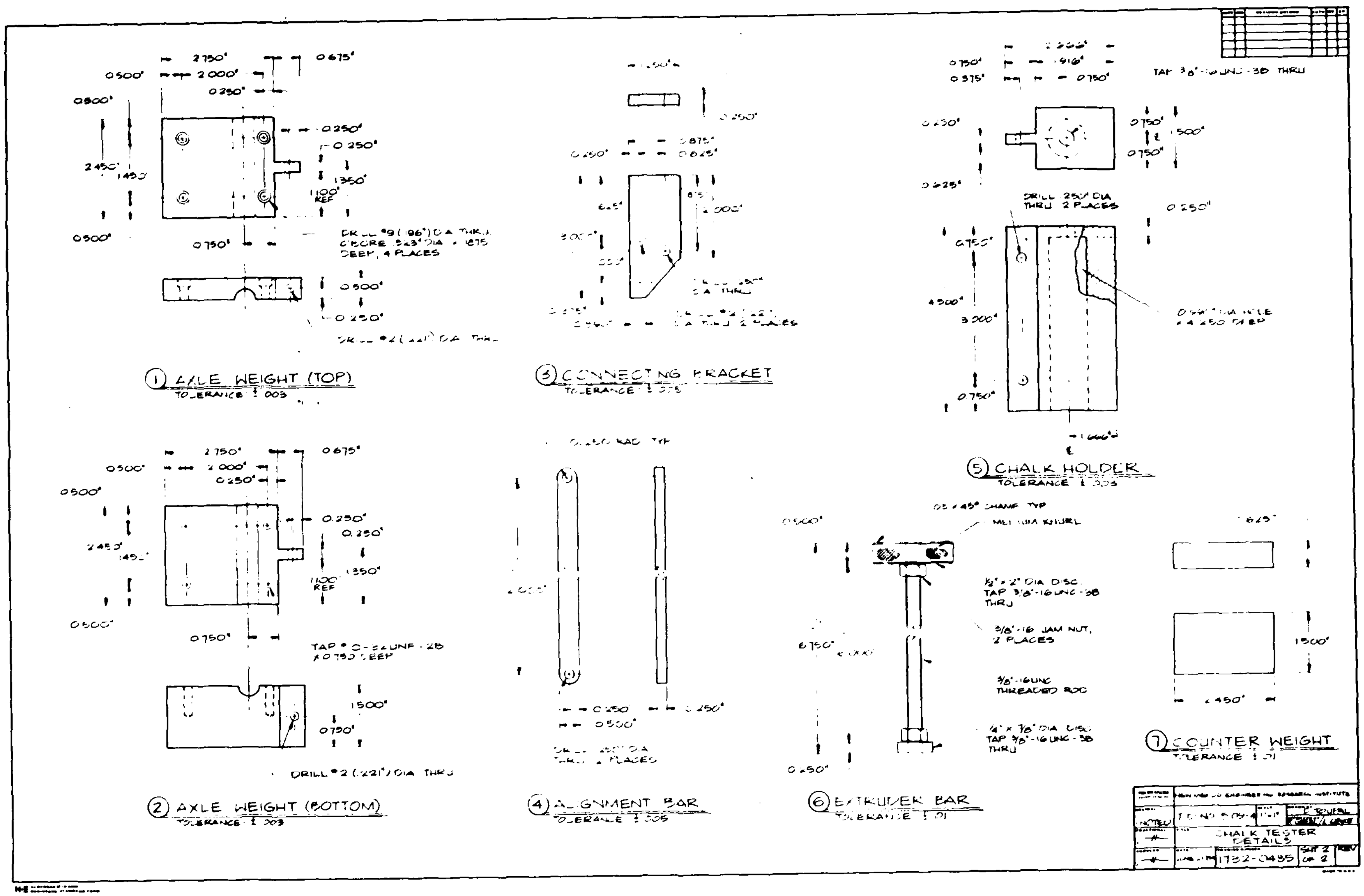

FIGURE C-3. CHALK WEAR TESTER DETAILS

TEST PROCEDURE

1. Check the chalk for wear. Replace the chalk when it has worn beyond half of its original length. This will be evident since the chalk is tapered and will fall from its holder at this time. (The tapered end of the chalk is inserted into the chalk guide.)

2. Extrude approximately 1/2 inch of chalk from tester.

3. Measure chalk length* at four places, 90-deg offset from each other, to the nearest 1/100 inch (R_1).

4. Inspect the pavement surface and ensure that it is clean and dry. When testing, always test in direction of travel.

5. Gently place the chalk on the ground where the test is to start.

6. Tilt the cart back and check that the front axle weight is level and the chalk guide is normal to the ground.

7. Keep handle at a comfortable height and be careful that axle weight is level and chalk guide is normal to the ground. Walk slowly forward at a uniform pace (about 1 mi/h).

8. Test a section of at least 10 feet when practical.

9. Measure the length of test section (length of chalk mark) to the nearest inch (L_w).

10. Measure the chalk length* at four places (90-deg offset) to the nearest 1/100 inch (R_2).

11. Calculate chalk wear per unit length of test surface.

$$W = \frac{\frac{\Sigma R_1 - \Sigma R_2}{4}}{L_w}$$

12. When replacing chalk, use No. 888 enamel-coated white railroad chalk produced by the American Crayon Company. A parts list for the chalk tester is shown in Table C-1.

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*Measurements made with reference to bottom of chalk guide.

Table C-1. CHALK WEAR TESTER PARTS LIST

Quantity	Description
1	Cart, Harper fold-a-truck, Model No. FT-80EN
1	Balancing counterweight
1	Axle weight
1	Hinge
1	Connecting bracket
2	Alignment bars
1	Chalk holder
1	Extruder screw
	Enamel-coated white railroad chalk--produced by the American Crayon Company No. 888.

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APPENDIX D
PREDICTED VERSUS MEASURED MU-METER VALUES

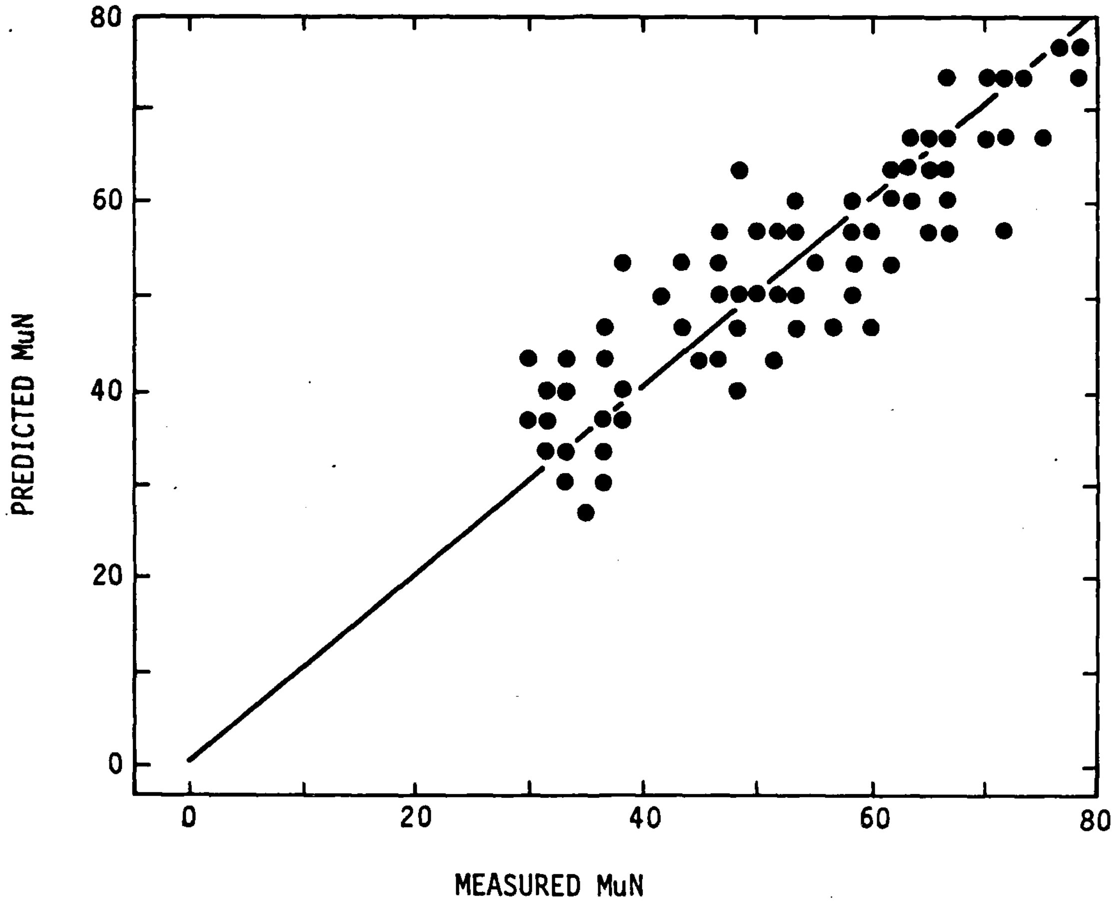

FIGURE D-1. COMPARISON PLOT OF PREDICTED VERSUS MEASURED WET MU-METER VALUES AT 40 mi/h FOR CENTERLINE BEFORE RUBBER REMOVAL

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