SKID RESISTANCE CONSIDERATIONS IN THE FLEXIBLE PAVEMENT DESIGN SYSTEM

by

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A System Analysis of Pavement Design
and Research Implementation

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PREFACE

This report is issued as a result of research conducted under Research Project No. 1-8-69-123, "A System Analysis of Pavement Design and Research Implementation." The project was initiated in 1969 and is being conducted jointly by the Texas Highway Department, the Center for Highway Research, and the Texas Transportation Institute. The study is part of a cooperative research program with the Department of Transportation, Federal Highway Administration.

This study was conducted to include pavement surface skid resistance considerations in the computer program developed by the project for designing flexible pavements.

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ABSTRACT

This report summarizes work completed by Research Project 123 at the Center for Highway Research concerning skid resistance considerations in Flexible Pavement System (FPS). The study traces the progression of analysis and the development of a skid resistance decay model. Also presented is a method which the design engineer may find useful in applying skid resistance considerations to FPS. The method allows the elimination from FPS of those aggregates which would not provide adequate skid resistance performance for the given roadway requirements.

KEY WORDS: flexible pavement system, flexible pavement, seal coat, overlay, aggregate, skid resistance, coefficient of friction, skid trailer, trailer coefficient, British Accelerated Polishing Machine, British portable tester number, nomograph, Texas Highway Department, Center for Highway Research, Texas Transportation Institute, systems analysis.

SUMMARY

This report presents information supplied by Research Project 126 for the implementation of skid resistance considerations in Flexible Pavement System (FPS). Research Project 123 used this information to develop an equation to describe the traffic-skid resistance relationship and included the skid resistance considerations in FPS.

To avoid calculations for aggregates with infeasible skid decay, a method was developed which will eliminate aggregates that have inadequate skid resistance life under given traffic conditions. This method is graphical but can be included in FPS with little trouble.

IMPLEMENTATION STATEMENT

The computer program developed by Project 1-8-69-123 for designing flexible pavement uses more than 50 physical inputs and constraints to obtain a set of recommended pavement design strategies based on the net present worth of the lowest total cost. This study was initiated to consider in the calculation of pavement design strategies the different skid resistance performance characteristics of aggrega es used in the surface mix. Certain skid resistance considerations were included in the computer program so that if the proper input parameters of the aggregate are known, skid resistance performance can be included in obtaining the pavement design strategies.

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION

In a pavement system, many variables affect the performance and physical condition of the highway. The effects of these variables will influence construction, maintenance, and managerial decisions, which will in turn affect the final cost of the pavement system. Therefore, the more accurately one can predict the effects that the variables will have on the pavement, the more closely the actual cost can be estimated.

This report concerns aggregate variables which affect the seal coat schedules of flexible pavements. These variables are incorporated as inputs in Flexible Pavement System (FPS), where they are utilized in seal coat schedule and overall pavement system cost calculations.

BACKGROUND

Due to the complex nature of highway pavements, systems analysis is the best means for realistic analyses of pavement design and management problems (Ref 1). Research Project 32 at the Texas Transportation Institute developed this "Systems Approach" to the design of flexible pavements (Ref 2). The design system accounts for both physical and cost variabl s and provides means for making design decisions based on probable overall costs rather than on initial construction costs alone.

The set of explicit mathematical models for the systems analysis process was formulated in Project 32 by Scrivner, Moore, McFarland, and Carey, in Report 32-11, "A Systems Approach to the Flexible Pavement Design Problem" (Ref 2). These models have an accompanying computer program for reaching solutions. The computer program, developed by the Texas Transportation Institute and being implemented by certain Districts of the Texas Highway Department, has more than 50 physical input variables and constraints. However, in computing the seal coat schedule, and the resulting cost, only two input variables are considered - the time to first seal coat after initial or overlay construction and the time between seal coats (Ref 1). Consequently, the program describes all surfaces as having a fixed life. But, if skid resistance criteria are included in the analysis, different aggregates will provide different surface skid resistance performance characteristics. These differences in performance will affect the seal coat schedules and resulting costs. Therefore, the cost analysis should include skid resistance criteria.

In applying skid resistance criteria to FPS, Projects 45 and 126 of the Highway Department provided the required basic information. Project 45 obtained field measurements of skid resistance loss with traffic and criteria for upgrading (Refs 3, 4, 5, 6, and 7), and Project 126 suggested a method for predicting the skid resistance loss using a laboratory analysis of the aggregate (Ref 8).

This report concerns work which progresses from information supplied by Project 126. The results of this work are to be used in connection with Research Project 123 at the Center for Highway Research in considering skid resistance in FPS.

OBJECTIVE

The objective of this study is to incorporate into FPS consideration of skid resistance criteria. This report is primarily intended to aid those using FPS in design to more easily and effectively choose those aggregates which have adequate skid resistance characteristics.

SCOPE

Included in this report are a discussion of and the limitations of an equation which may be used to predict asphalt concrete pavement skid resistance with respect to traffic. Also included is a method of eliminating from FPS those aggregates with unsatisfactory skid resistance performance. The method is a manual procedure which can, however, be programmed into the FPS computer program with little difficulty. In addition, the method can be revised if a more desirable formula for traffic-skid resistance prediction becomes available.

Chapter 2 provides background information used in this report. Chapter 3 involves the development of the skid resistance performance equation used in FPS, and Chapter 4 concerns the development of the procedures used to eliminate infeasible aggregates from consideration in FPS. Finally, Chapter 5 outlines a user procedure and presents a sample problem to illustrate the procedure.

CHAPTER 2. BACKGROUND INFORMATION

In order to predict skid resistance performance and, thereby, incorporate skid resistance considerations into FPS, an equation is needed to describe the skid resistance performance of the different aggregates used in pavements. This chapter summarizes the findings presented by Kenneth Hankins of Project 126 in developing an equation to describe the skid resistance performance. Also contained in this chapter is a laboratory method which Project 126 suggested could be used to predict actual skid resistance performance.

PROJECT 126 FINDINGS

Project 126 of the Texas Highway Department is currently working to determine a relationship between laboratory polish (polishing an aggregate with the British Accelerated Polishing Machine) and traffic polish (the polishing of an aggregate by actual vehicle applications). The findings of Project 126 are being used by Project 123 to incorporate skid resistance considerations into FPS. To determine the relationship between laboratory polish and traffic polish, Project 126 is studying different aggregates to determine the following as reported by Hankins (Ref 8):

(1) The relationship between pavement surface coefficient of friction and traffic using the skid trailer to measure pavement surface coefficient of friction. Based on previous observations of field performance, it was assumed that a curve fitted through actual traffic polish data takes the form

$$f_{40-N} = \left[\frac{1}{(N+1)^{b_{field}}} \right] f_{40-MAX} \tag{2.1}$$

or

$$\log f_{40-N} = \log f_{40-MAX} - b_{field} \log(N + 1) \tag{2.2}$$

where

f_{40-N} = trailer coefficient at 40 mph (Ref 3) and N vehicle applications,

N = number of vehicle applications (trucks and cars counted equally),

b_{field} = a constant for each aggregate that depends on its traffic polishing characteristic,

f_{40-MAX} = trailer coefficient at 40 mph before any vehicle applications.

In other words, a straight-line relationship between log f_{40-N} and log (N + 1) is assumed, with $-b_{field}$ as the slope of the line (see Fig 1).

(2) The relationship between the British Portable Tester number (Ref 9) and polish hours. A good linear correlation exists between the log of the British Portable Tester number and the log of polish hours.

(3) The relationship between the British Portable Tester number and the pavement surface coefficient of friction.

(4) The relationship between the slopes of the aforementioned plots of the log trailer coefficient versus log vehicle applications and the log of the British Portable Tester number (converted to trailer coefficient versus the log of polish hours).

LABORATORY METHOD FOR PREDICTING SKID PERFORMANCE

Project 126 suggested that a laboratory method for predicting actual skid resistance performance under traffic could consist of the following:

(1) Polish a specimen with the British Accelerated Polishing Machine.

(2) Determine laboratory rate of polish (b_{lab}) of the straight-line fit of the log of the British Portable Tester number versus the log of hours of polish (It is acknowledged that there is a limited coefficient of correlation in the linear fit above, and better correlations may be obtained by a polynomial regression analysis).

(3) Determine the final laboratory polish value and convert it to final trailer coefficient.

(4) Find a corresponding field rate of polish under traffic (b_{field}) from a relationship which might exist between b_{lab} and b_{field}.

(5) Determine the number of vehicle applications N at which a specified minimum allowable coefficient of friction (f_{40-N}) will occur using an equation describing actual pavement performance.

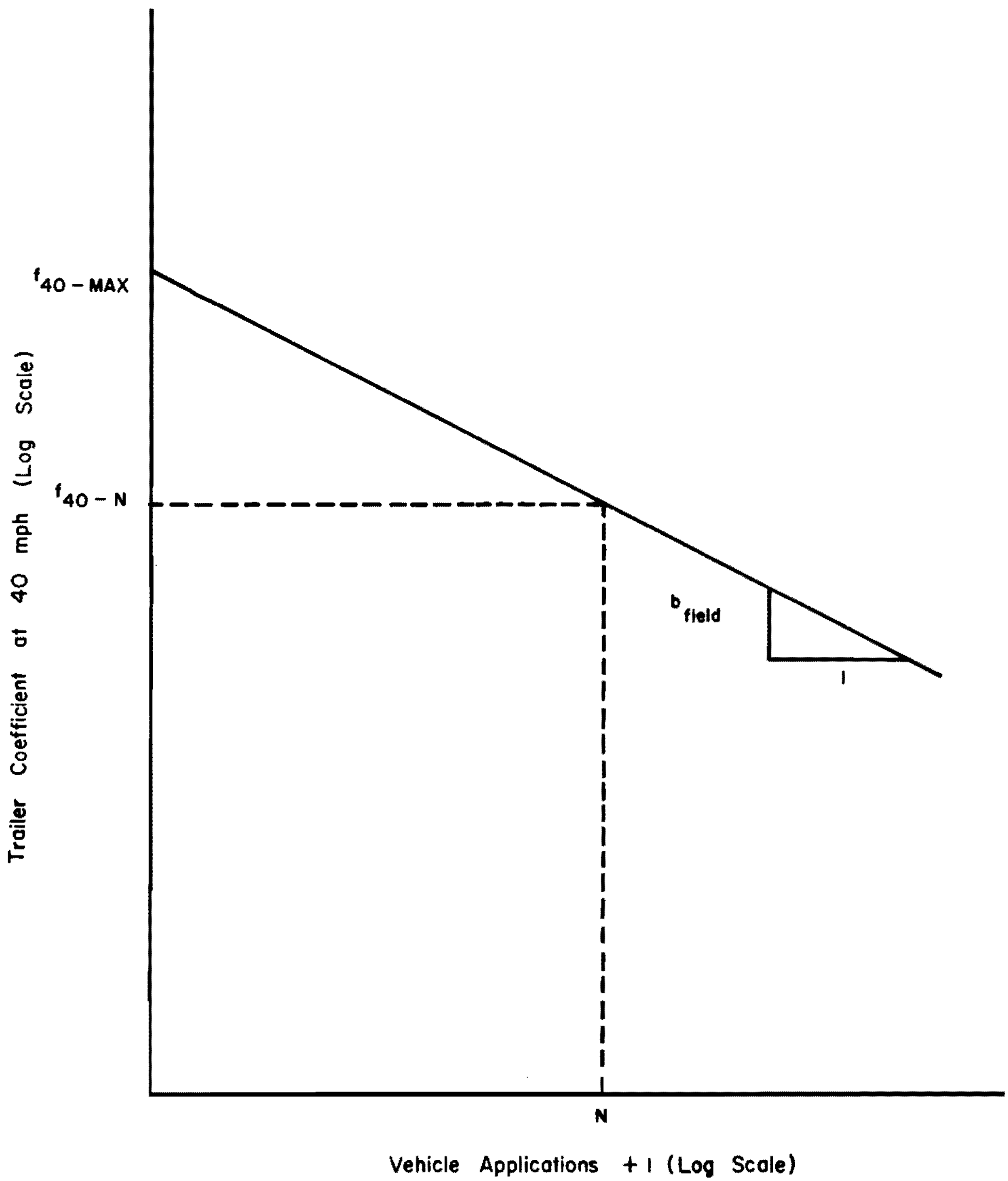


Fig 1. Relation of trailer coefficient with vehicle application.

SUMMARY

In order to incorporate skid resistance considerations into flexible pavement system, an equation must be available to describe skid resistance performance of various aggregates. Project 126 is working to determine this equation and has outlined the required information. They have also outlined a laboratory method for predicting actual skid resistance performance under traffic.

CHAPTER 3. DEVELOPMENT OF SKID DECAY MODELS FOR FPS

If a model were available for describing aggregate skid resistance performance, skid resistance considerations could be applied to FPS. This chapter discusses the development of the skid resistance performance equation for use in FPS.

DEVELOPMENTAL APPROACH

If a model were available for calculating the number of vehicle application at various coefficients of friction, the number of vehicle applications to a minimum allowable coefficient of friction could be determined. This value obtained for number of vehicles N could then be equated to the formula used in FPS for defining total vehicle applications over the roadway with respect to time:

$$N = 365\,(LDF) \int_{t=o}^{t_1} r \cdot dt$$

or

$$N = 365(LDF)\left[(r_o)(t_1) + \left(\frac{r_C - r_o}{2C}\right)\left(t_1^{\,2}\right)\right] \qquad (3.1)$$

where

C = design life of pavement in years;

r = average daily traffic (one direction);

r_o = average daily traffic (one direction) at initial pavement construction;

r_C = average daily traffic (one direction) at the end of the design life;

t = time after initial construction, in years;

t_1 = time after initial construction to N vehicle applications, in years;

LDF = lane distribution factor of most heavily traveled lane.

The above equation assumes a linear increase in traffic during the design life C to correspond with the assumption in FPS (Ref 2). The equation yields the total number of vehicles expected to have passed over the pavement since construction at any specified time t .

After substituting the value of N obtained from a traffic-coefficient equation, Eq 3.1 can be solved for t_1 , the time in years to the first seal coat. The subsequent seal coats at t_2 , t_3 , etc. can be obtained similarly:

$$N = 365(LDF) \int_{t_1}^{t_2} r \cdot dC$$

or

$$N = 365(LDF)\left[(r_o)(t_2 - t_1) + \left(\frac{r_C - r_o}{2C}\right)\left(t_2^2 - t_1^2\right)\right] \qquad (3.2)$$

where

t_2 = time after initial construction, in years.

In general, Eq 3.1 and 3.2 can be expressed as follows:

$$N = 365(LDF)\left[(r_o)(t_{k+1} - t_k) + \left(\frac{r_C - r_o}{2C}\right)\left(t_{k+1}^2 - t_k^2\right)\right] \qquad (3.3)$$

where

t_{k+1} and t_k = subsequent times after initial construction, in years.

In calculating the seal coat schedule, FPST-6, a revised FPS program with skid resistance considerations included, will compute t_1 , the time to the first seal coat; t_2 , the time to the second seal coat; etc. However, if an overlay is constructed, e.g., between the time t_1 and t_2 , the program considers the time from initial construction to the first seal coat as the first skid resistance performance period; the time from the first seal coat to overlay is the second skid resistance performance period; and the time from overlay to the second seal coat is the third skid resistance performance period. Therefore, the third performance period is the time the overlay takes to polish to the minimum allowable coefficient of friction (see Fig 2).

POLISH MODEL

Project 123 considered several formulas for describing the coefficient of friction of aggregates with respect to the number of vehicle applications. The formula which yielded the desired accuracy for analysis in FPST-6 defined the aggregate skid performance in terms of three parameters.

$$N = \left(\frac{f_{40 - N_i}}{f_{40 - N}}\right)^{\frac{1}{b_{field}}} \left(N_i\right) \qquad (3.4)$$

The equation describes the straight-line, logarithmic plot of traffic polish (see Fig 3). The value $f_{40 - N_i}$ is the coefficient at 40 mph of the pavement initially measured at N_i vehicle applications, $f_{40 - N}$ is a specified minimum allowable coefficient for the particular installation, and $-b_{field}$ is the slope of the line.

The value of $f_{40 - N_i}$ would have to be correlated from laboratory polish data. Likewise, b_{field} would have to be obtained from laboratory analysis and correlation. Restricted utility in using Eq 3.4 is suspected since the number of vehicle applications N_i at which the initially measured coefficient occurs would have to be evaluated. However, defining the performance of the aggregates by these three parameters implicitly defines the number of vehicle applications at which the final coefficient for each aggregate is reached.

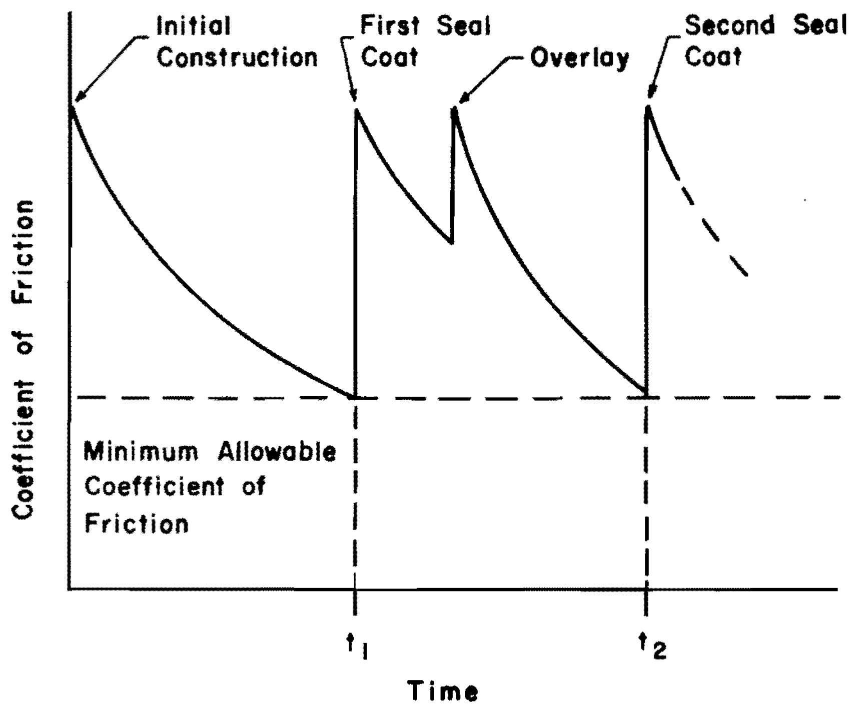


Fig 2. Lime to seal coats.

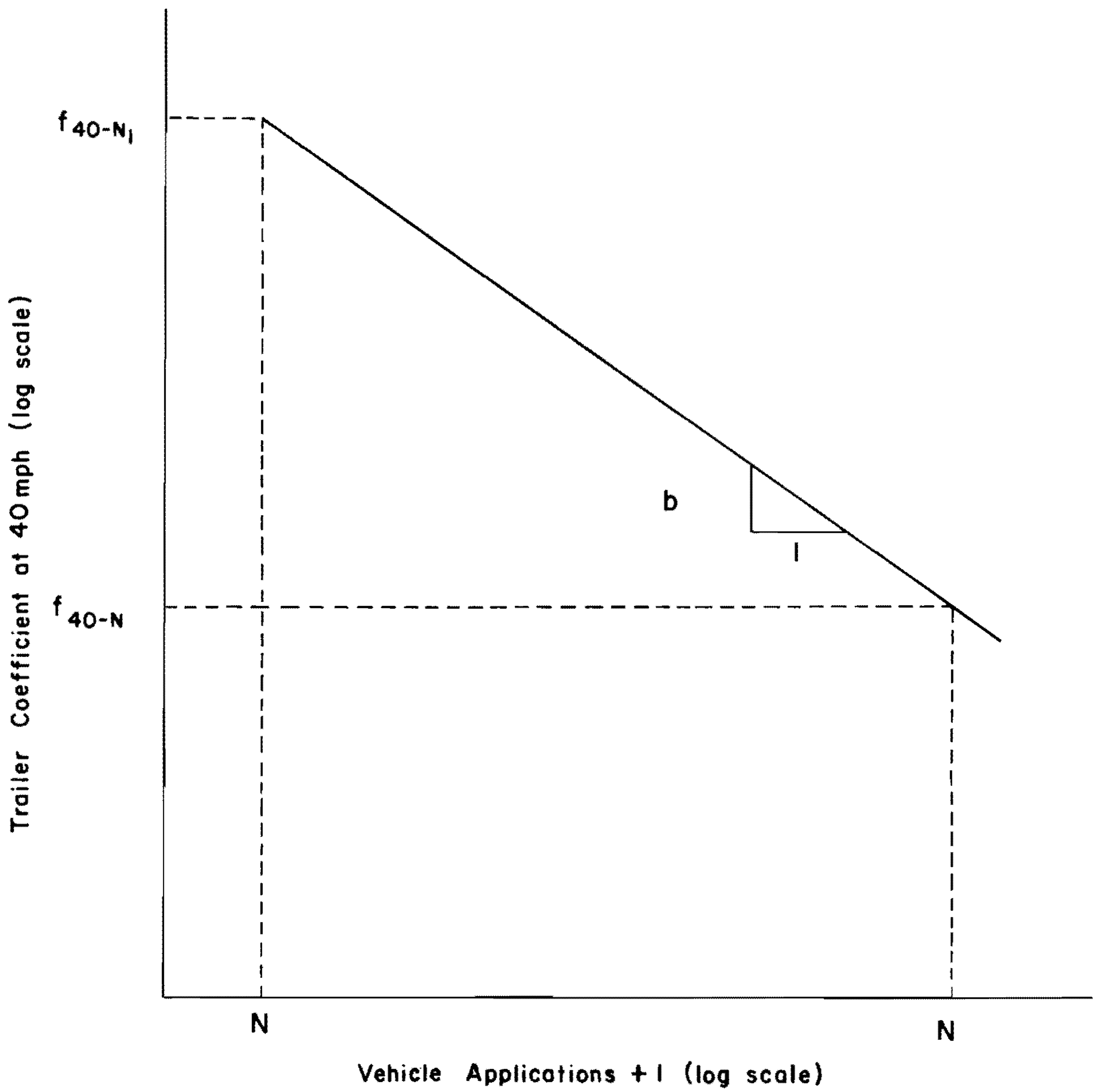


Fig 3. Modified relationship of trailers coefficient with vehicle applications.

It may be conceived that the estimation of N_i from a laboratory procedure could be a very difficult task. However, if the actual initial trailer coefficients of the aggregates in the field used to obtain the laboratory correlation were all measured at the same number of vehicle applications of, say, 50,000, the aggregate parameter N_i would become a constant. This would, of course, greatly simplify the field correlation from laboratory data.

SUMMARY

Project 123 formulated Eq 3.4 to define the aggregate skid resistance performance for determining seal coat schedules in FPST-6. Equation 3.4 assumes a linear correlation between the log of the coefficient of friction at 40 mph and the log of the number of vehicle applications. To utilize the equation, a method must be developed to determine the slope of the above line, the coefficient of friction of the pavement measured near its initial exposure to traffic, and the number of vehicle applications at the initial coefficient of friction measurement.

CHAPTER 4. DEVELOPMENT OF PROCEDURES

With the desired equation for aggregate skid performance established, the procedure for the useful utilization of the concept needs to be modeled. As discussed before, Eqs 3.3 and 3.4 can be used to compute the time between seal coats for different aggregates and under different traffic conditions. The value thus obtained can be used in two ways. First, it can be used to calculate the cost of seal coats over a specified length of time; FPST-6 uses it to calculate the total seal coat cost during the design life of the pavement system. Second, the value for time between seal coats can be compared to design standards or to the times obtained for other aggregates; FPST-6 currently compares it to the maximum allowable time between seal coats, the smaller of the two being used in the cost calculation above. However, the calculated time could be compared to the minimum time between seal coats of the project for the purpose of eliminating infeasible aggregates.

This chapter discusses the meaning of the models being used to calculate the time between seal coats, the problem with the indiscriminate use of aggregates in FPS, and the solution to the above problem. In addition, a nomograph is presented that can be used to eliminate from consideration in FPS those aggregates which are infeasible due to design criteria or other specifications.

DISCUSSION OF MODELS

Meaning of Models

The relative effect of $f_{40 - N_i}/f_{40 - N}$ and b_{field} from Eq 3.4 on the seal coat schedule will vary depending on traffic volume. In other words, a small variation in, say, b_{field} will have a different relative effect on the seal coat schedule of a lightly traveled highway than on the seal coat schedule of a heavily traveled highway. The same relationship is true with $f_{40 - N_i}/f_{40 - N}$.

The above consideration can be observed by examining the equations presented earlier. Consider a particular highway of which the design life and traffic parameters of Eq 3.3 are known. Furthermore, assume that due to economic considerations a minimum time between seal coats is set at one year and due to pavement aging (cracking, weathering, etc) a maximum time is set at six years. The above time values substituted into Eq 3.3 will give the number of vehicle applications at one year and at six years. Therefore, for the skid resistance characteristics of an aggregate on this installation to be used to the optimum, the aggregate should reach the minimum allowable coefficient of friction within the range of vehicle applications obtained above. Various combinations of the aggregate parameters of Eq 3.4 will yield vehicle applications within the range. For a given N_i , the various combinations of $f_{40 - N_i}/f_{40 - N}$ and b_{field} which satisfy the range of vehicle applications can be calculated and then illustrated graphically. Figure 4 contains aggregate parameter requirements for several different traffic volumes.

Problem

Figure 4 shows that, for particular traffic volumes, there is only a narrow band of aggregate parameter combinations which will satisfy the seal coat requirements. Therefore, only a portion of the several available aggregates may satisfy the required conditions. If the several aggregates are indiscriminantly input to an FPST-6 program, the unsatisfactory aggregates will consume time in computer operations.

It should be noted that if an aggregate falls to the right of a particular aggregate requirement band in Fig 4 (i.e., requires a seal coat after six years), the skid resistance life of that aggregate will not be fully utilized. However, this should not eliminate that aggregate from consideration in FPST-6; since the aggregate actually lasts longer than is required. In this case, a cost analysis (as in FPS) would be necessary to determine its feasibility. Therefore, aggregates should be initially eliminated only if they fall to the left of the band.

Solution

In this analysis, a nomograph was developed to eliminate from consideration in FPST-6 infeasible aggregates, i.e., aggregates falling to the left of the band in Fig 4. However the aggregate elimination can be performed by the computer, if added to FPST-6, so that for a particular traffic volume, seal coat schedules for only the feasible aggregates will be calculated.

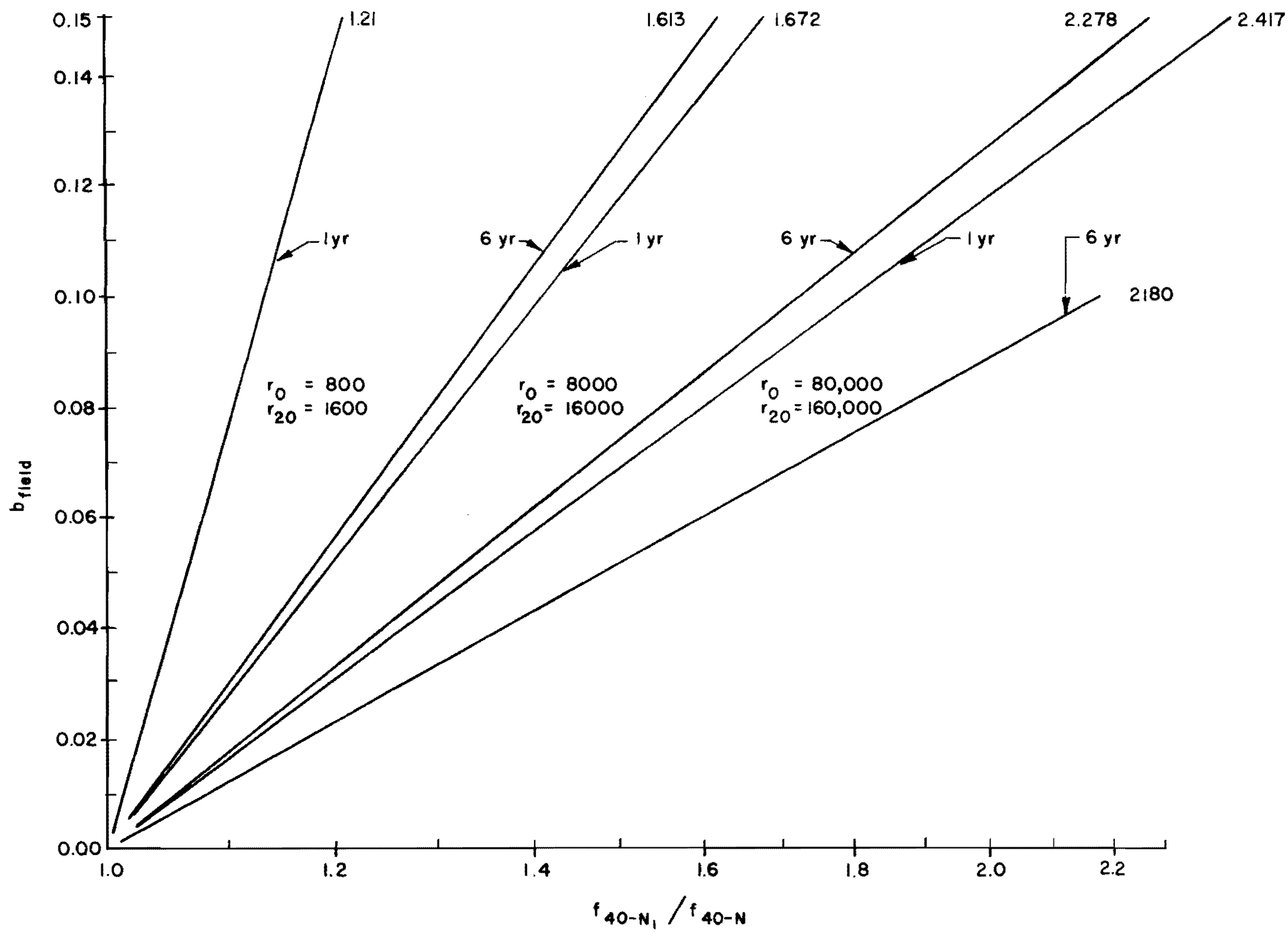


Fig 4. Skid resistance parameters of aggregates required for different traffic volumes.

NOMOGRAPH

The time between seal coats for the aggregates being examined can be determined by using Eq 3.4 to calculate the number of vehicle applications N which the aggregate will withstand before reaching the minimum allowable coefficient of friction $f_{40 - N}$. Then the time between seal coats t can be estimated using Eq 3.1 and the value of N obtained above.

The mathematical procedure described above has been incorporated into a nomograph which will solve for t . The procedure for using the nomograph for aggregate elimination is included in the next chapter.

CHAPTER 5. USER PROCEDURE

The previous chapters have presented the background and development of a procedure for eliminating from FPS those aggregates which have unacceptable skid resistance performance. This chapter outlines the procedure and presents a sample problem to illustrate the procedure.

PROCEDURAL STEPS

The first step in the aggregate elimination procedure, as illustrated in Fig 5, is to obtain the required parameters for each aggregate under consideration. The aggregate parameters required are the initially measured coefficient of friction at 40 mph f_{40-N_i} of a pavement using the aggregate being considered; the number of vehicles N_i applied to the pavement before f_{40-N_i} is measured; the slope $-b_{field}$ of a straight-line fit of the log of vehicle applications versus the log of the coefficient at 40 mph for the aggregate; and the final coefficient at 40 mph f_{40-MIN} to which the aggregate polishes; and the minimum allowable coefficient at 40 mph f_{40-N}. These aggregate parameters can be obtained through experience, from data of aggregate performance under traffic, or, as mentioned in Chapter 2, through correlation, from polishing the aggregate in the laboratory.

Next, the traffic characteristics should be obtained. These items include the initial average daily traffic r_o, the design life of the pavement C, the expected average daily traffic at the end of the design life r_C and the lane distribution factor LDF, for the most heavily traveled lane.

The third step is to establish the minimum time between seal coats. This value t_{MIN} is a design requirement obtained through qualitative analysis of climate, roadway use, economics, past experience, etc.

Then the minimum allowable coefficient is compared to the final coefficient of the aggregate. If the minimum allowable coefficient is smaller than or equal to the final coefficient, the aggregate can be input to FPS without additional analysis for elimination. If the minimum allowable coefficient is

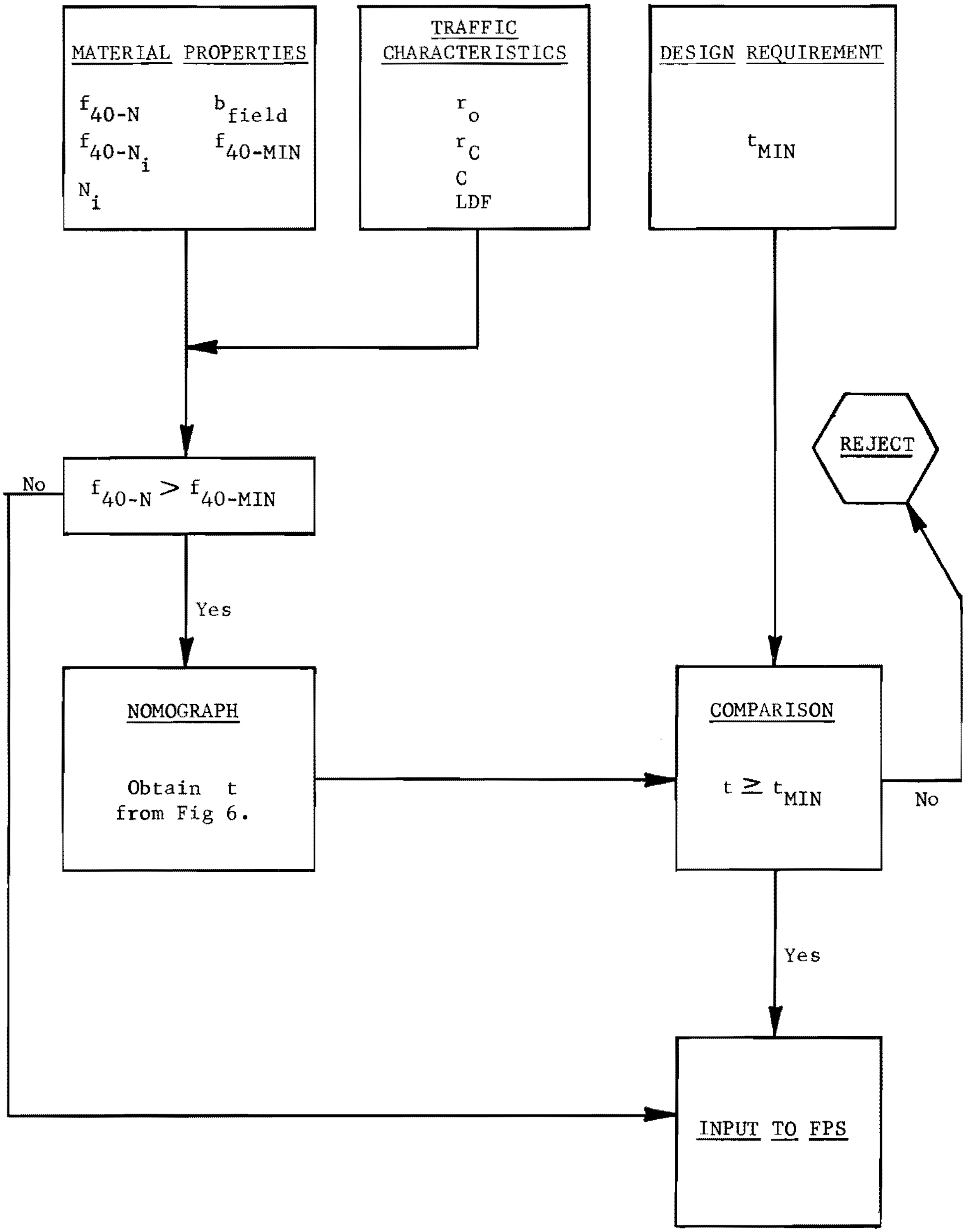


Fig 5. Procedure for using Nomograph method to eliminate infeasible aggregates from FPST-6.

greater than the final coefficient, the aggregate must be examined further for feasibility, using the nomograph in Fig 6.

If the minimum allowable coefficient is in fact greater than the final coefficient, the next step is to enter Fig 6 with the material properties and traffic characteristic values and solve the nomograph for t. This value will be the approximate time between seal coats for the aggregate being examined and under the conditions prescribed.

Then the value obtained for t is compared to the minimum allowable time between seal coats t_{MIN}. If the time between seal coats for the aggregate is greater than or equal to the minimum allowable time, use of the aggregate is feasible and it can be input to FPS; otherwise, the aggregate should be rejected from consideration in FPS for this particular application.

To complete the aggregate elimination process, the material properties for the remaining aggregates are obtained and the procedure described above is repeated.

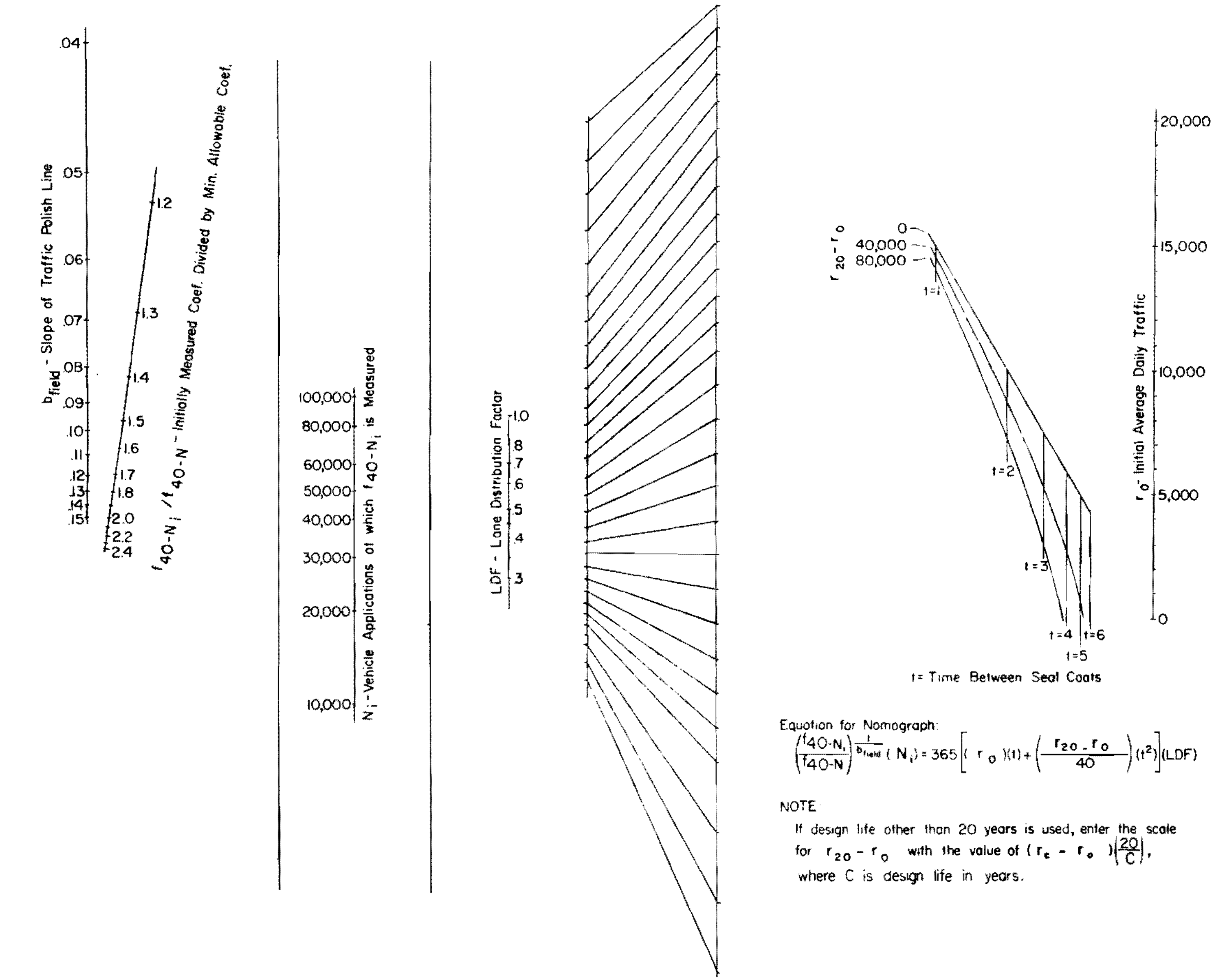
In every case the aggregates can fulfill the feasibility criteria in one of two ways - if f_{40-N} is less than or equal to f_{40-MIN} or if t obtained from Fig 6 is greater than or equal to t_{MIN}. Otherwise, t will be less than t_{MIN}, and the aggregate will be rejected.

EXAMPLE PROBLEM

The following example of the infeasible aggregate elimination method includes four aggregates for consideration. The aggregates to be considered are lightweight, dolomite, trap, and limestone.

The minimum allowable coefficient of friction f_{40-N} is 35, and the material properties for the aggregates are summarized below.

	Lightweight	Dolomite	Trap	Limestone
f_{40-N_i}	67	58	58	52
N_i	50,000	50,000	50,000	50,000
b_{field}	0.041	0.121	0.096	0.136
f_{40-MIN}	50	34	34	26



Equation for Nomograph:

$$\left(\frac{f_{40-N_i}}{f_{40-N}}\right)^{\frac{1}{b_{field}}}(N_i) = 365\left[(r_o)(t) + \left(\frac{r_{20} - r_o}{40}\right)(t^2)\right](LDF)$$

NOTE

If design life other than 20 years is used, enter the scale for $r_{20} - r_o$ with the value of $(r_c - r_o)\left(\frac{20}{C}\right)$, where C is design life in years.

Fig 6. Time to seal coat.

The pavement will have a design life of 20 years and an initial one-directional average daily traffic r_o of 8,000. The lane distribution factor LDS is 0.6, and the average daily traffic at the end of the design period r_C is expected to be 16,000. Also, it is required that resurfacing of the pavement due to skid resistance considerations not be needed at intervals of less than two years ($t_{MIN} = 2$).

The f_{40-N} value is now compared to the value of f_{40-MIN} for each aggregate. For lightweight, f_{40-MIN} is greater than f_{40-N}, and, therefore, lightweight is input to FPS. For the other aggregates f_{40-MIN} is less than f_{40-N}, and the value of t for each aggregate must be obtained from Fig 6 before the aggregates are input to FPS.

For dolomite, $f_{40-N_i}/f_{40-N} = 58/35 = 1.66$. Entering Fig 6 with the required values for dolomite, extend a line from b_{field} of 0.121 through f_{40-N_i}/f_{40-N} of 1.66 to the turning line. From that point on the turning line, extend a line through N_i of 50,000 to the next turning line. From there, extend a line through LDS of 0.6 to the next line. From that point, continue to the next line with a line consistent with the two adjacent lines. Connect the point thus obtained to r_o of 8,000 on the scale on the right. Where that line crosses $r_{20} - r_o$ of 8,000, read t to be slightly larger than two years. And, since t is greater than t_{MIN} of two years, dolomite is input to FPS.

For trap, f_{40-N_i}/f_{40-N} also equals 1.66. The value for t from Fig 6 is found to be more than six years. And, since t is greater than t_{MIN} of two years, trap is input to FPS.

For limestone, f_{40-N_i}/f_{40-N} is equal to 1.49, and the value for t from Fig 6 is found to be much less than the two-year minimum. Therefore, limestone is rejected from consideration in FPS for the design requirements.

In summary, lightweight, dolomite, and trap are feasible aggregates for this highway application from skid resistance considerations and are input to FPS. Limestone, however, does not meet the feasibility criteria and is not applied to FPS.

The output from the application of the above feasible aggregates to FPS is included in the Appendix.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

The conclusions derived from this study are as follows:

(1) The criteria developed from previous research projects, on skid resistance, 45 and 126, have been incorporated into FPS to provide skid resistance criteria for selecting the optimum design. The criteria are applied only to seal coats.

(2) The skid resistance consideration introduces safety as a decision criterion for the first time in FPS.

(3) The skid resistance criterion (minimum allowable time between seal coats) for given traffic conditions can be satisfied only by aggregates with particular combinations of properties. If a combination of aggregate properties for an aggregate does not satisfy the skid resistance criteria, the aggregate should not be considered in FPS.

It is recommended that

(1) the revised model of FPS containing the skid resistance criteria developed herein be designated by an FPS number for use in implementation,

(2) the User's Manual be revised to include the required parameters for this FPS model, and

(3) further studies be made to produce skid decay equations with increased utility suitable to a laboratory-field correlation.

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APPENDIX

PROB RUDA CALCULATIONS FOR FEASIBLE AGGREGATES

THE CONSTRUCTION MATERIALS UNDER CONSIDERATION ARE

LAYER	MATERIALS CODE	NAME	COST PER CY	STR. COEFF.	MIN. DEPTH	MAX. DEPTH	SALVAGE PCT.	THICKNESS INCREMENT
1	A	ASPHALTIC CONCRETE	12.00	.75	1.00	6.00	35.00	.50
2	B	CRUSHED STONE	4.00	.65	4.00	16.00	35.00	1.00
3	C	GRAVEL	1.50	.40	4.00	20.00	35.00	2.00
		SUBGRADE		.23				

NUMBER OF OUTPUT PAGES DESIRED(8 DESIGNS/PAGE)	1
TOTAL NUMBER OF INPUT MATERIALS,EXCLUDING SUBGRADE	3
LENGTH OF THE ANALYSIS PERIOD (YEARS)	20.0
WIDTH OF EACH LANE (FEET)	12.0
DISTRICT TEMPERATURE CONSTANT	25.0
SERVICEABILITY INDEX OF THE INITIAL STRUCTURE	4.2
SERVICEABILITY INDEX P1 AFTER AN OVERLAY	4.0
MINIMUM SERVICEABILITY INDEX P2	3.0
SWELLING CLAY PARAMETERS -- P2 PRIME	1.50
B1	.0200
ONE-DIRECTION ADT AT BEGINNING OF ANALYSIS PERIOD (VEHICLES/DAY)	8000
ONE-DIRECTION ADT AT END OF ANALYSIS PERIOD (VEHICLES/DAY)	16000
ONE-DIRECTION 20-YR ACCUMULATED NO. OF EQUIVALENT 18-KIP AXLES	2760000
PROPORTION OF ADT ARRIVING EACH HOUR OF CONSTRUCTION (PERCENT)	7.0
THE ROAD IS IN A RURAL AREA.	
MINIMUM TIME TO FIRST OVERLAY (YEARS)	2.0
MINIMUM TIME BETWEEN OVERLAYS (YEARS)	3.0
MAX TIME TO FIRST SEAL COAT AFTER INITIAL OR OVERLAY CONST.(YEARS)	6.0
MAX TIME BETWEEN CONSECUTIVE SEAL COATS (YEARS)	6.0
MAX FUNDS AVAILABLE PER SQ.YD. FOR INITIAL DESIGN (DOLLARS)	4.00
MAXIMUM ALLOWED THICKNESS OF INITIAL CONSTRUCTION (INCHES)	25.0
MINIMUM OVERLAY THICKNESS (INCHES)	.5
ACCUMULATED MAXIMUM DEPTH OF ALL OVERLAYS (INCHES)	5.0
ASPHALTIC CONCRETE PRODUCTION RATE (TONS/HOUR)	75.0
ASPHALTIC CONCRETE COMPACTED DENSITY (TONS/C.Y.)	1.98
C.L. DISTANCE OVER WHICH TRAFFIC IS SLOWED IN THE O.D. (MILES)	1.00
C.L. DISTANCE OVER WHICH TRAFFIC IS SLOWED IN THE N.O.D. (MILES)	1.00
DETOUR DISTANCE AROUND THE OVERLAY ZONE (MILES)	0.00
OVERLAY CONSTRUCTION TIME (HOURS/DAY)	11.0
NUMBER OF OPEN LANES IN RESTRICTED ZONE IN O.D.	1
NUMBER OF OPEN LANES IN RESTRICTED ZONE IN N.O.D.	2
PROPORTION OF VEHICLES STOPPED BY ROAD EQUIPMENT IN O.D. (PERCENT)	.01
PROPORTION OF VEHICLES STOPPED BY ROAD EQUIPMENT IN N.O.D. (PERCENT)	.01
AVERAGE TIME STOPPED BY ROAD EQUIPMENT IN O.D. (HOURS)	.004
AVERAGE TIME STOPPED BY ROAD EQUIPMENT IN N.O.D. (HOURS)	.004
AVERAGE APPROACH SPEED TO THE OVERLAY ZONE (MPH)	60.0
AVERAGE SPEED THROUGH OVERLAY ZONE IN O.D. (MPH)	30.0
AVERAGE SPEED THROUGH OVERLAY ZONE IN N.O.D. (MPH)	50.0
TRAFFIC MODEL USED IN THE ANALYSIS	3

PROB BUDA CALCULATIONS FOR FEASIBLE AGGREGATES

FIRST YEAR COST OF ROUTINE MAINTENANCE (DOLLARS/LANE MILE)	50.00
INCREMENTAL INCREASE IN MAINT. COST PER YEAR (DOLLARS/LANE MILE)	20.00
INTEREST RATE OR TIME VALUE OF MONEY (PERCENT)	5.0
THE NUMBER OF AGGREGATES USED IN SEAL COATS.	3
THE MINIMUM ALLOWABLE COEFFICIENT OF FRICTION.	35
THE PERCENT OF ADT IN THE MOST HEAVILY TRAVELED LANE.	60
THE AGGREGATES UNDER CONSIDERATION ARE.	
FOR AGGREGATE DOLO	
THE INITIAL COEFFICIENT OFFRICTION.,	58
THE FINAL COEFFICIENT OF FRICTION.	34
THE FIELD RATE OF POLISH.	.121
TRAFFIC AT WHICH INITIAL COEFFICIENT OF FRICTION IS MEASURED.	50000
COST OF A SEAL COAT (DOLLARS/LANE MILE).	1000
FOR AGGREGATE TRAP	
THE INITIAL COEFFICIENT OFFRICTION.,	58
THE FINAL COEFFICIENT OF FRICTION.	34
THE FIELD RATE OF POLISH.	.096
TRAFFIC AT WHICH INITIAL COEFFICIENT OF FRICTION IS MEASURED.	50000
COST OF A SEAL COAT (DOLLARS/LANE MILE).	1110
FOR AGGREGATE LTWT	
THE INITIAL COEFFICIENT OFFRICTION.,	67
THE FINAL COEFFICIENT OF FRICTION.	50
THE FIELD RATE OF POLISH.	.041
TRAFFIC AT WHICH INITIAL COEFFICIENT OF FRICTION IS MEASURED.	50000
COST OF A SEAL COAT (DOLLARS/LANE MILE).	1782

PROB BUDA CALCULATIONS FOR FEASIBLE AGGREGATES

FOR THE 1 LAYER DESIGN WITH THE FOLLOWING MATERIALS--

	MATERIALS		COST	STR.	MIN.	MAX.	SALVAGE	THICKNESS
LAYER	CODE	NAME	PER CY	COEFF.	DEPTH	DEPTH	PCT.	INCREMENT
1	A	ASPHALTIC CONCRETE	12.00	.75	1.00	6.00	35.00	.50
		SUBGRADE		.23				

THE CONSTRUCTION RESTRICTIONS ARE TOO BINDING TO OBTAIN A STRUCTURE
THAT WILL MEET THE MINIMUM TIME TO THE FIRST OVERLAY RESTRICTION.

PROB BUDA CALCULATIONS FOR FEASIBLE AGGREGATES

FOR THE 2 LAYER DESIGN WITH THE FOLLOWING MATERIALS--

LAYER	MATERIALS CODE	NAME	COST PER CY	STR. COEFF.	MIN. DEPTH	MAX. DEPTH	SALVAGE PCT.	THICKNESS INCREMENT
1	A	ASPHALTIC CONCRETE	12.00	.75	1.00	6.00	35.00	.50
2	B	CRUSHED STONE	4.00	.65	4.00	16.00	35.00	1.00
		SUBGRADE		.23				

2 THE OPTIMAL DESIGN FOR THE MATERIALS UNDER CONSIDERATION--

FOR INITIAL CONSTRUCTION THE DEPTHS SHOULD BE

ASPHALTIC CONCRETE 6.00 INCHES
CRUSHED STONE 7.00 INCHES

THE SCI OF THE INITIAL STRUCTURE = .230
THE LIFE OF THE INITIAL STRUCTURE = 16.56 YEARS
THE OVERLAY SCHEDULE IS
1.50 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER 16.56 YEARS.
TOTAL LIFE = 30.63 YEARS

SEAL COATS WITH AGGREGATE LTWT AFTER
(1) 6.00 YEARS
(2) 12.00 YEARS

THE TOTAL COSTS PER SQ. YD. FOR THESE CONSIDERATIONS ARE

INITIAL CONSTRUCTION COST	1.278
TOTAL ROUTINE MAINTENANCE COST	.327
TOTAL OVERLAY CONSTRUCTION COST	.223
TOTAL USER COST DURING OVERLAY CONSTRUCTION	.080
TOTAL SEAL COAT COST	.330
SALVAGE VALUE	-.388
TOTAL OVERALL COST	1.849

NUMBER OF FEASIBLE DESIGNS EXAMINED FOR THIS SET -- 99

AT THE OPTIMAL SOLUTION,THE FOLLOWING
BOUNDARY RESTRICTIONS ARE ACTIVE--
1. THE MAXIMUM DEPTH OF LAYER 1

PROB BUDA CALCULATIONS FOR FEASIBLE AGGREGATES

FOR THE 3 LAYER DESIGN WITH THE FOLLOWING MATERIALS--

LAYER	MATERIALS CODE	NAME	COST PER CY	STR. COEFF.	MIN. DEPTH	MAX. DEPTH	SALVAGE PCT.	THICKNESS INCREMENT
1	A	ASPHALTIC CONCRETE	12.00	.75	1.00	6.00	35.00	.50
2	B	CRUSHED STONE	4.00	.65	4.00	16.00	35.00	1.00
3	C	GRAVEL	1.50	.40	4.00	20.00	35.00	2.00
		SUBGRADE		.23				

3 THE OPTIMAL DESIGN FOR THE MATERIALS UNDER CONSIDERATION--

FOR INITIAL CONSTRUCTION THE DEPTHS SHOULD BE
ASPHALTIC CONCRETE 6.00 INCHES
CRUSHED STONE 4.00 INCHES
GRAVEL 4.00 INCHES

THE SCI OF THE INITIAL STRUCTURE = .269
THE LIFE OF THE INITIAL STRUCTURE = 14.31 YEARS
THE OVERLAY SCHEDULE IS
1.50 INCH(ES) (INCLUDING 1 INCH LEVEL-UP) AFTER 14.31 YEARS.
TOTAL LIFE = 26.27 YEARS

SEAL COATS WITH AGGREGATE LTWT AFTER
(1) 6.00 YEARS
(2) 12.00 YEARS

THE TOTAL COSTS PER SQ. YD. FOR THESE CONSIDERATIONS ARE

INITIAL CONSTRUCTION COST	1.111
TOTAL ROUTINE MAINTENANCE COST	.279
TOTAL OVERLAY CONSTRUCTION COST	.249
TOTAL USER COST DURING OVERLAY CONSTRUCTION	.084
TOTAL SEAL COAT COST	.330
SALVAGE VALUE	-.366
TOTAL OVERALL COST	1.686

NUMBER OF FEASIBLE DESIGNS EXAMINED FOR THIS SET -- 577

AT THE OPTIMAL SOLUTION,THE FOLLOWING
BOUNDARY RESTRICTIONS ARE ACTIVE--
1. THE MAXIMUM DEPTH OF LAYER 1
2. THE MINIMUM DEPTH OF LAYER 2
3. THE MINIMUM DEPTH OF LAYER 3

PROB RODA CALCULATIONS FOR FEASIBLE AGGREGATES

A SUMMARY OF THE BEST DESIGN FOR EACH COMBINATION
OF MATERIALS, IN ORDER OF INCREASING TOTAL COST

DESIGN NUMBER	TOTAL COST
3	1.686
2	1.849

THE MATERIALS ASSOCIATED WITH EACH OF THE FOLLOWING DESIGN
NUMBERS DO NOT HAVE AT LEAST ONE FEASIBLE DESIGN.

1

PROB BUDA CALCULATIONS FOR FEASIBLE AGGREGATES

SUMMARY OF THE BEST DESIGN STRATEGIES
IN ORDER OF INCREASING TOTAL COST

	1	2	3	4	5	6	7	8
MATERIAL ARRANGEMENT	ABC	AB	ABC	ABC	ABC	ABC	ABC	ABC
INIT. CONST. COST	1.111	1.278	1.278	1.306	1.333	1.361	1.389	1.417
OVERLAY CONST. COST	.249	.223	.203	.203	.205	.212	.210	.209
USER COST	.084	.080	.077	.077	.077	.078	.078	.078
SEAL COAT COST	.330	.330	.384	.384	.384	.330	.330	.330
ROUTINE MAINT. COST	.279	.327	.345	.345	.345	.345	.345	.345
SALVAGE VALUE	-.366	-.388	-.366	-.370	-.374	-.333	-.337	-.341
TOTAL COST	1.686	1.849	1.921	1.945	1.971	1.994	2.015	2.038
NUMBER OF LAYERS	3	2	3	3	3	3	3	3
LAYER DEPTH (INCHES)								
D(1)	6.00	6.00	5.50	5.50	5.50	4.50	4.50	4.50
D(2)	4.00	7.00	4.00	5.00	6.00	4.00	5.00	6.00
D(3)	4.00		8.00	6.00	4.00	10.00	8.00	6.00
NO.OF PERF.PERIODS	2	2	2	2	2	2	2	2
PERF. TIME (YEARS)								
T(1)	14.3	16.6	18.4	18.4	18.3	17.6	17.8	17.9
T(2)	26.3	30.6	34.4	34.4	34.2	32.7	33.2	33.2
OVERLAY POLICY(INCH) (INCLUDING LEVEL-UP)								
O(1)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
NUMBER OF SEAL COATS	2	2	4	4	4	2	2	2
SEAL COAT SCHEDULE								
AGGREGATE	LTWT	LTWT	TRAP	TRAP	TRAP	LTWT	LTWT	LTWT
SC 1)	6.0	6.0	4.9	4.9	4.9	6.0	6.0	6.0
SC 2)	12.0	12.0	9.0	9.0	9.0	12.0	12.0	12.0
SC 3)			12.6	12.6	12.6			
SC 4)			15.8	15.8	15.8			

THE TOTAL NUMBER OF FEASIBLE DESIGNS CONSIDERED WAS 676

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