THE EFFECT OF PLASTICITY AND QUANTITY OF
FINES ON STABILITY OF SOIL-GRAVEL MIXTURES

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JOINT HIGHWAY RESEARCH PROJECT
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THE EFFECT OF PLASTICITY AND QUANTITY OF FINES ON STABILITY OF SOIL-GRAVEL MIXTURES

File: 6-18-10

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Final Report

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STABILITY OF SOIL-GRAVEL MIXTURES

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Faiz Makdisi-Ilyas

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ABSTRACT

Makdisi-Ilyas, Faiz. M.S.C.E., Purdue University, June 1972.
The Effect of Plasticity and Quantity of Fines on Stability of Soil-Gravel Mixtures. Major Professor: E. J. Yoder.

This thesis reports the results of a laboratory investigation of the effects of quantity and quality of fines on the stability of soil-gravel mixtures as measured by the Texas triaxial test. Thirty six different combinations were tested at their optimum moisture content. Five tests were run on each mixture and three different lateral pressures were used.

The granular portion of the mixes was a locally available terrace gravel used in combination with three types of soil having different plasticities. The gradations of the samples were kept constant down to the passing No. 8 sieve portion and from there they were varied to obtain skip-graded specimens as well as well graded ones. These gradations essentially confirmed with Indiana specification No. 53 aggregate.

The tests used in this study were:

1. Atterberg limits tests;
2. Compaction tests;
3. Texas triaxial compression test.

The test data were analyzed statistically using regression and analysis of variance techniques. It was determined that a low percent of the material passing No. 30 sieve was desirable particularly if the dust ratio (ratio of percent passing No. 200 sieve to percent passing

No. 30 sieve) was high. For this case high plasticity indices (15% - 20%) did not harm the mixture. When the percent passing No. 30 sieve became high, mixtures with low dust ratios were more stable and high plasticity indices had an adverse effect on the stability of the mixtures.

INTRODUCTION

Most specifications for base materials require that the plasticity index (P. I.) of the passing No. 40 portion of the mix be no greater than 6% and that the liquid limit (L. L.) be no greater than 25%. The origin of these limits dates back to 1936 when Hogentogler and Willis(10) concluded, "For base courses the material passing the #40 sieve should have a plasticity index of not more than 6 and a liquid limit not more than 25."

Carpenter and Willis(4,5) arrived at the same conclusion after conducting circular-track tests on sand-clay, and gravel-sand-clay materials. Table 1 shows the specifications they set for gravel-sand-clay mixtures.

The results mentioned above were then adopted by AASHO. These specified values of plasticity index (P. I.) and liquid limit are widely used by many highway departments. Along with this, specifications generally require that the material be well graded, and special emphasis is placed on the amount of fines permitted in the mix.

It is believed that these limits are in certain cases somewhat restrictive. For example, when the amount of fines contained in the base course is low, it may be possible to permit some leeway in plasticity requirements without causing great harm to the mix. This would be particularly true for areas that are not subjected to frost action.

TABLE 1. Specifications for soil and gravel base courses.

	TYPE B BASE COURSES			
	B-1, 1 INCH MAX SIZE		B-2, 2 INCH MAX SIZE	
	MAX.	MIN.	MAX.	MIN.
Percentage passing				
2-inch sieve	---	---	---	100
1½-inch sieve	---	---	70	100
1-inch sieve	---	100	55	85
¾-inch sieve	70	100	50	80
⅜-inch sieve	50	80	40	70
⅙-inch sieve	35	65	30	60
No. 4 sieve	25	50	20	50
No. 10 sieve	15	30	10	30
No. 40 sieve	5	15	5	15
No. 200 sieve	---	---	---	---
Percentage of material finer than No. 40 sieve	---	---	---	---
passing No. 200 sieve	---	50	---	50
Liquid limit (material finer than No. 40 sieve)	---	25	---	25
Plasticity index (material finer than No. 40 sieve)	---	6	---	6

(From Carpenter and Willis, PUBLIC ROADS, Vol. 20, No. 1)

Many factors influence properties of soil-aggregate mixtures including permeability, grain size distribution, density, maximum size of aggregate, type of aggregate, particle shape and plasticity. These variables affect the behavior of base materials in a complex and inter-related manner. The work done herein attempts to separate some of these variables and concentrate on the interrelated effects of plasticity, the amount of material passing No. 30 sieve, and the amount of fines (passing No. 200 sieve) on the stability of soil-gravel mixes.

PURPOSE AND SCOPE

The purpose of this study is to investigate the effect of: varying the amount of material passing the No. 30 sieve; the amount of fines passing the No. 200 sieve; and the quality of these fines on stability of gravel-soil mixtures used as measured by the triaxial test. It is realized that the factors affecting the properties of soil-aggregate mixtures are many; however, as mentioned earlier emphasis was placed on evaluation of the effect of quantity and quality of fines on stability because it was felt that the specifications for these may be restrictive in some cases.

The material used was graded between the 1" and No. 8 sieves according to the following equation:

$$P = \sqrt{\frac{d}{D}} (100)$$

where:

P = percent by weight finer than a given sieve.

d = size of sieve opening in question.

D = maximum size of aggregate.

The gradation curve for this equation lies within the limits of Indiana No. 53 aggregate (11).

A completely randomized $3 \times 3 \times 4$ factorial design was used. Three levels of percent passing No. 30 sieve, three types of fines (material passing the No. 200 sieve), and four levels of dust ratio were tested.

Dust ratio is defined as the ratio of the amount of material passing No. 200 sieve to the amount of material passing No. 30 sieve.

The three levels of percent material passing the No. 30 sieve were 10 percent, 15 percent, and 20 percent respectively. The four levels of dust ratios were 1.0, 0.75, 0.5 and 0.25. The three types of fines were: Crosby soil (low compressibility clay), Brookston soil (moderately compressible clay), and Limestone Residual (highly compressible clay).

The properties that were kept constant in this study were: the maximum size of gravel; the quality of the gravel, such as hardness and roughness; and the gradation down to the No. 8 sieve. The study was restricted to gravel aggregates with no crushed particles.

REVIEW OF LITERATURE

Many individuals have investigated the properties of base course and subbase course materials. These studies have included evaluations based on laboratory tests as well as field performances.

Yoder (16) studied the effect of the amount of fines on the CBR of soil-aggregate mixtures. The results of this study indicated that maximum dry density of materials with maximum size aggregate of 3/4" occurred with about 8-10 percent passing the No. 200 sieve, and that maximum California Bearing Ratio (CBR) occurred with about 6-8 percent passing the No. 200 sieve. In this study the plasticity of the fine fraction was held constant. Figure 1 and Figure 2 show the variation of density and CBR with the amount of fines.

Deklotz (7) studied the effect of the quality of soil (designated by $\frac{PI}{LL} \times 100$) on the stability as determined by California Bearing Ratio. His tests indicated that there was a definite relationship between the quality and quantity of soil and the stability. He also concluded that the practice of rejecting aggregates on the basis of Atterberg limits tests, without consideration for the relative importance of the quantity of soil in the mix, may often be uneconomical. A summary of his results are shown in Figures 3, 4, and 5. Figure 3 shows the variation of bearing value (CBR) with percent soil passing No. 40 sieve and it appears that there is an optimum amount of passing No. 40 sieve for which the strength is maximum. It may be noted that the higher the plasticity

FIGURE 1. Variation of density and California Bearing Ratio with quantity of fines (gravel).
(From Yoder, PRINCIPLES OF PAVEMENT DESIGN, 1959)

FIGURE 2. Variation of density and California Bearing Ratio with quantity of fines (crushed stone).
(From Yoder, PRINCIPLES OF PAVEMENT DESIGN, 1959)

Average of Ratio of Bearing Value to
Corresponding Standard Value in Percent

FIGURE 3. Effect of Variation in Quantity.

FIGURE 4. Effect of Variation in "D"

FIGURE 5. Combined Effect of Variation of Quantity and "D"

Soil	L.L.	P.I.	%Clay
A	25.4	41	20
B	33.0	135	60
C	44.0	212	100

$$"D" = \frac{P.I.}{L.L.} \times 100$$

(FIGURES 3, 4, and 5 from Deklotz, PROCEEDINGS, HIGHWAY RESEARCH BOARD, 1940)

the less is the strength. Figure 4 shows the effect of "D" ($\frac{PI}{LL}$) on the CBR for different percentages of soils. Figure 5 combines the two figures in one by having the abscissae as the product of percent soil by "D".

The stability test used by Yoder(14) and Deklotz(7) was the California Bearing Ratio test. Other investigators have used the triaxial test for evaluation of granular mixtures.

Gray(9) studied the effect of quantity and plasticity of fines on gravel and crushed stone materials utilizing the triaxial test. He concluded that for different maximum sizes there are different optimum amounts of passing No. 200 material that will give maximum strength. He suggested that a grading curve approaching $n = 1/3$ in the equation $P = (\frac{d}{D})^{1/3}(100)$ as the most desirable.

Jewell(12) investigated the suitability of the AASHO specifications for plasticity and concluded that these limits are restrictive for conditions in Western Australia. His experimental program included CBR tests, Texas triaxial tests, and field investigations. Of the 20 materials evaluated by Jewell, only six met the AASHO index limits; 15 of the 20 mixtures had shown satisfactory results in the field even though they had PI values as high as 17 to 18 percent. It is believed that the excellent performance results reported by Jewell can be explained in part by the low quantity of fines contained in the mixtures he evaluated. It should be remembered that Western Australia is a non-frost area and the results of the study must be modified accordingly.

The A & H Engineering and Testing Corporation(2) conducted a study into the "Physical Properties of Illinois Aggregates Affecting

Load Bearing Strength and Performance". The effect of the dry density of the mixture on stability was dramatic. For example, increasing the density of the crushed stone from 138 to 143 pounds per cubic foot resulted in an increase in the triaxial compressive strength of approximately 50 percent. As for the optimum quantity of fines, they concluded that for crushed stone it is approximately nine percent and for gravel it is approximately 11 percent. There was a significant reduction in the strength of the granular materials when the quantity of fines varied from optimum. With reference to the plasticity index, they concluded that as the PI increases the strength of the granular material is substantially reduced. They believe that this becomes more pronounced as the quantity of fines increased, and "it may be concluded that the lowest PI should be strived for to achieve the best performance".

The Texas Highway Department specifications for base materials(13) differ from the AASHO specifications. Texas uses a triaxial compressive strength together with consistency limits and grain size distribution for evaluating the adequacy of base course material. Table 2 shows the Texas requirements for flexible base materials.

McDowell(14) compared the AASHO and Texas specifications for base materials and concluded that the AASHO limits on PI and LL are restrictive for Texas and that for Texas, these soil constants showed no relationship with the performance of roads. He suggested that the limits on PI and LL be raised to 12 percent and 35 percent respectively. This would hold particularly for materials with low quantities of fines.

Faiz(8) conducted a study on the effect of physical properties on stability. The soil-gravel mixtures he tested indicated a Texas class

TABLE 2. PHYSICAL REQUIREMENTS FOR FLEXIBLE BASE MATERIAL* (FROM TEXAS HIGHWAY DEPARTMENT).

TYPES	GRADES				LIMITS on PLANS
	GRADE 1: TRIAXIAL CLASS I MIN. COMPRESSIVE STRENGTH PSI: 45 AT 0 LB. LATERAL PRESSURE AND 175 AT 15 LB LATERAL PRESSURE	GRADE 2 (TRIAxIAL CLASS I TO 2.3) MIN. COMPRESSIVE STRENGTH PSI 35 AT 0 LB. LATERAL PRESSURE AND 175 AT 15 LB LATERAL PRESSURE	GRADE 3: (UNSPECIFIED TRIAxIAL CLASS RANGE PROBABLY FROM 2.3 TO 3.7)	GRADE 4: SHOW SPECIAL	
TYPE A CRUSHED OR BROKEN AGGREGATE	RETAINED ON % SQ. SIEVE 1 3/4" 0 7/8" 8-30 3/8" 30-50 NO. 4 45-65 NO. 40 70-80 MAX. LL 35 MAX. PI 12 MAX. WET BALL MILL 40 MAX. LA WEAR + 4 40	RETAINED ON % SQ. SIEVE 1 3/4" 0-10 NO. 4 45-75 NO. 40 60-85 MAX. LL 40 MAX. PI 12 MAX. WET BALL MILL 50	RETAINED ON % SQ. SIEVE 1 3/4" 0-10 NO. 40 60-85 MAX. LL 45 MAX. PI 15 WET BALL MILL 55	1	THIS GRADE AND TYPE OF FLEXIBLE BASE MATERIAL IS INTENDED FOR USE AS UNTREATED SUBBASE OR AS STABILIZED BASE OR SUBBASE AND SHOULD NOT BE USED AS A FINAL COURSE OR UNTREATED BASE WITHOUT SPECIAL APPROVAL.
TYPE B GRAVEL AGGREGATE		RETAINED ON % SQ. SIEVE 1 3/4" 0-10 NO. 4 30-75 NO. 40 70-85 MAX. LL 35 MAX. PI 12	RETAINED ON % SQ. SIEVE 1 3/4" 0-5 NO. 4 30-75 NO. 40 65-85 MAX. LL 35 MAX. PI 12	2	
TYPE C IRON ORE TOP SOIL		RETAINED ON % SQ. SIEVE 2 1/2" 0 NO. 40 50-85 MAX. LL 35 MAX. PI 12	RETAINED ON % SQ. SIEVE NO. 40 45-85 MAX. LL 35 MAX. PI 12	3	
TYPE D SAND- SHELL		RETAINED ON % SQ. SIEVE 1 3/4" 0-10 NO. 4 45-65 NO. 40 50-70 MAX. LL 35 MAX. PI 12	RETAINED ON % SQ. SIEVE 1 3/4" 0-10 NO. 40 45-65 MAX. LL 35 MAX. PI 12	4	
TYPE E SHELL WITH SAND AND CALICHE ADMIXTURE		RETAINED ON % SQ. SIEVE 1 3/4" 0 NO. 40 45-65 MAX. LL 35 MAX. PI 10	RETAINED ON % SQ. SIEVE 1 3/4" 0 NO. 40 45-65 MAX. LL 35 MAX. PI 12	5	

* LIMIT TESTS MADE AFTER MATERIAL IS PREPARED BY WET METHOD

3.4 to 4, whereas the crushed stone showed a range of 1.0 to 2.6.

Other results obtained in the study suggest that the effect of plasticity on the stability of a soil-aggregate mix depends to a great degree on the amount of fines in the mix. When the amount of fines is small, the effect of plasticity becomes insignificant. As far as skip grading the material between the No. 30 and No. 200 sieves was concerned, the soil-gravel mixes showed adequate strength characteristics although the plasticity index and liquid limit were above those specified by AASHO.

DESIGN OF THE EXPERIMENT

The variables considered in this study were: the quantity of material between No. 30 and No. 200 sieves; the quantity of the fines passing No. 200 sieve; and the quality of the fines. Therefore, the study was confined to gravel mixtures of the same maximum size and of the same gradation down to the sieve No. 8. Three levels of the amount of material passing No. 30 sieve, four levels of dust ratio (ratio of passing No. 200 to passing No. 30), and three types of fines, were utilized.

The experimental investigation was based on a $3 \times 3 \times 4$ factorial design with two replicates per cell. The replicates were necessary to determine the experimental error for the analysis of variance technique. Three lateral pressures were used in the triaxial test to obtain the first value of stability in any cell. These lateral pressures were 0, 7.5, and 15 psi. The replicate value was obtained from two lateral pressures (0 and 15 psi). Five triaxial tests were run on each of the 36 samples. Thus, a total of 180 triaxial tests were run. The tests were run on the samples in a completely randomized manner. The replicates were run after the first run was completed for all the samples. In this way, precautions were taken so that the learning process and the time factor would not have a bearing on the results obtained. The design of the experiment is summarized in Table 3.

TABLE 3. Summary of Design of Experiment

PERCENT PASSING NO. 30 SIEVE		DUST RATIO							
		1.0		0.75		0.50		0.25	
10	C	Y_{1111}	Y_{1112}	Y_{1121}	Y_{1122}	Y_{1131}	Y_{1132}	Y_{1141}	Y_{1142}
	B	Y_{1211}	Y_{1212}	Y_{1221}	Y_{1222}	Y_{1231}	Y_{1232}	Y_{1241}	Y_{1242}
	R	Y_{1311}	Y_{1312}	Y_{1321}	Y_{1322}	Y_{1331}	Y_{1332}	Y_{1341}	Y_{1342}
15	C	Y_{2111}	Y_{2112}	Y_{2121}	Y_{2122}	Y_{2131}	Y_{2132}	Y_{2141}	Y_{2142}
	B	Y_{2211}	Y_{2212}	Y_{2221}	Y_{2222}	Y_{2231}	Y_{2232}	Y_{2241}	Y_{2242}
	R	Y_{2311}	Y_{2312}	Y_{2321}	Y_{2322}	Y_{2331}	Y_{2332}	Y_{2341}	Y_{2342}
20	C	Y_{3111}	Y_{3112}	Y_{3121}	Y_{3122}	Y_{3131}	Y_{3132}	Y_{3141}	Y_{3142}
	B	Y_{3211}	Y_{3212}	Y_{3221}	Y_{3222}	Y_{3231}	Y_{3232}	Y_{3241}	Y_{3242}
	R	Y_{3311}	Y_{3312}	Y_{3321}	Y_{3322}	Y_{3331}	Y_{3332}	Y_{3341}	Y_{3342}

LEGEND— MATERIAL PASSING NO. 200 SIEVE

C—Crosby Soil

B—Brookston Soil

R—Limestone Residual

DUST RATIO— P 200 to P 30

 Y_{ijkl} — STABILITY VALUE AS MEASURED FROM THE TEXAS TRIAXIAL TEST WHERE:

i=1,2,3, LEVELS OF PERCENTAGE PASSING NO.30 SIEVE,

j=1,2,3, LEVELS OF QUALITY OF FINES,

k=1,2,3,4, LEVELS OF DUST RATIO,

l=1,2, NUMBER OF REPETITIONS.

As can be noted from Table 3, the advantage of using the dust ratio variable instead of passing No. 200 sieve variable is obvious. Eight levels of P. No. 200 sieve would have been necessary to describe our mixes, however, four levels of dust ratio were sufficient.

The order of testing the specimens was determined by use of tables of random numbers, Ostle(15). All of the tests were run at random including the compaction tests.

The levels of the material passing No. 30 sieve and the dust ratio levels were chosen to represent common ranges of gradations. They were not chosen randomly.

PREPARATION OF MATERIALS

The gravel used in this study was obtained locally. The gradation that was used conformed essentially with Indiana Specification size No. 53 aggregate. The maximum size used was 1", and the gradation curve was that given by the following equation:

$$P = 100 \sqrt{\frac{d}{D}}$$

Since $D = 1"$, then

$$P = 100 \sqrt{d}$$

Figures 6, 7, 8, and 9 illustrate the different gradations used. It can be noted that three different levels of material passing No. 30 sieve were used: 10%, 15%, and 20% respectively, and with each of these, four levels of dust ratio were used: 1.0, 0.75, 0.50, and 0.25. The dust ratio is defined as the ratio of the material passing No. 200 sieve to the material passing the No. 30 sieve. For a dust ratio of 1.0 the gradation is skip-graded between the No. 30 and No. 200 sieves as shown in the figures.

The soil binder (passing No. 200 sieve) used in this study consisted of three different soils: a clay of low compressibility, a moderately plastic clay, and a highly compressible clay. These are classified by the unified system as CL, CL-CH, and CH respectively. These classifications were based on the PI and LL being run on the

FIGURE 6. GRAIN SIZE DISTRIBUTION OF TEST MIXTURES WITH DUST RATIO = 1.0.

FIGURE 8. GRAIN SIZE DISTRIBUTION OF TEST MIXTURES WITH
DUST RATIO = .5.

FIGURE 9. GRAIN SIZE DISTRIBUTION OF TEST MIXTURES WITH DUST RATIO = .25

portion passing the No. 200 sieve. These soils will be referred to here as Crosby, Brookston, and Limestone Residual respectively. When they were mixed with gravel and sand the soil limit tests were then run on the portion passing the No. 40 sieve.

Table 4 shows the grain size distribution of the mixtures used in this study and Table 5 shows the consistency limits for the fines alone. Table 6 shows the consistency limits for all the mixes used, the tests being done on the passing No. 40 sieve.

The gravel used was first washed, dried and separated into different sizes after it was brought from the site. Every size was stored in a different barrel. The soil part of the mixes was obtained locally, and was dried, crushed, and sieved through the No. 200 sieve. The portion that passed through the No. 200 sieve was retained and stored for testing. Representative samples were taken of these portions and tested for the plastic and liquid limits and were classified as shown in Table 5 according to the unified soil classification system.

Testing Procedures

The tests that were used in the experimental program were:

1. Atterberg limits tests;
2. Compaction tests;
3. Texas triaxial tests.

The test mixtures were prepared by recombining the already washed and dried fractions, according to the gradations mentioned earlier. The test mixtures were put in the oven 24 hours before being tested to insure freedom from moisture.

TABLE 4. GRAIN SIZE DISTRIBUTION OF TEST MIXTURES.

DUST RATIO	1.00			0.75			0.50			0.25		
	10	15	20	10	15	20	10	15	20	10	15	20
PERCENT PASSING NO 30 SIEVE												
GRAIN SIZE	PERCENT FINER			PERCENT FINER			PERCENT FINER			PERCENT FINER		
1"	100	100	100	100	100	100	100	100	100	100	100	100
3/4"	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5
1/2"	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0
3/8"	61.0	61.0	61.0	61.0	61.0	61.0	61.0	61.0	61.0	61.0	61.0	61.0
NO. 4	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0
NO. 8	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0
NO. 30	10.0	15.0	20.0	10.0	15.0	20.0	10.0	15.0	20.0	10.0	15.0	20.0
NO. 200	10.0	15.0	20.0	7.5	11.25	15.0	5.0	7.5	10.0	2.5	3.75	5.0

TABLE 5. PLASTICITY CHARACTERISTICS OF VARIOUS TYPES OF FINES.

TYPE	L.L.	P.L.	P.I.	CLASSIFICATION
CROSBY	36.1	21.9	14.2	CL
BROOKSTON	51.8	25.1	26.7	CL-CH
LIMESTONE RESIDUAL	59.7	27.5	32.2	CH

TABLE 6. PLASTICITY CHARACTERISTICS OF THE VARIOUS GRADATIONS.

MATERIAL	DUST RATIO							
	1.00		0.75		0.50		0.25	
	P.I.	L.L.	P.I.	L.L.	P.I.	L.L.	P.I.	L.L.
CROSBY	14.2	36.1	12.5	30.7	9.1	24.1	Non-plastic	
BROOKSTON	26.7	51.8	20.0	41.5	14.6	31.2	Non-plastic	
LIMESTONE RESIDUAL	32.2	59.7	24.4	46.7	15.6	33.2	4.1	21.0

Atterberg Limits Tests

The liquid and plastic limits were determined in accordance with ASTM Designations, D423-61T and D424-59 respectively(2). However, since the method of preparing samples was by recombining portions already separated, the samples for the Atterberg tests were also recombined in the same manner. Portions retained between No. 40 and No. 200 sieves were thoroughly mixed with the portions passing the No. 200 sieve according to the percentages shown on the previous gradation curves.

Duplicate tests were performed on each sample and the average of the two tests was used.

Compaction Tests

Compaction tests were performed prior to the Texas triaxial tests, to determine the optimum moisture contents and the necessary densities for compaction of the samples.

To determine the optimum moisture content and the dry density for the Texas triaxial test, the same compactive effort was used in the compaction test as in the triaxial test. The compaction mold was 6 in. in diameter and 8 in. in height and was identical to the triaxial test mold. The soil was compacted in four layers with 50 blows applied to each layer. A 10 lb. hammer with a free fall of 18 in. was used. The procedure for determining the optimum moisture content and the maximum dry density is the same as outlined in AASHTO Designation T212-65(1).

Texas Triaxial Test

The method used here conforms essentially with AASHTO Designation T212-65(1) for flexible base and subbase materials with considerable amounts of coarse particles except that the mixtures were not left to

soak for 4 hours as specified in article 5.16.1 (1, same designation). In addition, the specimens were not subjected to overnight capillarity as in article 5.16.3 (1, same designation), but rather tested immediately after molding. Two tests were performed at zero psi, one at 7.5 psi, and two at 15 psi. The tests were run in this manner because of limitations of time and equipment (one triaxial cell was available only).

RESULTS

Test data are presented in Appendix A. Table A-1 shows the compaction test data for the different gravel-soil mixtures. Tables A-2, A-3, and A-4 show the results of the Texas triaxial tests in terms of Texas class, compressive strength at 15 psi lateral pressure, and the angle of internal friction, respectively.

The results are presented in a manner that every cell contains two values, one being the replicate of the other.

Tables A-5, A-6, and A-7 are similar to Tables A-2, A-3, and A-4 except that the mean observations are used rather than the replicates.

Statistical Analysis

Both the analysis of variance and the regression analysis tools were used to analyze the test data. The analysis of variance was used to help determine the significant factors, if any, to be used in the regression analysis. For example, it was possible to establish from the analysis of variance whether the interaction terms were significant and if so, the trends each conveyed; such as, a linear by linear, or linear by quadratic, or a linear by cubic interaction effect. In addition, when the main effects were studied it was possible to determine if a quadratic term or even a cubic term was necessary in the regression equation. These concepts will be illustrated during the discussion of the detailed ANOVA Tables.

The model that would represent the results of the experiment had to be a Fixed Effects Model since the factors such as the passing No. 30 sieve, the dust ratio, and the quality of the material were not selected at random from their respective populations.

The following analysis of variance model was formulated for the Texas triaxial test results.

$$Y_{ijkl} = U + A_i + B_j + C_k + AB_{ij} + AC_{ik} + BC_{jk} + ABC_{ijk} + E_{l(ijk)}$$

where:

Y_{ijkl} = Texas triaxial value obtained from a given test,

U = true mean effect for the population,

A_i = true effect of the passing No. 30 sieve,

B_j = true effect of the quality of the fines,

C_k = true effect of the dust ratio,

$E_{l(ijk)}$ = true random error, normally distributed.

The other terms denote the interactions among the factors A, B, and C. The subscripts assume the values:

$i = 1, 2, 3$

$j = 1, 2, 3$

$k = 1, 2, 3, 4$

$l = 1, 2.$

To check the assumption of the homogeneity of variance, a computer program available at Purdue, called DATASUM, was used. This program performs the Bartlett test and the Foster-Burr test (Q-test). Since the two replicates were equal in many cases, the Bartlett test could not be performed on most variables. The results of the Foster-Burr test are shown in Table 7 where the Q statistic shown is compared with

$Q_{.05}$ obtained from the Table given with DATASUM program. If the Q statistic is less than the $Q_{.05}$ obtained from the Table, then the variables have homogeneous variances.

TABLE 7. FOSTER-BURR TEST FOR HOMOGENEITY OF VARIANCE

Variable Name	Average DF Per Sample	Degrees of Freedom	No. of Samples	Q Statistic	$Q_{.05}$
Texas Class	1	1	36	.0728	0.129
Compressive Str. at 15 psi	1	1	36	.0774	0.129
Angle of Int. Friction	1	1	36	.0918	0.129
Compressive Str. at 0 psi	1	1	36	.0882	0.129
Cohesion	1	1	36	.0724	0.129

Since all the Q statistics are less than 0.129, the hypothesis of homogeneity of variance is accepted, and there is no need of transforming the dependent variables.

Since homogeneity of the variance is assumed, we can also assume the distribution is normal. As a matter of fact, the F -test is quite robust even if normality is not strictly satisfied. There is no reason to doubt the assumptions of additivity and independence of errors.

It was decided that only three dependent variables were to be used in the analysis of variance and regression analysis. These were: the Texas Triaxial Class; the compressive strength at 15 psi lateral pressure; and the angle of internal friction.

The F -tests were performed assuming the model is fixed and the design was a completely randomized three factor factorial. The reader may refer to Ostle(15) for a detailed discussion about performing the

F-tests. The sums of squares, the degrees of freedom, and the mean squares shown in the ANOVA Tables 8, 9, 10, 11, 12, and 13 were obtained by utilizing a computer program available at Purdue, BMD2V. The first three tables (8, 9, and 10) are the usual summary ANOVA tables, the last three tables (11, 12, and 13) are more detailed tables which show trends and explain whether the variation is due to a linear effect, quadratic, cubic, or a combination of these.

Table 8 summarizes the results of analysis of variance of data presented in Table A-2 (Appendix A) which is for the Texas Class. Each main effect and interaction was tested for significance. This was done by taking the ratio of the mean square for the effect under analysis and the experimental error mean square and comparing this with the F-statistic obtained from published tables (Ostle, 15). The tests were conducted at an α level of 0.05. Significance was indicated by the letter 'S' and non-significance by the letters 'NS'.

Table 9 summarizes the results of the analysis of variance of data presented in Table A-3 (Appendix A) which is for compressive strength at 15 psi lateral pressure. Table 10 also summarizes the results of ANOVA for data presented in Table A-4 (Appendix A) which is for the angle of internal friction.

An examination of the results of significance tests reduces the model that was previously formulated to:

1. For Texas Class:

$$Y_{ijkl} = U + A_i + B_j + AB_{ij} + AC_{ik} + ABC_{ijk} + E_{l(ijk)}$$

TABLE 8. Summary of Analysis of Variance — Texas Class

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F-TEST	F-.05	SIGNIFICANCE
A PASSING NO. 30 SIEVE	2	.66521	.33260	14.49	3.27	S
B TYPE OF FINES	2	.27437	.13719	5.98	3.27	S
C DUST RATIO	3	.19177	.06392	2.79	2.88	NS
AB	4	.54417	.13604	5.93	2.65	S
AC	6	1.25062	.20844	9.08	2.38	S
BC	6	.08312	.01385	0.60	2.38	NS
ABC	12	1.42417	.11868	5.17	2.04	S
WITHIN REPLICATES	36	.82625	.02295			
TOTALS	71	5.25969				

TABLE 9. Summary of Analysis of Variance — Compressive Strength at 15psi. Lateral Pressure

SOURCE OF VARIATION		DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F-TEST	F-05	SIGNIFICANCE
A	PASSING	2	6327.9936	3163.9968	49.90	3.27	S
	NO. 30 SIEVE						
B	TYPE OF FINES	2	2078.4311	1039.2156	16.39	3.27	S
C	DUST RATIO	3	2126.2344	708.7448	11.18	2.88	S
	AB	4	1105.7647	276.4412	4.36	2.65	S
	AC	6	9543.7964	1590.6327	25.09	2.38	S
	BC	6	330.0822	55.0137	0.87	2.38	NS
	ABC	12	4033.5194	336.1285	5.30	2.04	S
	WITHIN REPLICATES	36	2282.6200	63.4061			
TOTALS		71	27828.4644				

TABLE 10. Summary of Analysis of Variance — Angle of Internal Friction

SOURCE OF VARIATION		DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F-TEST	F-05	SIGNIFICANCE
A	PASSING NO. 30 SIEVE	2	788.8125	394.4063	122.53	3.27	S
	TYPE OF FINES	2	135.2708	67.6354	21.01	3.27	S
C	DUST RATIO	3	492.7882	164.2627	51.03	2.88	S
	AB	4	147.1667	36.7917	11.43	2.65	S
AC		6	711.1597	118.5266	36.82	2.38	S
BC		6	67.7847	11.2975	3.51	2.38	S
ABC		12	209.8611	17.4884	5.43	2.04	S
WITHIN REPLICATES		36	115.8750	3.2188			
TOTALS		71	2668.7188				

2. For compressive strength at 15 psi lateral pressure:

$$Y_{ijkl} = U + A_i + B_j + C_k + AB_{ij} + AC_{ik} + ABC_{ijk} + E_{l(ijk)}$$

3. For angle of internal friction:

$$Y_{ijkl} = U + A_i + B_j + C_k + AB_{ij} + AC_{ik} + BC_{jk} + ABC_{ijk} + E_{l(ijk)}$$

Further examination of the detailed ANOVA tables as presented in Tables 11, 12, and 13 corresponding respectively to Tables 8, 9, and 10 would reveal the significance of the quadratic components for all main effects. Also for the interaction terms the quadratic by linear component was sometimes significant. Other times, the 'quadratic by quadratic' component was significant, etc.

The conclusions that can be drawn from the ANOVA summary tables are the following:

1. The amount of material passing No. 30 sieve had a significant effect on the strength characteristics as measured by Texas Class, the compressive strength at 15 psi lateral pressure, and the angle of internal friction.
2. The type of fines had a significant effect on the strength characteristics.
3. The dust ratio had also a significant effect on the strength characteristics.
4. The interaction effects also were significant and so they had to be introduced in the regression equation.

TABLE II. Detailed Analysis of Variance — Texas Class

SOURCE OF VARIATION		DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F-TEST	F-.05	SIGNIFICANCE
A	PASSING NO.30 SIEVE	2	.66521	.33260	14.49	3.27	S
	LINEAR (L-1)	1	.37630	.37630	16.40	4.13	S
	QUADRATIC (Q-1)	1	.28891	.28891	12.59	4.13	S
B	TYPE OF FINES	2	.27437	.13718	5.98	3.27	S
	LINEAR (L-2)	1	.15188	.15188	6.62	4.13	S
	QUADRATIC (Q-2)	1	.12250	.12250	5.34	4.13	S
C	DUST RATIO	3	.19177	.06392	2.79	2.88	NS
	LINEAR (L-3)	1	.04117	.04117	1.79	4.13	NS
	QUADRATIC (Q-3)	1	.01253	.01253		4.13	NS
	CUBIC (C-3)	1	.13806	.13806	6.02	4.13	S
AB		4	.54417	.13604	5.93	2.65	S
(L-1) X (L-2)		1	.52531	.52531	22.89	4.13	S
(L-1) X (Q-2)		1	.00667	.00667		4.13	NS
(Q-1) X (L-2)		1	.00094	.00094		4.13	NS
(Q-1) X (L-2)		1	.01125	.01125		4.13	NS
AC		6	1.25062	.20844	9.08	2.38	S
(L-1) X (L-3)		1	1.11384	1.11384	48.53	4.13	S
(L-1) X (Q-3)		1	.00255	.00255		4.13	NS
(L-1) X (C-3)		1	.01001	.01001		4.13	NS
(Q-1) X (L-3)		1	.08342	.08342		4.13	NS
(Q-1) X (Q-3)		1	.02127	.02127		4.13	NS
(Q-1) X (C-3)		1	.01953	.01953		4.13	NS
BC		6	.08312	.01384	0.60	2.38	NS
(L-2) X (L-3)		1	.04004	.04004	1.75	4.13	NS
(L-2) X (Q-3)		1	.00021	.00021		4.13	NS
(L-2) X (C-3)		1	.00038	.00038		4.13	NS
(Q-2) X (L-3)		1	.01089	.01089		4.13	NS
(Q-2) X (Q-3)		1	.01361	.01361		4.13	NS
(Q-2) X (C-3)		1	.01800	.01800		4.13	NS
ABC		12	1.42417	.11868	5.17	2.04	S
WITHIN REPLICATES		36	.82625	.02295			
TOTALS		71	5.25969				

TABLE. 12. Detailed Analysis of Variance— Compressive Strength*

SOURCE OF VARIATION		DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F-TEST	F-.05	SIGNIFICANCE
A	PASSING NO.30 SIEVE	2	6327.9936	3163.9968	49.90	3.27	S
	LINEAR (L-1)	1	5510.5105	5510.5105	86.91	4.13	S
	QUADRATIC (Q-1)	1	817.4832	817.4832	12.89	4.13	S
B	TYPE OF FINES	2	2078.4311	1039.2156	16.39	3.27	S
	LINEAR (L-2)	1	1810.5634	1810.5634	28.56	4.13	S
	QUADRATIC (Q-2)	1	267.8677	267.8677	4.22	4.13	S
C	DUST RATIO	3	2126.2344	708.7448	11.18	2.88	S
	LINEAR (L-3)	1	1624.7751	1624.7751	25.62	4.13	S
	QUADRATIC (Q-3)	1	408.0272	408.0272	6.44	4.13	S
	CUBIC (C-3)	1	93.4321	93.4321	1.47	4.13	S
AB		4	1105.7647	276.4412	4.38	2.65	S
(L-1) X (L-2)		1	981.2451	981.2451	15.47	4.13	S
(L-1) X (Q-2)		1	24.2004	24.2004		4.13	NS
(Q-1) X (L-2)		1	55.5104	55.5104		4.13	NS
(Q-1) X (Q-2)		1	44.8089	44.8089		4.13	NS
AC		6	9543.7964	1590.6327	25.09	2.38	S
(L-1) X (L-3)		1	8973.1517	8973.1517	141.52	4.13	S
(L-1) X (Q-3)		1	62.7919	62.7919		4.13	NS
(L-1) X (C-3)		1	25.0260	25.0260		4.13	NS
(Q-1) X (L-3)		1	206.8316	206.8316	3.26	4.13	NS
(Q-1) X (Q-3)		1	273.6267	273.6267	4.32	4.13	S
(Q-1) X (C-3)		1	2.3690	2.3690		4.13	NS
BC		6	330.0822	55.01370		2.38	NS
(L-2) X (L-3)		1	246.0375	246.0375	3.88	4.13	NS
(L-2) X (Q-3)		1	508.408	508.408		4.13	NS
(L-2) X (C-3)		1	.0167	.0167		4.13	NS
(Q-2) X (L-3)		1	.2067	.2067		4.13	NS
(Q-2) X (Q-3)		1	4.3403	4.3403		4.13	NS
(Q-2) X (C-3)		1	28.6402	28.6402		4.13	NS
ABC		12	4033.5419	336.1285	5.30	2.04	S
WITHIN REPLICATES		36	2282.6200	63.4061	* AT 15PSI LATERAL PRESSURE		
TOTALS		71	27828.4644				

TABLE 13. Detailed Analysis of Variance—Angle of Internal Friction

SOURCE OF VARIATION		DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F-TEST	F-.05	SIGNIFICANCE
A	PASSING NO.30 SIEVE	2	788.8125	394.4063	122.53	3.27	S
	LINEAR (L-1)	1	720.7500	720.7500	223.92	4.13	S
	QUADRATIC (Q-1)	1	68.0625	68.0625	21.15	4.13	S
B	TYPE OF FINES	2	135.2708	67.6354	21.01	3.27	S
	LINEAR (L-2)	1	128.3802	128.3802	39.89	4.13	S
	QUADRATIC (Q-2)	1	6.8906	6.8906	2.14	4.13	NS
C	DUST RATIO	3	492.7882	164.2627	51.03	2.88	S
	LINEAR (L-3)	1	454.5007	454.5007	141.20	4.13	S
	QUADRATIC (Q-3)	1	38.2813	38.2813	11.89	4.13	S
	CUBIC (C-3)	1	.0063	.0063		4.13	NS
AB		4	147.1667	36.7917	11.43	2.65	S
(L-1) X (L-2)		1	124.0313	124.0313	38.53	4.13	S
(L-1) X (Q-2)		1	11.3438	11.3438	3.52	4.13	NS
(Q-1) X (L-2)		1	.5104	.5104		4.13	NS
(Q-1) X (Q-2)		1	1.12813	1.12813	3.50	4.13	NS
AC		6	711.1597	118.5266	36.82	2.38	S
(L-1) X (L-3)		1	653.4000	653.4000	203.00	4.13	S
(L-1) X (Q-3)		1	.0833	.0833		4.13	NS
(L-1) X (C-3)		1	.2667	.2667		4.13	NS
(Q-1) X (L-3)		1	51.7347	51.7347	16.07	4.13	S
(Q-1) X (Q-3)		1	5.0625	5.0625	1.57	4.13	NS
(Q-1) X (C-3)		1	.6125	.6125		4.13	NS
BC		6	67.7847	11.2975	3.51	2.38	S
(L-2) X (L-3)		1	38.8010	38.8010	12.05	4.13	S
(L-2) X (Q-3)		1	19.3802	19.3802	6.02	4.13	S
(L-2) X (C-3)		1	1.5844	1.5844		4.13	NS
(Q-2) X (L-3)		1	7.1004	7.1004	2.21	4.13	NS
(Q-2) X (Q-3)		1	.0156	.0156		4.13	NS
(Q-2) X (C-3)		1	.9031	.9031		4.13	NS
ABC		12	209.8611	17.4884	5.43	2.04	S
WITHIN REPLICATES		36	115.8750	3.2188			
TOTALS		71	2668.7188				

From the detailed ANOVA tables some general conclusions can be drawn:

1. For the main effects, the quadratic component of variation was almost always significant.
2. For the interaction terms, the linear by linear effect was always highly significant. Sometimes the linear by quadratic effect was significant; the cubic by linear or the cubic by quadratic effects were not significant.

A final comment on the ANOVA tables is that in terms of significance it can be seen that the F-tests on the angle of internal friction (Table 10) were highly significant. The compressive strength at 15 psi lateral pressure were also significant. As for the Texas Class, there was significance in the F-tests; however, not as impressive as the former two. Therefore, it should be expected that the regression analysis be better for the angle of internal friction and the compressive strength than for the Texas Class.

For the regression analysis, a program entitled BMD2R was used. In this program the regression analysis is done in a stepwise manner(6), where the independent variable that shows the highest correlation with the dependent variable is entered first and then at the next step the next highest is entered, and so on. Also, at every step there is a re-examination of the variables already in the model and if the F-ratio is no more significant then that variable is removed from the model. This program was utilized for our data where the F-level for inclusion and for removal was taken at 2.0. This F-level was chosen (2.0) so that in the process of inclusion we could incorporate an adequate number of variables; however, in the final model the variables that remained were those that had a significant F-value.

The original independent variables used in this study were the quantity passing No. 30 sieve, the dust ratio, the plasticity index, and the liquid limit. The dependent variables used in this study were the Texas Class, the compressive strength at 15 psi and the angle of internal friction. In addition to the original four independent variables some other independent variables were entered by using transgeneration cards. These cards were used to transform any of the independent variables to another form such as its quadratic, cubic, or any combination with another original independent variable. Since there were 36 samples with two replicates per sample, the computer program was run first for 72 observations and then it was re-run for 36 mean observations.

The models obtained were examined critically and the adequate ones were chosen. Their adequacy was determined by examining the R^2 which measures the "proportion of total variation about mean $\bar{Y}$ explained by the regression" (ref. 6). Also examination of the standard error was helpful. Finally an examination of the number of terms included and their nature was taken into consideration.

As a result of the above it was decided that a model for the Texas Class would not be significant although this does not exclude the possibility of the existence of a model that could not be attained because of the values of the Texas Class obtained. These values ranged between 3.2 and 4.5 for all the specimens tested and this is not a wide range of values.

Table 14 summarizes the models for the compressive strength at 15 psi. Three models were included for regressions run on the 72 observations and three other models were included for regressions run

TABLE 14. Summary of Compressive Strength Regression Models

NO OF OBS.	R ²	R	ST'D ERROR	F _{reg.}	MODEL
72	.63	.79	12.58	21.95	$81.11 + 1.56(P.30) + 18.04(D.R.) + 3.03(P.1.) - 19(P.30)(D.R.) - .09(P.30)(D.R.)(P.1.)$
	.66	.81	12.05	25.12	$22.02 + 10.36(P.30) + 4.5(P.1.) - 27(P.30)(P.1.) - 28(P.30)^2 - .03(P.1.)^2$
	.68	.825	11.53	3563	$78.45 + 11.20(P.30)(D.R.) - .074(P.30)(D.R.)(P.1.) + .11(P.30)^2 - .62(P.30)^2(D.R.)$
36	.67	.82	11.78	15.76	$86.57 + 1.54(P.30) + 3.56(P.1.) - .214(P.30)(P.1.) - .062(P.30)(D.R.)(P.1.)$
	.71	.85	11.14	15.05	$23.92 + 10.05(P.30) + 4.65(P.1.) - 27(P.30)(P.1.) - 28(P.30)^2 - .036(P.1.)^2$
	.67	.82	11.61	21.63	$106.03 - .0675(P.30)(D.R.)(P.1.) + 50.741(D.R.)^2 - .151(P.30)^2(D.R.)^2$

on the 36 mean observations. Table 15 summarizes the models for the angle of internal friction. Three models are for the 72 observations and 4 models are for the 36 mean observations.

Deklotz(7), in his paper, makes use of a term which he found useful in describing the quality of the soil. He designated it as "D" and it was defined as the ratio $\frac{P.I.}{L.L.}$. It was decided to make use of this variable to describe the quality of the fine material instead of using the P.I. and the L.L. as two separate variables. The models obtained using these variables were selected in the same manner as mentioned earlier. They are shown in Tables 16 and 17. Table 16 indicates the compressive strength at 15 psi lateral pressure and Table 17 shows the angle of internal friction.

Some comments which can be stated about the regression program outputs are:

1. The correlations between the different independent variables were sometimes very high. Due to these high correlations the increase in R^2 after the first variable was entered was not very high, i.e., the first variable entered in the regression was almost always responsible for more than one-half of the final R^2 when all the variables were in the model. Of course this would have not been the case if the variables were orthogonal.
2. It can be seen that the models which had quadratic terms had a higher R^2 than the models with no quadratic terms. Furthermore, it can be seen that there were no cubic terms present in the models which were obtained.

TABLE 15. Summary of Angle of Internal Friction Regression Models

NO. OF OBS.	R ²	R	ST'D ERROR	F _{reg.}	MODEL
72	.75	.86	3.18	494	$36.35 + .68(P.30) + 30.61(D.R.) - 1.93(P.30)(D.R.) - .022(P.30)(D.R)(P.I.)$
	.77	.88	3.03	44.77	$19.16 + 3.16(P.30) + 30.61(D.R.) - 1.93(P.30)(D.R.) - .022(P.30)(D.R)(P.I.) - .083(P.30)^2$
	.801	.895	2.84	53.21	$36.31 + .63(P.30) + 2.92(P.30)(D.R.) - 6.98(D.R.)^2 - .00003(P.30)^2(P.I.)^2 - .158(P.30)^2(D.R.)$
36	.73	.87	3.10	45.45	$46.99 + 7.53(D.R)(P.I.) - .068(P.30)(D.R)(P.I.)$
	.76	.87	3.01	252	$47.15 + 2.68(D.R)(P.I.) - .068(P.30)(D.R)(P.I.) - 18.58(D.R.)^2 - .044(P.I.)^2$
	.83	.91	2.69	19.6	$37.81 + 3.87(P.30)(D.R.) + 12.8(D.R)(P.I.) + .027(P.30)^2 - 22.31(D.R.)^2 - .00011(P.30)^2(P.I.)^2 - .0042(P.30)(P.I.)^2$
	.724	.851	3.16	43.25	$46.64 - .00012(P.30)^2(P.I.)^2 - .00138(P.30)(P.I.)^2 - 197(P.30)^2(D.R.)$

TABLE 16. Summary of Compressive Strength Regression Models

NO.OF OBS.	R ²	R	STD ERROR	F _{reg}	MODEL
72	.68	.82	11.77	22.62	$-26.33 + 11.73(P.30) + 216.9(D.R.) - 5.4(P.30)(D.R.) - 7.15(P.30)(D.R.)(P.I./L.L.) - .29(P.30)^2 - 69.71(D.R.)^2$
	.68	.825	11.61	28.07	$70.68 + 50.435(P.I./L.L.) + 12.275(P.30)(D.R.) - 11.23(P.30)(D.R.)(P.I./L.L.) + 0.92(P.30)^2 - .511(D.R.)(P.30)^2$
36	.73	.86	10.98	13.22	$-24.82 + 11.39(P.30) + 223.7(D.R.) - 5.55(P.30)(D.R.) - 6.85(P.30)(D.R.)(P.I./L.L.) - .28(P.30)^2 - 74.62(D.R.)^2$
	.733	.856	10.77	16.50	$71.25 + 53.80(P.I./L.L.) + 12.06(P.30)(D.R.) - 11.185(P.30)(D.R.)(P.I./L.L.) + .086(P.30)^2 - .502(D.R.)(P.30)^2$

TABLE 17. Summary of Angle of Internal Friction Regression Models

NO. OF OBS.	R ²	R	ST'D ERROR	F _{reg.}	MODEL
72	.73	.86	3.29	36.09	$19.16 + 3.2 (P.30) + 30.6(D.R.) - 185(P.30)(D.R.) - 129(P.30)(D.R)(P.I./L.L.) - .08(P.30)^2$
	.795	.892	2.90	42.073	$38.83 + 2.885(P.30)(D.R.) + 103.3(P.30)(\frac{P.I.}{L.L.}) + 0.265(P.30)^2 - 136(P.30)^2(\frac{P.I.}{L.L.})^2 - .163(P.30)^2(D.R.) - 18.164(D.R.)^2(\frac{P.I.}{L.L.})$
	.79	.89	2.92	18.45	$11.53 + 2.8(P.30) + 64.21(D.R.) - 1.14(P.30)(D.R.) - 2.53(P.30)(D.R)(P.I./L.L.) - .071(P.30)^2 - 24.95(D.R.)^2$
36	.77	.877	2.97	25.8	$34.19 + 3.757(D.R.) + 0.32(P.30)^2(D.R.) - 36.47(D.R.)^2(P.I./L.L.)$

In general, to choose a model from all possible models available, certain things need to be kept in mind:

1. The model should have a good R^2 value.
2. The standard error around the mean should be small.
3. The model for the 72 observations should agree to a certain degree with that of the 36 observations.
4. Some judgement is necessary as to simplicity and usability of the model.

As far as the compressive strength at 15 psi lateral pressure is concerned, the model was chosen from the 72 observations rather than the 36 observations. The reason being that the 36 observations in this case were the arithmetic means of the respective 2 x 36 observations and it is better to base the model on 72 observations rather than on 36 mean observations.

However, the 36 observations for the angle of internal friction are not the arithmetic means of the 72 observations, but rather a new observation based on a new Mohr envelope. It was obtained from averaging the compressive strengths at 0 and 15 psi, therefore, the model of the 36 observations is appropriate for the angle of internal friction. Another reason for this choice was that the standard procedure requires that the Texas Class be obtained after several triaxial tests at 0 psi and 15 psi have been averaged and then one Mohr envelope be drawn on the basis of the average circles.

Therefore, from Table 14 the model chosen for the compressive strength at 15 psi lateral pressure is:

$$\sigma_{15} = 78.45 + 11.20(P.30)(D.R.) - .074(P.30)(D.R.)(P.I.) + .11(P.30)^2 - .62(P.30)^2(D.R.)$$

There is also another model that was found interesting since it shows a quadratic effect of the plasticity index; this is:

$$\sigma_{15} = 22.02 + 10.36(P.30) + 4.5(P.I.) - .27(P.30)(P.I.) - .28(P.30)^2 - .03(P.I.)^2$$

If a model with $\frac{P.I.}{L.L.}$ as an independent variable is desired rather than P.I. alone, the following model chosen from Table 16 can be used.

$$\sigma_{15} = 70.68 + 50.435\left(\frac{P.I.}{L.L.}\right) + 12.275(P.30)(D.R.) - 11.23(P.30)(D.R.)\left(\frac{P.I.}{L.L.}\right) + .092(P.30)^2 - .511(D.R.)(P.30)^2$$

It is noted that the models were chosen for the 72 observations and that they are very similar to the models for the 36 mean observations.

The models for the angle of internal friction will be chosen for the 36 mean observations. From Table 15 the following model is chosen:

$$\phi = 37.81 + 3.87(P.30)(D.R.) + 1.28(D.R.)(P.I.) + .027(P.30)^2 - 22.31(D.R.)^2 + .00011(P.30)^2(P.I.)^2 - .0042(P.30)(P.I.)^2 - .197(P.30)^2(D.R.)$$

And from Table 17 and using $\frac{P.I.}{L.L.}$ instead of P.I. alone:

$$\phi = 11.53 + 2.8(P.30) + 64.21(D.R.) - 1.14(P.30)(D.R.) - 2.53(P.30)(D.R.)\left(\frac{P.I.}{L.L.}\right) - .071(P.30)^2 - 24.95(D.R.)^2$$

A final comment to consider on these models is the fact that the models for the angle of internal friction are more reliable, since they have a higher R^2 than those for the compressive strength at 15 psi. This is advantageous because the angle of internal friction conveys more information. Furthermore, it is more reliable than the compressive strength at 15 psi lateral pressure, because it is based on five experiments (five Mohr's circles).

INTERPRETATION OF RESULTS

The statistical analysis in the previous chapter provide the guidelines for the interpretation and evaluation of the results.

Density of Soil-Gravel Mixtures

As mentioned earlier, the moisture-density graphs were obtained for the purpose of molding the triaxial samples at optimum moisture content (or maximum dry density). It was noted that if we draw a graph of dry unit weight versus the percent passing No. 200 sieve then a curve of a characteristic shape is obtained. Figure 10 illustrates this aspect for three kinds of soils of different plasticities. It can be seen that the maximum density is obtained when the amount of fines is between 5 to 10 percent. There are cases where two ordinates are present for the same abscissae. This means that the two points are for two different gradations (i.e., two different dust ratios). It is observed that in most of these cases, the point with the lesser dust ratio has the higher density. This is logical since with a lesser dust ratio the gradation tends to be better graded, and approaches the maximum density curves given by the equation:

$$P = \left(\frac{d}{D}\right)^n \times 100\%$$

The results mentioned above agree with previous research conducted by various researchers.

FIGURE 10. Variation of Maximum Dry Unit Weights of Different Gradations with Percent Passing No.200 Sieve.

Atterberg Limits

It was also noticed in the output of the regression programs that the Atterberg limits had a high correlation with the dust ratio. This was to be expected since the limits depend on the amount of sand present in the passing No. 40 sieve portion of the mix. Figure 11 shows the variation of the liquid limit and the plasticity index with the dust ratio. It can be seen that the points in general fall on straight lines for different types of fines. For any type of fines (passing No. 200), if we get two points on the straight line (for two different gradations) we can determine the liquid limit and the plasticity index for any other gradation. It is also noted from the graph that the lines converge when the dust ratio decreases since the materials approach the non-plastic phase because the mixture is becoming more sandy.

Texas Triaxial Tests

The soil-gravel mixtures that were tested in this program had a triaxial class that ranged between 3.1 to 4.5. According to the Texas Highway Department specifications as shown in Table 2, these mixes would be satisfactory subbase materials and materials intended for use as stabilized bases.

Triaxial Strength at 15 psi Lateral Pressure

The first regression equation that was chosen for predicting compressive strength is shown graphically in Figure 12. The general features of this Figure are:

1. When the passing No. 30 sieve was equal to 10%, the higher the dust ratio, the better was the compressive strength, i.e., the

FIGURE 11. Variation of Liquid Limit and Plasticity Index with Dust Ratio.

FIGURE 12. Variation of Compressive Strength at 15psi Lateral Pressure with Plasticity Index.

- more skip-graded the material, the more stable it was for small amounts passing the No. 30 sieve.
2. When the passing No. 30 sieve became 15%, the same trend was shown, though not so markedly, as can be observed for the dust ratios of 0.75 and 1.0.
 3. For the material that had 20% passing the No. 30 sieve it is observed that as the dust ratio became larger, the stability became less, i.e., the more skip-graded the mix is, the less stable it was.
 4. The plasticity index as seen from the graphs had a more marked effect on the stability of the mixtures as the passing No. 30 sieve increased. It is important to note, however, that a plasticity index of more than six was not harmful, depending on the passing No. 30 sieve and the dust ratio. For example, when the passing No. 30 sieve was 10% and the dust ratio was 1.0, the mixture was more stable than almost all other mixtures with much lesser plasticity indices. The general conclusion most commonly expressed by many engineers is that the plasticity index greater than 6% is harmful. However, this is not completely factual because all aspects of every mixture should be considered. This includes the amount of passing No. 30 sieve (gradation); the amount of fines passing No. 200 sieve (dust ratio); and many others.

To clarify this point, one other equation chosen for compressive strength at 15 psi is illustrated in Figure 13. Here the dust ratio is not included in the model as an independent variable because of the high correlation between it and the plasticity index. Its effect,

FIGURE 13. Variation of Compressive Strength at 15psi Lateral Pressure with Plasticity Index.

however, is present since the plasticity is higher when the dust ratio is higher, as was shown in Figure 10. Further examination of Figure 12 leads to the following conclusions:

1. When the passing No. 30 sieve was 10% then the more the plasticity index is increased, the more stable was the mixture.
2. When the passing No. 30 sieve was 15%, then there was an optimum plasticity for which the compressive strength is highest. This was approximately at a P.I. of 9%.
3. Finally, when the passing No. 30 sieve became 20%, then the plasticity had an adverse effect, and the greater the plasticity index, the poorer was the stability as measured by the compressive strength of the mixture. The best mixture here would be the non-plastic one.

The Angle of Internal Friction

The prediction equation that was chosen for the angle of internal friction is shown graphically in Figure 14. Data from this figure suggest:

1. When the passing No. 30 sieve was at 10%, the dust ratio and the plasticity index did not greatly affect the angle of internal friction. But it is apparent here that the higher the dust ratio, the higher the angle of internal friction. In other words, the more skip-graded the mixture was, the better the stability.

The effect of the plasticity index here depended on the various dust ratios. For the low dust ratio of 0.25, the angle of internal friction increased with an increase in

FIGURE 14. Variation of Angle of Internal Friction with Plasticity Index.

plasticity index. For a dust ratio of 0.5, there was an optimum plasticity index value, as shown in Figure 13, that is approximately 11%. For a dust ratio of 0.75, the optimum plasticity index shifted to about 15%, and for a dust ratio of 1.0, the optimum plasticity index was approximately 20%.

2. When passing No. 30 sieve was 15%, the effect of the plasticity index became more significant. In this case, as the dust ratio increased, the angle of internal friction did not necessarily increase. It increased to a certain limit, depending on the plasticity index. It is observed, for example, that for a dust ratio of 1.0 (skip-graded) the angle of internal friction was almost always less than that for the 3 other dust ratios.

For the low dust ratio of 0.25, the angle of internal friction increased with an increase in P.I. For a dust ratio of 0.5 the optimum P.I. was approximately 8%. For a dust ratio of 0.75 the optimum P.I. was about 13% and for a dust ratio of 1.0 the optimum P.I. was about 16%. It is noted that these optimum plasticity indices are generally less than the optimum plasticity indices for passing No. 30 sieve of 10%.

3. When the passing No. 30 became 20%, it was observed that quite an opposite occurrence took place, as compared to the first case when passing No. 30 sieve was 10%. Here, as the dust ratio increased, the angle of internal friction became significantly lower. The case of completely skip-graded material, as seen in Figure 13, have quite low values of the angle of internal friction.

Also, the effect of the plasticity index became more pronounced when the mix contained 20% passing the No. 30 sieve. For a dust ratio of 0.25, there is an optimum P.I. at 4% (virtually non-plastic). For the dust ratios of 0.50 and 0.75, the lower the plasticity index the greater the stability (higher angles of internal friction). For the dust ratio of 1.0, the optimum P.I. was approximately 16%. Therefore, the larger the plasticity index, the more harmful the effect on the stability of this mixture.

Here also the optimum P.I.'s decreased, as compared with the first two cases. This leads to the conclusion that, as the passing No. 30 sieve increases, the optimum P.I. for maximum stability decreases, for different dust ratios.

Effect of Ratio P.I./L.L.

The predition models to be examined here are those where the quality of soil (P.I./L.L.) is used as an independent variable instead of P.I. alone. The purpose of examining these models is to see if the conclusions here agree with those obtained earlier by Deklotz(7).

Figure 15 illustrates the variation of compressive strength at 15 psi lateral pressure with the quality of soil. Figure 16 illustrates the variation of the angle of internal friction with the same variable.

Comparing Figures 15 and 12, it becomes obvious that the same general conclusions hold for the two equations. It is noted that for small amounts of passing No. 30 sieve, skip-grading of the material between the No. 30 and No. 200 sieves results in higher stabilities than well graded material. Also the P.I. has a very minor harmful

FIGURE 15 Variation of Compressive Strength at 15psi Lateral Pressure with Quality of Soil.

FIGURE 16. Variation of Angle of Internal Friction with Quality of Soil.

effect. On the other hand, for a large amount of passing No. 30 sieve, skip-grading between the No. 30 and No. 200 sieves is harmful especially when the plasticity index of the fines is high.

CONCLUSIONS

All conclusions stated herein are based upon laboratory triaxial tests and are necessarily limited to the materials and condition of tests used in this study. The results of this study indicate that a reliable stability test should be conducted on soil-gravel mixtures to determine their adequacy as base or subbase course materials. Classification tests, prescribed limits set by specifications on gradation, and Atterberg limits tests may not be a sufficient basis for judgement.

The purpose of this study was to determine the effect of three variables on the stability of soil-gravel mixtures. These variables were: (1) the amount of material passing the No. 30 sieve; (2) the amount of fines (passing No. 200 sieve), or the effect of varying the dust ratio (ratio of P. 200 to P. 30); and (3) the quality of fines as measured by the liquid limit and the plasticity index.

It should be emphasized that these conclusions are based only on the results of Texas triaxial test for stability. Factors such as permeability, climate, pumping, etc. were not evaluated.

1. For the aggregate tested, when the amount of material passing the No. 30 sieve was low (10%), the plasticity index did not have a harmful effect with regard to stability. In fact, some plasticity proved to be desirable.

In this case (passing No. 30 = 10%), the dust ratio was a more important variable than the plasticity index, as shown in Figures 12 and 14. Here, for a given value of P.I. the higher the dust ratio the better the stability. Skip-grading the material between the No. 30 and the No. 200 sieves improved the stability of the soil-gravel mixture.

2. When the passing No. 30 sieve was high (20%), the plasticity index began to influence the stability, particularly at high dust ratios. It was beneficial to have lower dust ratios, with remaining variables kept constant, as shown in Figures 12 and 14. Here skip-grading the material between the No. 30 and No. 200 sieves was harmful. In this case, the data indicate a plasticity index of approximately 6%, regardless of the existing dust ratio, was best.
3. For intermediate values of passing No. 30 sieve (15%), the behavior of the soil-gravel specimens became rather complicated. This situation resulted in a compromise between the first two cases and both plasticity index and the dust ratio combine to affect stability.

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APPENDIX A

TABLE A-1. Compaction Test Data

PERCENT PASSING NO. 30 SIEVE		DUST RATIO							
		1.0		0.75		0.50		0.25	
		w	γ_d	w	γ_d	w	γ_d	w	γ_d
10	C	5.7	140.6	5.7	141.4	6.4	139.0	6.9	134.9
	B	5.9	138.3	6.8	137.6	6.3	141.1	6.8	140.6
	R	7.3	135.8	6.6	138.2	6.7	139.3	6.5	136.4
15	C	6.0	140.0	5.8	141.5	5.7	141.9	5.8	139.8
	B	6.9	135.2	6.9	136.5	6.4	140.6	6.5	140.3
	R	7.9	135.0	6.7	137.6	6.2	141.0	6.4	140.0
20	C	7.4	137.2	6.4	139.6	5.2	143.5	5.4	141.6
	B	7.4	135.0	7.2	135.0	5.7	140.5	5.9	142.0
	R	8.1	132.8	7.5	135.4	6.8	138.6	6.0	141.7

LEGEND

C - Crosby Soil
 B - Brookston Soil
 R - Limestone Residual
 w - Percent Moisture
 γ_d - Dry Density

TABLE A-2. Texas Triaxial Class
Results

PERCENT PASSING NO. 30 SIEVE		DUST RATIO			
		1.0	0.75	0.50	0.25
10	C	3.4 , 3.7	3.7 , 3.8	3.7 , 3.8	3.7 , 3.8
	B	3.2 , 3.6	3.5 , 3.6	3.4 , 3.8	3.7 , 3.9
	R	3.4 , 3.5	3.5 , 3.6	3.3 , 3.6	3.8 , 3.8
15	C	3.1 , 3.4	3.5 , 3.6	3.7 , 3.7	3.7 , 3.8
	B	3.3 , 3.5	3.5 , 3.8	3.3 , 3.4	3.4 , 3.7
	R	4.1 , 4.0	3.4 , 3.5	3.4 , 3.6	3.6 , 3.7
20	C	4.1 , 4.2	3.6 , 3.7	3.1 , 3.4	3.5 , 3.5
	B	3.9 , 3.95	3.9 , 3.9	3.6 , 3.6	3.4 , 3.6
	R	3.8 , 4.2	4.3 , 4.5	3.9 , 4.1	3.4 , 3.9

LEGEND

C—Crosby Soil
B—Brookston Soil
R—Limestone Residual

TABLE A-3. Compressive Strength at
15p.s.i. Lateral Pressure

PERCENT PASSING NO. 30 SIEVE		DUST RATIO			
		1.0	0.75	0.50	0.25
10	C	116.8 , 129.7	111.9 , 110.6	108.8 , 108.9	94.7 , 97.7
	B	117.2 , 125.3	119.7 , 126.2	113.7 , 120.5	98.5 , 113.5
	R	113.9 , 121.0	115.1 , 121.6	106.1 , 110.3	93.5 , 100.1
15	C	118.0 , 123.9	110.3 , 132.7	111.2 , 111.4	95.8 , 123.3
	B	102.6 , 114.7	101.0 , 101.8	119.7 , 121.2	104.1 , 114.0
	R	72.8 , 74.4	100.1 , 119.8	111.0 , 126.3	99.6 , 100.6
20	C	60.7 , 64.1	88.6 , 107.6	113.0 , 133.0	118.5 , 118.8
	B	64.1 , 70.7	85.7 , 88.7	99.6 , 107.0	108.7 , 122.6
	R	61.1 , 72.1	49.7 , 57.5	70.6 , 87.8	109.5 , 121.3

LEGEND

C - Crosby Soil

B - Brookston Soil

R - Limestone Residual

TABLE A-4 Angle of Internal Friction

PERCENT PASSING NO. 30 SIEVE		DUST RATIO			
		1.0	0.75	0.50	0.25
10	C	48 , 49	46.5 , 48	48 , 47	43 , 43
	B	46 , 47.5	47.5 , 49	48.5 , 47	47.5 , 44.5
	R	47 , 46	48.5 , 48.5	46.5 , 45.5	49 , 48
15	C	45 , 47	50 , 45.5	47 , 47	50 , 46
	B	46 , 42	42.5 , 44.5	45.5 , 48	45.5 , 45
	R	37.5 , 37	48 , 43	48 , 47	43.5 , 45
20	C	29.5 , 29.5	45.5 , 41.5	48 , 45.5	48.5 , 48.5
	B	33.5 , 30	40 , 40	45 , 43	48 , 47
	R	31 , 24	28.5 , 25.5	40 , 36	47.5 , 47.5

LEGEND

C—Crosby Soil

B—Brookston Soil

R—Limestone Residual

TABLE A-5. Texas Triaxial Class
Results

PERCENT PASSING NO. 30 SIEVE		DUST RATIO			
		1.0	0.75	0.50	0.25
10	C	3.5	3.7	3.8	3.8
	B	3.4	3.6	3.6	3.8
	R	3.4	3.5	3.6	3.8
15	C	3.2	3.5	3.7	3.8
	B	3.4	3.6	3.3	3.5
	R	4.1	3.5	3.5	3.7
20	C	4.1	3.65	3.2	3.5
	B	4.1	3.9	3.6	3.5
	R	4.1	4.3	4.0	3.6

LEGEND

C - Crosby Soil
 B - Brookston Soil
 R - Limestone Residual

TABLE A-6. Compressive Strength at
15 p.s.i. Lateral Pressure

PERCENT PASSING NO. 30 SIEVE		DUST RATIO			
		1.0	0.75	0.50	0.25
10	C	123.3	111.3	108.8	96.2
	B	121.3	123.0	115.9	106.0
	R	117.5	128.4	108.2	96.8
15	C	121.0	121.5	111.3	109.2
	B	108.7	101.4	120.5	109.0
	R	73.6	109.9	118.7	99.8
20	C	62.4	98.1	123.0	118.7
	B	67.4	87.2	103.3	110.7
	R	66.6	53.6	79.2	115.4

LEGEND

C - Crosby Soil

B - Brookston Soil

R - Limestone Residual

TABLE A-7. Angle of Internal Friction

PERCENT PASSING NO. 30 SIEVE		DUST RATIO			
		1.0	0.75	0.50	0.25
10	C	49.5	47.5	47.5	43.0
	B	47.0	49.0	48.0	46.5
	R	47.0	50.0	45.0	43.5
15	C	46.5	48.0	47.0	47.5
	B	45.0	44.0	48.0	46.0
	R	33.5	46.0	47.0	43.5
20	C	32.5	43.5	46.5	48.5
	B	32.5	40.0	44.0	47.0
	R	29.7	27.0	39.3	47.7

LEGEND

C—Crosby Soil

B—Brookston Soil

R—Limestone Residual