

EFFECT OF COARSE AGGREGATES ON THE DESIGN AND PERFORMANCE OF CRCP IN TEXAS

B. Frank McCullough and C. L. Saraf
Center for Transportation Research
The University of Texas at Austin
Austin, Texas

This paper describes a study which was conducted to investigate the effect of coarse aggregate types on the performance of continuously reinforced concrete pavements (CRCP) built in Texas. As is the case for most agencies, the Texas State Department of Highways and Public Transportation (SDHPT) specifications for Portland cement concrete are based on the hypothesis that all coarse aggregates will give the same performance if surrogate tests such as grading, hardness are met. Long term performance studies of PCC pavements, previously reported, show that the performance is a function of coarse aggregate type. The study reported herein covers the selection of the coarse aggregate types for study, measurement of properties for mechanistic models, and design of CRCP.

A survey of coarse aggregate types used in Texas indicated that most concrete pavements were constructed with either crushed limestone (LS) or siliceous river gravel (SRG). Therefore, these two types of aggregates were selected for this study.

The laboratory testing program was predicated on selecting test procedures that provided results for use in mechanistic models. Cement concrete mixes containing LS and SRG aggregates were prepared in the laboratory, and the following mechanistic material properties were measured:

1. modulus of elasticity,
2. tensile strength by indirect method,
3. thermal coefficient of expansion, and
4. drying shrinkage.

An experimental testing factorial was developed for preparing and curing the mixes in the laboratory. The factorial was designed to use statistical models that predicted the material property of interest in terms of pertinent factors. This factorial included the following factors at various levels based on a study of Texas environmental conditions as listed below:

<u>Factors</u>	<u>Levels</u>
1. Coarse Aggregates	SRG, LS
2. Moisture Condition (Percent Relative Humidity)	40, 100
3. Curing Temperature	50, 75, and 100°F
4. Curing Time	1, 3, 7, 28, and 90 days

The full factorial contained 60 cells for each mix property measured in the laboratory. Three replicate samples were tested

within each cell. Statistical analysis of data was performed to estimate the effect of various factors (listed above) on the measured properties, and a regression model was developed for each mix property measured in the laboratory. These models are presented in this paper.

A mechanistic model, i.e., computer program, CRCP, was used to estimate the performance of CRCP in Texas. The output of CRCP computer model included three performance parameters – longitudinal crack spacing, crack width, and steel stress. For this purpose, the state of Texas was divided into three environmental zones and a city representing each environmental zone was selected. Four typical seasons representative of the state of Texas were selected for placing new concrete pavements in the field and the performance of pavement sections was estimated for each placement season.

Hypothetical pavement sections varying in thickness from 8 to 15-inches, reinforcing steel from 0.4 to 0.7 percent, and bar sizes from #4 to #7 were analyzed with the help of CRCP program. A total of 3,072 runs were made to obtain the estimates of performance of 128 hypothetical pavement sections constructed with concrete mixes containing LS and SRG and placed during four different seasons at three typical locations in Texas. These models are also presented in the paper.

The values of the performance parameters for each pavement section were compared with the limiting values specified in the new AASHTO Design Guide to determine if the given pavement will perform satisfactorily or not under the environmental and other conditions used as input to the CRCP model. Thus, all those pavements which performed satisfactorily under the specified performance criteria (crack spacing, crack width, and steel stress) were screened from 3,072 outputs of CRCP computer runs, and steel design charts were developed for two types of pavements using SRG and LS as shown in Figs 5 and 6. These charts provide a range of acceptable designs considering percent steel, bar diameter, and pavement thickness for the material properties and environmental conditions considered.

The design charts developed as a results of this analysis predict a significant difference in steel requirement between pavements built with LS and those built with SRG aggregates. Thus, the variation in concrete mix properties due to the use of these two aggregate types was translated into different steel requirements for a given pavement design.

INTRODUCTION

Past practice in the design and construction of Continuously Reinforced Concrete Pavements (CRCP) did not

consider the variation in the concrete properties of the mixes containing different types of coarse aggregates. It was generally assumed that as long as the aggregates meet gradation and other requirements, the performance of the mixes used in concrete pavement will be satisfactory. However, field observations of CRCP performance in Texas indicated that pavements built with different coarse aggregate types showed significant differences in their performance (1). Therefore, the Texas SDHPT initiated a study in 1986 to investigate the effect of coarse aggregates on the design and performance of CRCP in Texas. This paper presents the results of the first phase of the study.

The objectives of the study described in this paper were as follows:

1. Evaluate the effect of coarse aggregate type on concrete pavement performance.
2. Ascertain the causes.
3. Develop design and specifications providing equal performance for various aggregate types.

This paper describes the details of the research undertaken to accomplish the objectives stated above.

RESEARCH APPROACH

Past research has indicated that the following factors can be used to assess the performance of CRC pavements (2):

1. transverse crack spacing,
2. crack width, and
3. stresses in reinforcing steel.

A brief explanation of the relationship between these factors and CRC pavement performance is as follows:

Transverse crack in CRC pavements divide the slab into segments bounded by successive cracks. Due to passage of traffic these cracks may spall and pavement segments may start losing continuity with the rest of the slab. Due to partial or no load transfer across these cracks, the pavement segment may experience excessive stresses and ultimately fail due to development of longitudinal cracks along the wheel path.

Since the stresses in pavement segment depend upon the magnitude of wheel load due to traffic and the size of the segment (bounded by the transverse cracks), there is an obvious relation between the spacing of transverse cracking and the performance of the CRC pavements. Closer crack spacing is likely to produce higher live load stresses, greater potential for its failure and hence poor performance. Therefore, generally crack spacings less than 3.5 feet are considered to be undesirable by pavement designers (2). Also, as the crack spacing becomes larger (greater than 8.0 feet), the crack opening becomes wide enough to allow surface water and other foreign material into the cracks and cause damage to the pavement.

The purpose of reinforcing steel in CRC pavement is not to strengthen the pavement, but to maintain the continuity due to cracking of the slab (this is an inherent characteristic of all CRC pavements). When transverse crack spacing is large enough to produce excessive tensile stresses in reinforcing bars, these bars fail and the continuity of the slab is broken. This will cause failure in the pavement segments bounded by transverse cracks.

The factors described above were used in the study to estimate the performance of pavements using mixes which contain two different kinds of coarse aggregates.

A computer program was developed by the research staff of the Center for Transportation Research at The University of Texas at Austin to estimate the transverse crack spacing, crack width, and steel stress in CRC pavements. This program, which is known as CRCP-2, was used in this study to estimate the performance of several CRC pavements selected for this study. The results of this analysis were used to determine the effect of coarse aggregates on the performance of various pavements included in the study. The following inputs were developed for this purpose:

1. strength and thermal properties of concrete mixes selected for this study,
2. reinforcing steel strength and thermal properties,
3. typical environmental zones within the state of Texas,
4. subgrade soil support characteristics, and
5. subbase friction characteristics.

The following paragraphs briefly describe the study conducted to develop the inputs listed above.

EXPERIMENTAL FACTORIAL FOR LABORATORY TESTING OF MIXES

Majority of CRC pavements built in the state of Texas contain either limestone (LS) or siliceous river gravel (SRG) aggregates in their mixes. Therefore, these two aggregates were selected for the first phase of this study. Portland cement concrete mix samples containing these aggregates were prepared according to the current Texas SDHPT specifications. These samples were tested to determine the following mix properties:

1. modulus of elasticity (E),
2. flexural strength,
3. tensile strength using split cylinder test,
4. thermal coefficient of expansion, and
5. drying shrinkage of concrete.

Each property was measured for the following conditions:

1. Curing Conditions - 40 and 100 percent relative humidity;
2. Curing Temperature - 50, 75, and 100°F; and
3. Curing Times - 1, 3, 7, 28, and 90 days.

A complete factorial used for measuring each mix property is shown in Fig 1. The methods of testing the mixes are described in Center for Transportation Research Research Report 422-2 (3). Three samples were tested for each cell of the factorial shown in Fig 1.

Analysis of the measurements was performed to develop a relationship between the measured property and the variables included in the experimental factorial. The results of this analysis are summarized in Eqs 1 through 4. The flexural strength test data were not used in this study, therefore, these data were not analyzed.

STEEL REINFORCEMENT PROPERTIES

ASTM Grade 60 steel was considered for this study. The following properties were used for CRCP-2 analysis.

1. Yield strength: 60 ksi
2. Modulus of elasticity: 29,000 ksi
3. Coefficient of thermal expansion: 5×10^{-6} inch/inch/°F

ENVIRONMENTAL DATA

In order to study the effect of environmental factors on the performance of CRC pavements, suitable environmental data was gathered for the state of Texas. Based on the input needs of CRCP-2 computer program, the state was divided into three climatological regions as shown in Fig 2. Cities representing these typical regions were selected so that the results could be related to real sites rather than hypothetical locations.

The calendar year was divided into four seasons. Months representing each season are shown in Table 1. Seasonal daily temperature drops and the number of days before maximum temperature drop occurs at each site are listed in Table 2 and Table 1, respectively. Values listed in these tables were used for CRCP-2 analysis of the pavements.

SUBGRADE SOIL SUPPORT CHARACTERISTICS

A common soil support condition was assumed for all pavements in order to compare the effect of aggregates on the performance of CRC pavements. A value of 300 pci was assumed for the modulus of subgrade reaction.

SUBBASE FRICTION RELATIONSHIP

Since the primary objective of this study is to compare the performance of pavements using two different types of aggregates, a common subbase friction relationship was assumed for all pavements used in this study. This relationship is shown in Fig 3.

DESIGN OF EXPERIMENTAL FACTORIAL

A factorial was designed to study the effect of aggregate types on the performance of CRC pavements. The following variables were selected for this purpose:

1. Coarse aggregate types - 2 (LS, SRG);
2. Concrete placement seasons - 4 (winter, summer, autumn, and spring);
3. Geographic locations - 3 (Brownsville, Port Arthur, and Amarillo);
4. Steel reinforcement
 - (a) Bar sizes - 4 (# 4, # 5, #6, and # 7);
 - (b) Percent steel - 4 (0.4, 0.5, 0.6, and 0.7);
5. Pavement thicknesses - 8 (8 inch to 15 inches with 1 inch increments).

A typical factorial for a given location and one season is shown in Fig 4. A total of 3,072 pavement sections representing the entire experiment were analyzed with the help of CRCP-2 computer program. The results of data analysis are described in the next section of the paper.

ANALYSIS OF DATA

Two sets of data were collected for this study. The first set consisted of concrete mix properties measured in the laboratory and the second set consisted of CRCP-2 analysis of 3,072 CRC pavement sections. The results of each set are briefly described in the following paragraphs.

Analysis of Concrete Mix Properties Data

Laboratory test data were used to develop relationship between the measured property and the test variables. Regression analysis method was used to develop these relationships. The results of this analysis are summarized below.

Modulus of elasticity of concrete mix (E):

$$E = [e^{(5.26 + 0.104x)}] [t^{0.097}] [H^{0.152}] \quad (1)$$

where

- E = modulus of elasticity of mix ($\times 10^4$ psi);
 t = concrete age, days;
 H = relative humidity, percent; and
 x = coarse aggregate type used in mix
 x = 0, if SRG;
 x = 1, if LS.

Tensile strength (f_t) of mix determined by split cylinder test:

$$f_t = [e^{(4.74 + 0.0642x)}] [t^{0.0926}] [T^{0.18}] [H^{0.03}] \quad (2)$$

where

- f_t = tensile strength, psi;
 T = curing temperature, D_F ; and
 t, H, and x = same as defined in Eq 1.

Thermal coefficient of expansion of mix:

The analysis of data indicated that for the first 90 days of curing, the mixes did not show any effect of variables on the value of thermal coefficient. Therefore, constant values were assumed for each mix. These values are as follows:

SRG - 8×10^{-6} inch/inch/°F

LS - 6×10^{-6} inch/inch/°F (3)

Drying shrinkage (Z_t) for mixes:

$$Z_t = [e^{(0.0422 - 0.092x - 8.72/x)}] [T^{1.35}] \quad (4)$$

where

Z_t = drying shrinkage in 10^{-6} inch/inch/°F.

Other terms of Eq 4 are the same as in Eqs 1 and 2.

It is important to note here that if a test variable did not show significant effect on the measured property, then, this variable was not included in the regression equation. For

example, T (curing temperature) did not show significant effect on E (modulus of elasticity). Therefore, this variable was not included in Eq 1.

Analysis of CRC Pavement Sections

CRCP-2 computer program was used to analyze 3,072 CRC pavement sections selected for this study according to the partial factorial shown in Fig 4. The output of this analysis included the transverse crack spacing, crack width, and reinforcing steel stress for each pavement.

The results of the analysis were compiled to summarize the results in the form of regression equations. These equations represent the relationship between the performance variables (crack spacing, crack width, and steel stress) and the analysis variables shown in the factorial (see Fig 4). The resulting equations are as follows:

Crack Spacing

The following log model was developed for the crack spacing criteria:

$$\ln CS = -2.31 + S + A + B + 1.304 \ln D - 1.97 \ln PS \quad (5)$$

where

- CS = crack spacing (feet),
- S = coefficient for season (see Table 3),
- A = coefficient for aggregate type (see Table 3),
- B = coefficient for bar number (see Table 3),
- D = slab thickness (inches), and
- PS = percent steel reinforcement.

Crack Width

Equation 6 describes the model developed for the crack width criteria:

$$\ln CW = -2.59 + S + A + B + 1.23 \ln D + 1.94 \ln PS \quad (6)$$

where

- CW = crack width x 10^{-2} inch.

Other variable notation is similar to Eq 5. Coefficient values for the equation may be obtained from Table 4.

Steel Stress

The model developed for steel stress is represented by the relationship

$$\ln SS = -0.688 + S + A + B + 0.731 \ln D - 1.12 \ln PS \quad (7)$$

where

- SS = steel stress x 10^{-1} ksi.

Again, the remaining notations are identical to Eq 5. Coefficient values for this equation are listed in Table 5.

EFFECT OF COARSE AGGREGATE TYPE ON THE PERFORMANCE OF CRC PAVEMENTS

As stated earlier, the performance of CRC pavements is generally measured by its crack spacing (CS), crack width (CW), and steel stress (SS). Equations 5, 6, and 7 developed in this study can be used to estimate the effect of coarse aggregate types on these parameters as follows:

Suppose the crack spacing in CRC pavements built with LS and SRG aggregate mixes are represented by CS (LS) and CS (SRG), respectively. If R is ratio of these two crack spacings, then,

$$R = \frac{CS (LS)}{CS (SRG)} \quad (8)$$

or

$$\ln R = \ln CS (LS) - \ln CS (SRG) \quad (9)$$

Now, considering two identical pavement built with mixes containing LS and SRG, Eq 5 indicates that the terms on the right hand side of the equation will be identical except A. Therefore, substituting the values from Eq 5 in Eq 9, we get,

$$\ln R = A (LS) - A (SRG) \quad (10)$$

where A (LS) and A (SRG) are the coefficients A for LS and SRG aggregates, respectively.

Substituting the values of A from Table 3, we get

$$\ln R = 0.385$$

or,

$$CS (LS) = 1.47 * CS (SRG) \quad (11)$$

This indicates that the crack spacing in CRC pavements built with LS is about 47 percent larger than the pavements built with SRG aggregates for identical conditions.

Using the same procedure as described above, the relationships for the remaining two other performance parameters are as follows:

$$CW (LS) = 1.15 CW (SRG) \quad (12)$$

$$SS (LS) = 1.18 SS (SRG) \quad (13)$$

These relationships indicate that crack width (CW) as well as steel stress (SS) are also 15 and 18 percent, respectively, higher in LS mix pavements.

DISCUSSION OF RESULTS

An important implication of the above results is that if we consider a CRC pavement design which produces closer transverse crack spacings in SRG mixes (<3.5 feet), the same design will be satisfactory if LS mix is used in the construction of the pavement. On the other hand, if the design indicates longer crack spacings (close to 8 feet), LS mixes may produce unsatisfactory pavements. Therefore, in such cases, SRG mixes will produce satisfactory designs if the remaining two parameters are within the specified limits.

The results of this study summarized by Eqs 5 through 7 and Eqs 11 through 13 indicate that there is a significant difference in the performance of CRC pavements of SRG and LS aggregates. Therefore, the designer has to either specify the coarse aggregate for a specific design in order to obtain specific performance or provide two different designs (one for each coarse aggregate type). Therefore, using the results of this study, suitable design charts were developed to accommodate the use of either aggregate in the construction specifications. A brief description of these charts is included in the following paragraph.

STEEL REINFORCEMENT DESIGN FOR LS AND SRG MIX CRC PAVEMENTS

The design charts shown in Figs 5 and 6 were developed to design steel reinforcement for pavements using LS and SRG aggregates, respectively. Regression Eqs 5, 6, and 7 were used for this purpose. In order to determine the ranges in percentage of steel for each bar size, the following limits were used:

Crack spacing (CS)	3.5 feet to 8.0 feet,
Crack width (CS)	Less than 0.047 inch, and
Steel stress (SS)	Less than 60 ksi.

The most critical placement season was determined and regression Eqs 5 through 7 were rearranged to represent a relationship between the percentage of steel as a dependent variable and the other factors as independent variables. These equations were then used in conjunction with the limits stated above to arrive at the design charts shown in Figs 5 and 6. These charts represent pavements of equal performance and allow the designer to develop pavements of equal thicknesses and performances by selecting the appropriate steel percentage for each type of mix. For example, if a 10-inch-thick CRC pavement is to be designed using bar # 6, then, the steel for pavement reinforcement will be as follows:

- LS mix - 0.55 to 0.65 percent.
- SRG mix - 0.46 to 0.54 percent.

CONCLUSIONS

Portland cement concrete mixes containing LS and SRG aggregates were tested in the laboratory under identical conditions. The measured properties were different for each mix as represented by Eqs 1 through 4. Typical values for 28 day curing time are listed in Table 6.

CRC pavements containing these mixes were analyzed with the help of the computer program CRCP-2. A total of 1,536 pavements of each type were analyzed to estimate the performance of these pavements in terms of transverse crack spacing, crack width, and steel stress. It was observed that pavements containing LS mix developed 47 percent larger crack spacings, 15 percent larger crack widths, and 18 percent more steel stresses than pavements containing SRG mixes. This will result into poor performance of SRG pavements if they were designed for crack spacings closer to the lower limits (3.5 feet). However, the CRC pavement designed for crack spacings closer to higher limits (8 feet) will perform poorly if LS mixes are used in such pavements.

In order to provide designs of equal performance, design charts were developed from the data obtained in this study. These charts allow the design of pavements (CRC) of equal

performance and thicknesses by using different percentages of steel in the pavements. A simple example included in the test shows the use of these charts (Figs 5 and 6).

ACKNOWLEDGEMENTS

The authors are pleased to acknowledge the combined efforts and support of the Center for Transportation Research at The University of Texas at Austin and the Texas State Department of Highways and Public Transportation, in cooperation with the U. S. Department of Transportation Federal Highway Administration.

DISCLAIMER

The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

REFERENCES

1. Guitierrez de Velasco, Manuel, and B. Frank McCullough, "Summary Report for 1978 CRCP Condition Survey in Texas," Research Report 177-20, Center for Transportation Research, The University of Texas at Austin, January 1981.
2. "The AASHTO Guide for the Design of Pavement Structures," American Association of State Highway and Transportation Officials, 1986.
3. Aslam, Mohammad F., C. L. Saraf, Ramon L. Carrasquillo, and B. Frank McCullough, "Design Recommendations for Steel Reinforcement of CRCP," Research Report 422-2, Center for Transportation Research, The University of Texas at Austin, November 1987.

TABLE 1. NUMBER OF DAYS BEFORE MAXIMUM TEMPERATURE DROP FOR EACH SEASON

Season	Months	Number of Days Before Maximum Temperature Drop
Winter	Dec/Jan/Feb	360
Spring	Mar/Apr/May	270
Summer	Jun/Jul/Aug	180
Fall	Sep/Oct/Nov	90

TABLE 5. COEFFICIENTS FOR USE IN EQUATION 7

Season	Coefficient, S	Aggregate Type	Coefficient, A	Bar Number	Coefficient, B
Winter	0.018	Limestone	0.000	4	-0.040
Spring	0.104	Siliceous		5	-0.031
Summer	0.102	River Gravel	-0.168	6	0.000
Fall	0.000			7	0.000

TABLE 2. REVISED SEASONAL DAILY TEMPERATURE DROP VALUES

Location	Season			
	Winter	Spring	Summer	Fall
Brownsville	41	36	23	32
Port Arthur	34	30	23	28
Amarillo	47	45	41	39

TABLE 6. COMPARISON OF CONCRETE PROPERTIES OF LIMESTONE AND SILICEOUS RIVER GRAVEL AGGREGATES AT 28 DAYS

Concrete Property	Aggregate Type	
	Limestone	Siliceous River Gravel
Tensile strength, f_{t28}	411 psi	386 psi
Drying shrinkage, ϵ_{28}	149×10^{-6} in./in.	163×10^{-6} in./in.
Thermal coefficient, α_c	6×10^{-6} in./in./°F	8×10^{-6} in./in./°F
Elastic modulus, E_{28}	5.7×10^6 psi	5.1×10^6 psi

TABLE 3. COEFFICIENTS FOR USE IN EQUATION 5

Season	Coefficient, S	Aggregate Type	Coefficient, A	Bar Number	Coefficient, B
Winter	0.195	Limestone	0.000	4	-0.779
Spring	0.153	Siliceous		5	-0.541
Summer	0.035	River Gravel	-0.385	6	-0.283
Fall	0.000			7	0.000

TABLE 4. COEFFICIENTS FOR USE IN EQUATION 6

Season	Coefficient, S	Aggregate Type	Coefficient, A	Bar Number	Coefficient, B
Winter	-0.079	Limestone	0.000	4	-0.774
Spring	0.131	Siliceous		5	-0.537
Summer	0.181	River Gravel	-0.137	6	-0.283
Fall	0.000			7	0.000

COARSE AGGREGATE TYPES		MOISTURE CONDITIONS						
		40% REL HUM.			100% REL HUM.			
		CURING TEMPERATURES						
		50°F	75°F	100°F	50°F	75°F	100°F	
Limestone	CURING TIMES	Siliceous River Gravel	1					
		3						
		7						
		28						
		90						
		1						
		3						
		7						
		28						
		90						

Fig 1. Factorial for laboratory testing.

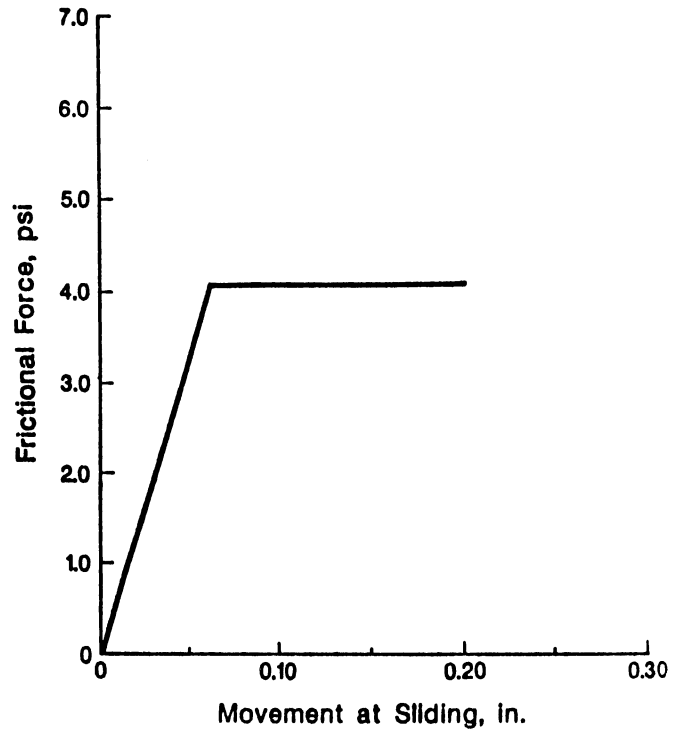
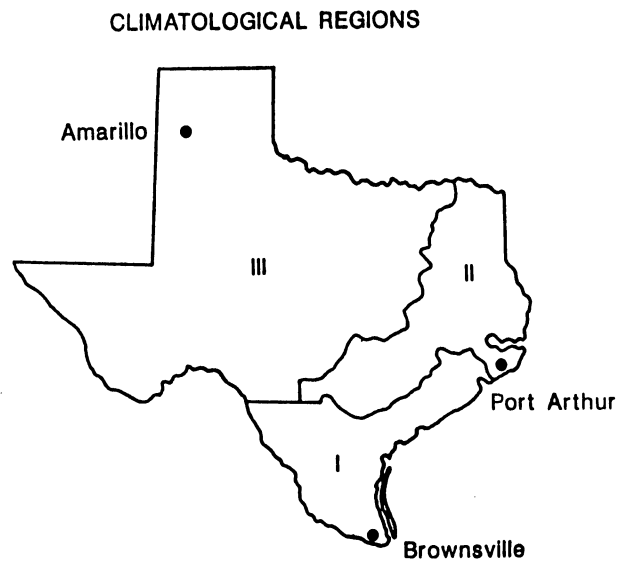


Fig 3. Slab subbase friction relationship.



ZONES	COMBINED DISTRICTS	SITES
I	Gulf Coast / Lower Valley	Brownsville
II	East Texas - South Central	Port Arthur
III	North and West Texas	Amarillo

Fig 2. Climatological regions of the state of Texas.

% Steel Bar #		0.4%				0.5%				0.6%				0.7%			
		4	5	6	7	4	5	6	7	4	5	6	7	4	5	6	7
SILICEOUS RIVER GRAVEL	8																
	9																
	10																
	11																
	12																
	13																
	14																
	15																
CRUSHED LIMESTONE	8																
	9																
	10																
	11																
	12																
	13																
	14																
	15																

Fig 4. Analysis factorial for one season at any one location.

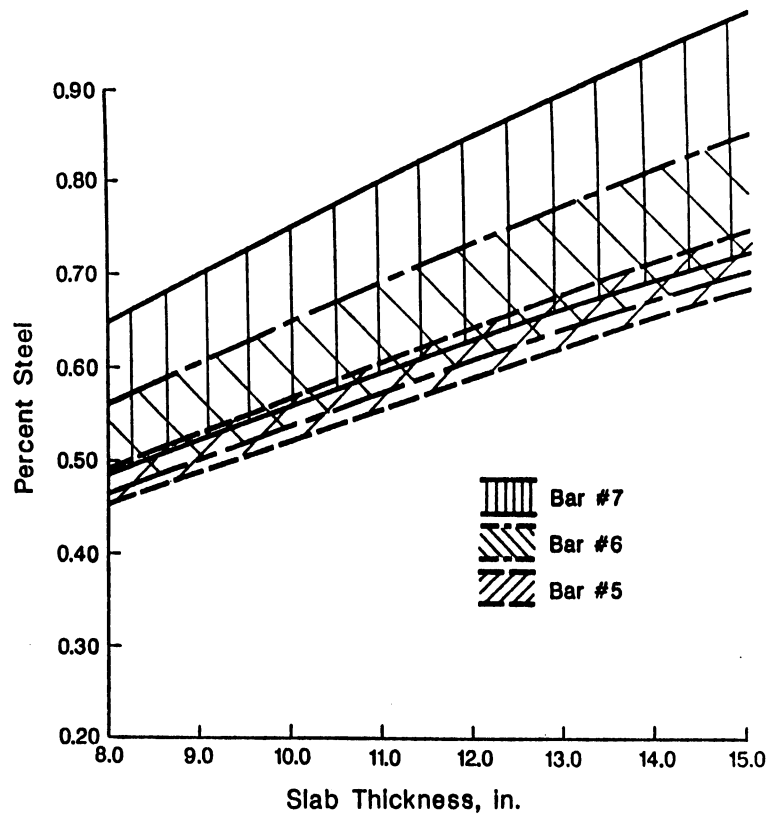


Fig 5. Steel design charts for limestone aggregate for all seasons and locations in Texas.

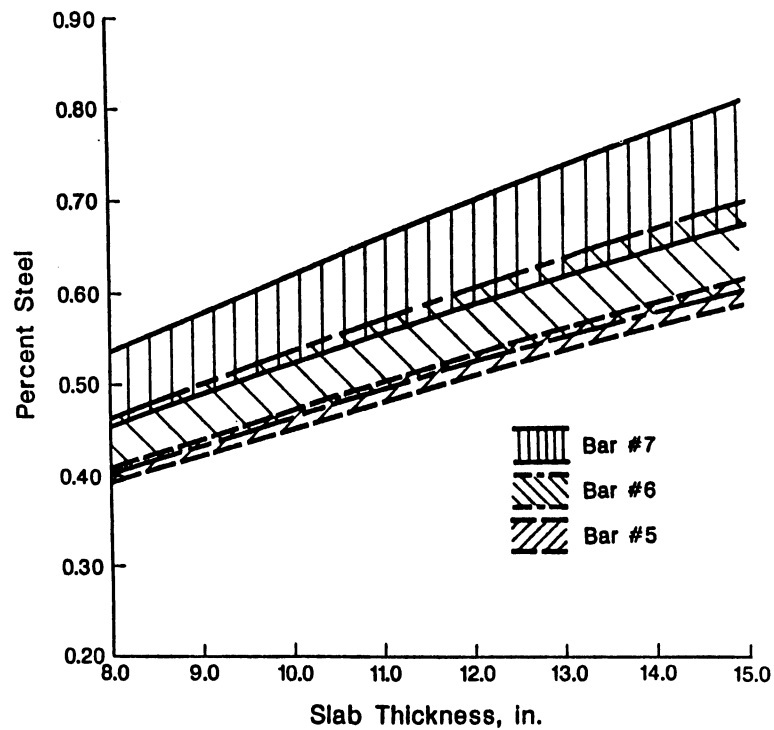


Fig 6. Steel design charts for siliceous river gravel aggregates for all seasons and locations in Texas.