

SUBBASE FRICTION EFFECTS ON CONCRETE PAVEMENTS

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Designing, constructing, and maintaining concrete pavements under rigorous and unpredictable traffic and environmental loads is a rather formidable challenge. Several effects of the environment on concrete pavements, including the effects of moisture and temperature, have been studied. However, one very important factor, the frictional characteristics between concrete pavements and stabilized subbases, has not been adequately researched. This paper presents findings of a study researching the frictional effects of stabilized and unstabilized subbases. The study was funded by the Texas State Department of Highways and Public Transportation and the Federal Highway Administration and conducted by the Center for Transportation Research at The University of Texas at Austin.

The paper first discusses the concepts of subbase friction, including defining that it consists of three components - an adhesion, or gluing, component between the concrete pavement and the subbase; a bearing component that is influenced by the surface texture of the subbase; and a shearing component which is induced by the movement of the slab across the subbase. The paper then covers the results of a literature search on the topic of subbase friction, which found, among other facts, that the frictional effects of stabilized subbases have not been adequately pursued until this study, and that, according to one report, the frictional effects of cement stabilized subbases are very large, on the order of 28 psi and higher.

Then, experiments on several subbases, in the form of push off tests, are discussed. These experiments were performed on cement stabilized, asphalt stabilized, lime treated clay, flexible, sand-stabilized shell, and untreated clay subbase materials and resulted in frictional restraint - movement graphs. The experimentation found that, on all but the cement stabilized subbases, the maximum frictional restraints ranged between 0.6 psi on an untreated clay subbase to 3.4 psi on a flexible subbase. However, a peak frictional restraint on the cement stabilized subbase could not be found without exceeding the testing equipment's maximum load capacity, and, as a result, it was conservatively estimated that the maximum frictional restraint of the subbase was 15.4 psi, 4-1/2 times larger than the flexible subbase's maximum frictional restraint.

Results and implications from the experiments are then presented in the paper. Discussion will include the observation that, for stabilized subbases, the failure planes resulting from the push-off tests were within the subbases itself, not at the slab-subbase interfaces. From the experimentation, it was also found that slab thickness, or overburden pressure, was not a significant factor in the frictional effects of stabilized subbases, the flexible subbase, and the sand-stabilized shell subbase. Since the 1986 AASHTO Guide for Design of Pavement

Structures assumes that slab thickness does affect the frictional properties of all subbases, as shown in its use of coefficients of friction, the Guide should be modified to account for this fact. In addition, results of testing on two asphalt stabilized subbase layers indicated that the subbase's thickness and internal temperature do have substantial effects on the subbase's frictional properties. It was also found that the asphalt stabilized subbase's surface texture does not significantly affect the frictional restraint. Results of using the indirect tensile testing of subbase cores to estimate subbase friction are also presented. The paper concludes with a discussion of how subbase friction could affect design of concrete pavements.

INTRODUCTION

The effects of several environmental loads on concrete pavements, including moisture and temperature, have been researched, but the effect of one very important environmental load, the frictional characteristics between concrete pavements and today's stabilized subbase materials, has not been adequately studied. Many researchers have studied the frictional characteristics of several unbound materials. Several specific tests have been conducted on cement-stabilized materials, including tests conducted for the Federal Highway Administration by the Portland Cement Association (PCA) (1). However, none of these studies tested a wide range of stabilized subbase materials, and only the Portland Cement Association study tested the effect of surface texture on frictional resistance (6).

Center for Transportation Research (CTR) Project 459, sponsored jointly by the Texas State Department of Highways and Public Transportation (SDHPT) and the Federal Highway Administration (FHWA), obtained stabilized subbase friction information. This was accomplished by reviewing literature on the subject; conducting push-off tests to obtain frictional resistance values for several subbases; and, using the test data as input, executing computer programs to see how concrete pavement behavior and distresses are affected by the frictional characteristics of the subbases. This paper first discusses the subbase friction concept and then covers the work done for this project, including a synopsis of literature reviewed for the study, the experimentation conducted, the results of the experimentation, and the implications of the findings on concrete pavement behavior and design (6).

CONCEPT OF SUBBASE FRICTION

Figure 1 shows a graphical representation of the classical friction model, where the frictional force is a shearing force between two surfaces and is proportional to the slab weight. However, as stated in the first report for this project (CTR Research Report 459-1) by Wesevich et al, subbase friction does not follow the classical model, since it is composed of three components: an adhesion, or gluing, component between the slab and the subbase; a bearing component that is influenced by the surface texture of the subbase; and a shearing component which is induced by the movement of the slab across the subbase (2). These components are illustrated in Fig 2.

As stated in CTR Research Report 459-1, subbase friction acts to counter horizontal concrete pavement movements. When the pavement's temperature or internal moisture increases, the pavement will expand, but subbase friction resists the movement, causing compressive stresses to develop in the concrete. Since concrete is strong in compression, this usually is not a problem. However, in situations where the pavement's temperature or internal moisture decreases, or, as in the case of prestressed pavements, when post-tensioning forces are applied to the pavement, the pavement will contract. Subbase friction, however, counters this movement, resulting in tensile stresses in the pavement. In prestressed pavements, this means that the desired amount of post-tensioning force is not achieved in the pavement, especially at the center of the pavement slab. For continuously reinforced concrete pavement (CRCP), jointed reinforced concrete pavement (JRCP), and other pavement types, the tensile stresses, in conjunction with traffic loads, cause cracking. In addition, the reinforcing steel stresses in concrete pavements would also be affected by subbase friction, since the steel is bonded to the concrete.

LITERATURE REVIEW SYNOPSIS

For this project, the researchers reviewed reports by Goldbeck, Timms, McCullough and Mendoza, and the PCA, among others. Synopses of these reports follow.

Goldbeck (3)

In his 1924 report "Friction Tests of Concrete on Various Subbases," Goldbeck tested the subbases used at that time for concrete pavements, including loam, clay, old macadam, gravel, sand, and trowelled concrete (the only stabilized subbase tested). Concrete slabs 6 feet long, 2 feet wide, and 6 inches thick were cast on these subbases. Then, the slabs were pulled across their respective subbases, and the pulling force and slab displacements were recorded until the slabs started to slide. These tests were conducted under two subbase conditions— a damp but very firm subbase condition, where seven subbases were tested; and an extremely wet and soft subbase condition, where five additional subbases, including the concrete, were tested along with the first seven subbases. Since the slab weight was known, a coefficient of friction was computed, and the results tabulated as shown in Tables 1 and 2. For the most part, the maximum frictional coefficients varied from 1 to more than 2.9.

As shown in the results, the coefficients of friction for the subbase materials were lower for the wet and soft subbase conditions than for the damp, but very firm subbase conditions. Also, Goldbeck was not able to achieve sliding for the slab cast on the concrete since the required force would exceed the capacity of the loading apparatus. Finally, Goldbeck

found that the application of oil on several subbases was ineffective in reducing the friction between the subbases and the slabs.

Timms (4)

Timms conducted tests for the U.S. Bureau of Public Roads in 1963 on several unbound subbases as well as asphalt and polyethylene sheeting. Test slabs were cast and then pushed across their respective subbases several times. Figure 3 shows the results of the testing of some of these subbases in terms of frictional coefficients. As shown in the figure, the frictional coefficients were greatest for the first movements of the slabs across their subbases than for the average subsequent movements. A significant result from this study is that the asphalt subbases, which are bound subbases, had considerably higher frictional coefficients than their unbound counterparts, and that the polyethylene sheeting had a very low frictional coefficient.

McCullough and Mendoza (5)

In "Report on a Mechanistic Analysis of the PCC Aprons at King Fahd International Airport, Kingdom of Saudi Arabia," McCullough and Mendoza presented results of push-off tests of concrete cylinders 16 inches thick and 22.5 inches in diameter on:

1. an aggregate base coated with a medium curing asphalt cutback (MC70),
2. a fine-graded bituminous base course, and
3. a one-sheet visqueen over a bituminous base course.

The results are presented in Fig 4. As shown, the MC70 was ineffective in reducing the frictional restraint of the underlying aggregate subbase, while the visqueen and the bituminous base course were effective. It was also found that the failure plane after sliding was not between the concrete cylinder and the subbase but through the MC70 and the subbase. The CTR study also found the same type of failure plane for all but one of the subbases in this study.

PCA Study for the FHWA (1)

In the report "Methods For Reducing Friction Between Concrete Slabs and Cement-Treated Subbases," the researchers investigated the effect of friction-reducing methods and subbase texture on cement-stabilized subbases. The subbase was coated with Shell SS-1 asphalt emulsion curing compound except for one area. The researchers then cast slabs on five possible friction reducers with three different surface textures per friction reducer. In addition, the researchers cast slabs directly on the subbase area without the curing compound and on the subbase with the compound. As shown in Tables 3 and 4, all but the 1/16" sand skin friction reducers were effective. However, it is more important to note the high frictional restraint values for the slabs cast on the 1/16" sand skin - from a coefficient of friction of 13.83 on the smooth texture (7.55 pounds per square inch of slab contact area) to 51.15 on the rough texture (28.3 pounds per square inch). In addition, the researchers were not able to push the slabs cast directly on the uncoated subbase and the coated subbase.

EXPERIMENTATION

The experiments conducted for this project, including push-off tests on various subbases and correlating the maximum frictional restraint of subbases to indirect tensile testing of subbase cores, are discussed.

First Phase (CTR Report 459-1) (2)

In the first phase of this project, the researchers conducted a survey of the Texas SDHPT Districts to find what subbases are currently being used under concrete pavements. From the survey, the following subbases were selected and tested:

1. a flexible subbase (12 inches thick),
2. an asphalt stabilized subbase bond-breaker (3/4 inch thick),
3. a concrete stabilized subbase (6 inches thick),
4. a lime treated clay subbase (6 inches thick), and
5. untreated clay.

Figure 5 graphically represents the subbases tested in the first phase of the study.

For each subbase, the researchers conducted push-off tests on one pair of test slabs, all of them being 14 feet long, 2 feet wide, and 3 1/2 inches thick, except for the slabs on the flexible base, which were 9 feet long, two feet wide, and 4 inches thick. Precast concrete blocks were stacked on one of the test slabs on each subbase to simulate 7-inch thick slabs (8-inch thick slabs for the flexible subbase). Each slab was then pushed across the subbase by use of a hydraulic jack set up against an anchor facing one end of the slab. The forces exerted on the slab and the corresponding horizontal and vertical slab movements were then recorded by use of a load cell between the jack and the slab and a pair of linear voltage distance transducers mounted on the slabs, respectively. Figure 6 shows a typical push-off test.

Since the force is equal to the frictional restraint of the subbase, a frictional restraint - movement curve can be generated for each test slab. For this study, such curves were generated for both horizontal and vertical movements. Figure 7 illustrates a typical frictional restraint - movement curve, with the restraint recorded in pounds per square inch of slab contact area (the slab length multiplied by the slab width), and the slab movement recorded in inches.

Table 5 lists the maximum frictional restraints and the corresponding horizontal slab movements for the subbases tested. As it can be seen, the frictional restraint, measured in psi, does not change significantly with slab thickness, except for the untreated clay, which does show increased frictional restraint with increased slab thickness. In addition, the researchers were unable to push the test slabs across the cement-stabilized subbase, the same result found in the PCA study mentioned earlier. Finally, it was found that the failure planes after the push-off tests were within the subbases themselves for the flexible subbase and the lime treated clay subbase; at the interface between the bond-breaker and the underlying materials for the asphalt stabilized subbase bond breaker; and at the interface between the test slab and the subbase for the untreated clay material.

Second Phase (CTR Report 459-2F) (6)

In the second phase of the project, it was decided to see how subbase depth and surface texture affected the frictional resistance of an asphalt stabilized subbase material. Push off

tests were conducted under constant temperature conditions on two layers of a Texas SDHPT Type D asphalt pavement - one layer five inches thick, the other two inches thick. As shown in Fig 8, a total of twelve slabs were cast on the layers, six slabs per layer. Each slab represented a certain thickness (either 3 1/2 inches or 7 inches) and rested upon a particular subbase surface texture (smooth, medium, and rough). Figure 9 shows the surface textures of the subbase, which were made by indenting the subbase with striations of varying spacings (2 inch spacing for the rough texture, 4 inch spacing for the medium texture, and no striations for the smooth texture). Push off tests similar to those conducted in the first phase of the project were then conducted, and, as before, frictional restraint - movement curves were generated.

Table 6 presents the results of the push-off tests for the two layers. As found in the study's first phase, the slab weight is not significant in the frictional resistance of the subbase, but the subbase depth is a definite factor. In addition, the surface texture does not seem to be a factor in the frictional restraint of this material. It also found that the failure plane was within the subbase for the 5-inch-thick layer and at the interface between the asphalt stabilized subbase layer and the underlying material for the two-inch-thick layer. Finally, the study found that the temperature of the subbase could significantly change its frictional resistance, possibly increasing it as much as 2 psi from the values measured in the field.

In addition, push-off tests were conducted on a sand-stabilized shell material under an in-service pavement on IH45 south of downtown Houston. The existing 8-inch jointed pavement overlying this subbase had been in service for forty years while exhibiting few signs of distress. As shown from the results in Table 7, the subbase reached a maximum frictional resistance of around 1 psi. Since the subbase's frictional properties were so low, the tensile stresses that developed in the concrete when it contracted due to temperature and moisture drops were also low. Thus, even with large traffic loads, the pavement suffered very few distresses.

In order to see if the frictional restraint of subbases could be determined by other means, the researchers examined the possibility of correlating the indirect tensile testing of subbase cores to the maximum frictional resistance values measured during the push-off tests. Data from CTR Research Reports 98-2 (8), 98-3 (9), and 98-4 (10) contained indirect split tensile strength data for cores on asphalt-stabilized, cement-stabilized, and lime-stabilized materials, respectively. A summary of these results are presented in Table 8. Using the maximum frictional restraint data from the project on the asphalt stabilized subbase and the lime-treated clay subbase (3.2 psi and 1.7 psi, respectively) and from the PCA report on the cement stabilized subbase with the 1/16-inch sand-skin layer (28 psi), a correlation can be drawn as shown in Fig 10.

DISCUSSION OF THE LITERATURE REVIEW AND THE PROJECT RESULTS

A summary of the findings from the literature review and the research conducted for this project follows.

Literature Review

In reviewing literature pertaining to subbase friction, the researchers found that the frictional resistances of the subbases were characterized, for the most part, by coefficients of friction. As will be discussed in this section, the researchers felt that frictional restraint measured in terms of pounds per square inch of slab contact area is a better measure of the subbase friction effect.

The study by McCullough and Mendoza found that the failure plane resulting from the push-off test on the subbase coated with MC-70 was not at the concrete-subbase interface but through the curing compound and the subbase (5). This was also found in the push-off tests conducted for this project for all of the subbases.

Finally, the finding from the PCA study that cement stabilized subbases have high friction characteristics is a possible explanation of why premature cracking and distresses occur on concrete pavements placed directly on such subbases, since the high frictional restraint causes high tensile stresses and thus unplanned-for cracking in concrete pavements (2). The report also shows the necessity of using friction reducers (or bond-breakers) between cement stabilized subbases and concrete pavements.

Push-Off Testing

As stated in the results, the resulting failure planes for all but the untreated clay subbases were either within the subbases, or, as in the case of the 3/4-inch-thick asphalt bond-breaker and the 2-inch-thick asphalt stabilized subbase, at the interface between the subbase and the underlying material. Figure 11 illustrates these failure planes to the asphalt stabilized subbase layers tested in CTR Report 459-2F. Thus, it seems that the adhesive component of subbase friction is actually greater than the subbases' material strength or, in the case of the thin asphalt subbase layers, the adhesive, bearing, and shear properties at the interface between the subbase and the underlying material. It also can be concluded from the results that frictional restraint is affected significantly by the depth of the subbase.

In addition, the researchers found that, for all of the subbases except the untreated clay, the slab weight does not significantly affect the frictional resistances (the untreated clay's frictional restraint, however, does depend on slab weight). This means that the frictional properties of these subbases do not follow the classical model; thus, a coefficient of friction is not proper in describing their frictional behavior. This finding from the project for these subbases would suggest that the methodology accounting for subbase friction in concrete pavement design procedures (such as the procedure in the 1986 AASHTO Guide) be changed to use subbase friction values in psi.

It was also found that the frictional restraint of the cement-stabilized subbase in this study was so much greater than the other subbases tested that the researchers were not able to achieve a maximum frictional restraint value. This would suggest that cement-stabilized subbases, if not covered with a friction reducer, would induce large tensile stresses in the concrete, causing premature distresses.

Finally, it was found that the surface texture on an asphalt stabilized subbase does not significantly affect the frictional resistance, but the subbase temperature could change the frictional properties significantly.

Indirect Split Tensile Test Correlation to Subbase Frictional Resistance

As shown in the results, it could be possible to correlate the indirect split tensile test to the subbase's frictional resistance if a large number of subbase cores are tested. One problem with this correlation, however, is the wide variation in the strengths of the subbase cores, as shown by the high standard deviations. However, the ability to achieve a correlation between the average indirect tensile strength and the frictional resistance is promising.

IMPLICATIONS OF THE FINDINGS FROM CTR PROJECT 459

It has been found from this and another study conducted at the Center for Transportation Research that the subbase friction characteristics of most subbases are not as significant in the behavior of continuously reinforced concrete pavements (CRCP) as other factors, such as the coarse aggregate type; the concrete tensile strength; and the percentage of steel reinforcement (6, 7). However, jointed and prestressed pavements are greatly influenced by subbase friction effects. In addition, large frictional restraints such as those generated by cement-stabilized subbases can have detrimental effects on any pavement, including CRCP. This has been observed in several instances across the state of Texas and the nation by other researchers.

Using the friction data generated from this project, the PCP1 computer program, developed at CTR to determine the behavior of prestressed pavements, was used to produce tensile stress data for plain concrete slabs containing limestone coarse aggregate (11). For the data input into the program, plain-jointed concrete pavements with no applied prestressing forces were assumed. The frictional restraint-movement curve input into the program, as conceptually shown in Fig 12, differs from the actual curves in that the maximum frictional restraint does not drop off. This was done since the program could generate reasonable values for the cement-stabilized subbase in this format. The results of the program are shown in Fig 13 for a 40° drop from the slab curing temperature. Assuming in this case that the concrete has a maximum tensile strength of 400 psi, this value would be reached at 15 feet from the slab end for the cement-stabilized subbase, around 79 feet for the flexible subbase, about 85 feet for the asphalt-stabilized subbase (the five-inch-thick layer), approximately 154 feet for the lime-treated clay, and 380 feet for the unbound shell subbase.

Possible joint spacings, then, could be arrived at from the graph by multiplying these values by a factor of two. This is, in effect, putting two ends of a long slab together to make a smaller slab which would theoretically experience a maximum tensile stress of approximately 400 psi at the center. So, using this method, joint spacings of 30, 160, 170, 300 and 760 feet can be achieved on cement-stabilized, flexible, asphalt-stabilized, lime-treated clay, and unbound shell subbases, respectively. However, to reflect pavement conditions other than those input into the PCP1 program, more realistic joint spacings can be generated using ratios of the above spacings. For example, assume that joint spacings of 30 feet have been successful for pavements overlying asphalt-stabilized subbases. Using the above joint spacings, generating ratios between the asphalt stabilized subbase and the other subbases (1 to 0.19 for asphalt-stabilized subbase to cement-stabilized subbase, 1 to 0.94 for asphalt-stabilized subbase to lime-treated clay subbase, and so on), and multiplying these ratios by thirty feet, the joint spacings shown in Fig 14 would result. Of course, large joint spacings would not be desirable because of large movements at the joints, but it is interesting to note how the effect of subbases can affect such spacings.

It is evident from Fig 14 that cement-stabilized subbases causes relatively large tensile stresses compared to other subbases. Thus, pavement designers are strongly encouraged to specify friction reducers or bond breakers between any concrete pavement and cement stabilized subbases.

CONCLUSION

Center for Transportation Research Project 459 generated much-needed information on subbase materials that are commonly used in modern concrete pavements. The findings

from this project should help produce more reliable and easier to maintain pavement structures.

For more detailed information about the project, CTR Reports 459-1, "Stabilized Subbase Friction Study For Concrete Pavements," by James W. Wesevich, B. Frank McCullough, and Ned H. Burns, and 459-2F, "Methods of Analyzing and Factors Influencing Frictional Effects of Subbases," by Andrew J. Wimsatt, B. Frank McCullough, and Ned H. Burns, are available from the Center for Transportation Research at The University of Texas at Austin and from the Federal Highway Administration.

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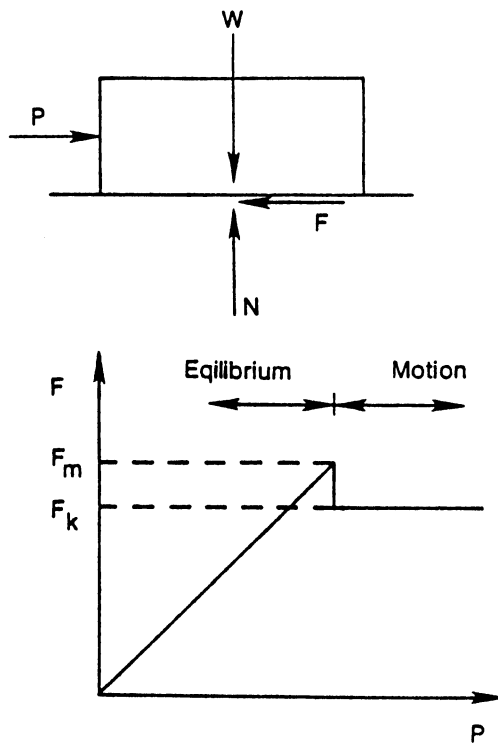


Fig 1. Classical friction model (11).

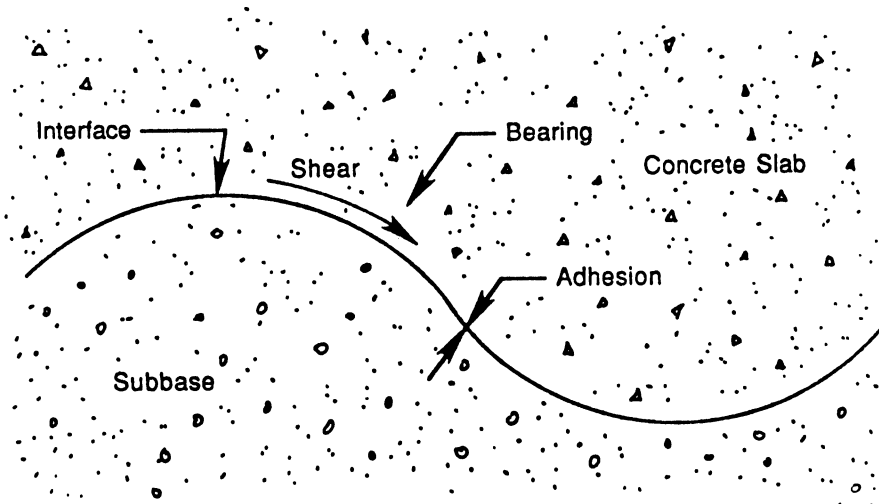


Fig 2. Adhesion, bearing, and shear components at the slab-subbase interface (2).

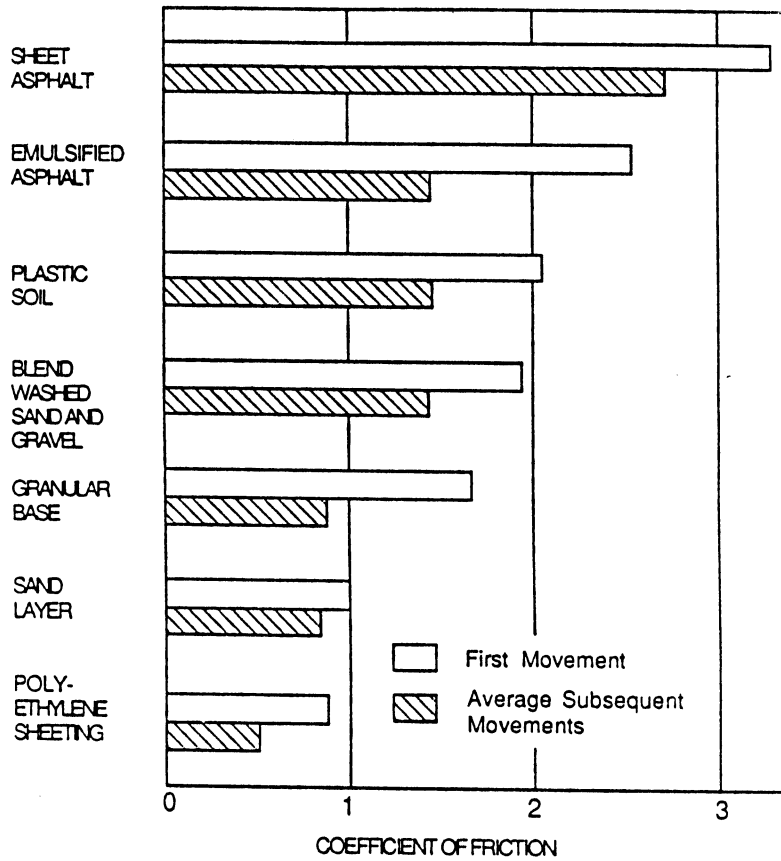


Fig 3. Summary of friction coefficients obtained by Timms (4).

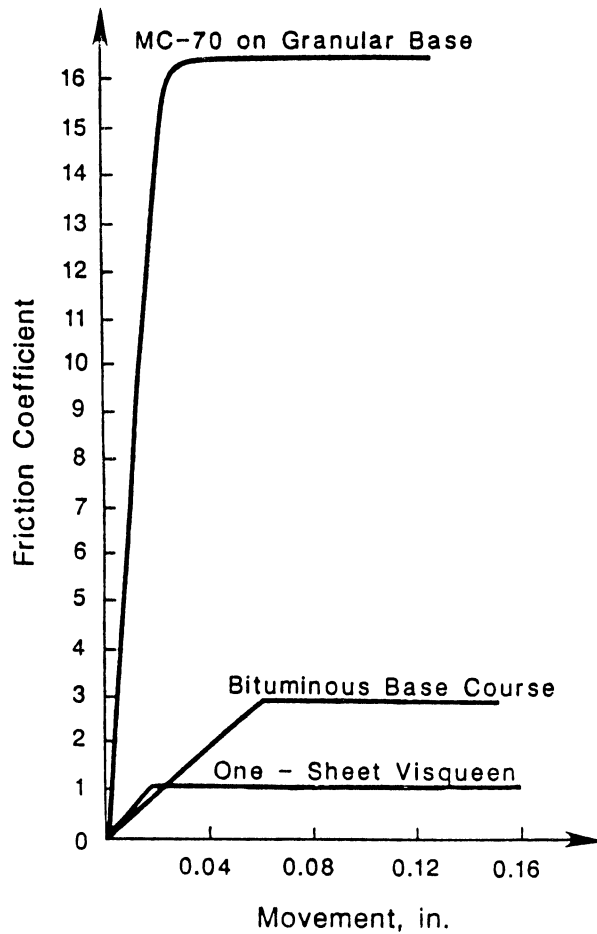


Fig 4. Friction coefficient versus movement for subbase tested in Saudi Arabia (5).

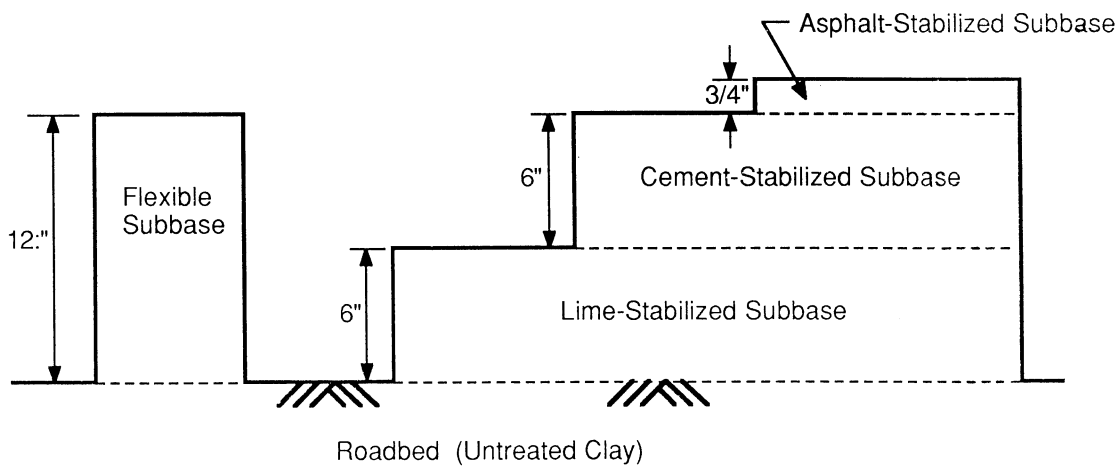


Fig 5. Subbases tested in CTR Research Report 459-1 (2).



Fig 6. Eight-inch simulated slab for second push-off test in Austin, Texas (2).

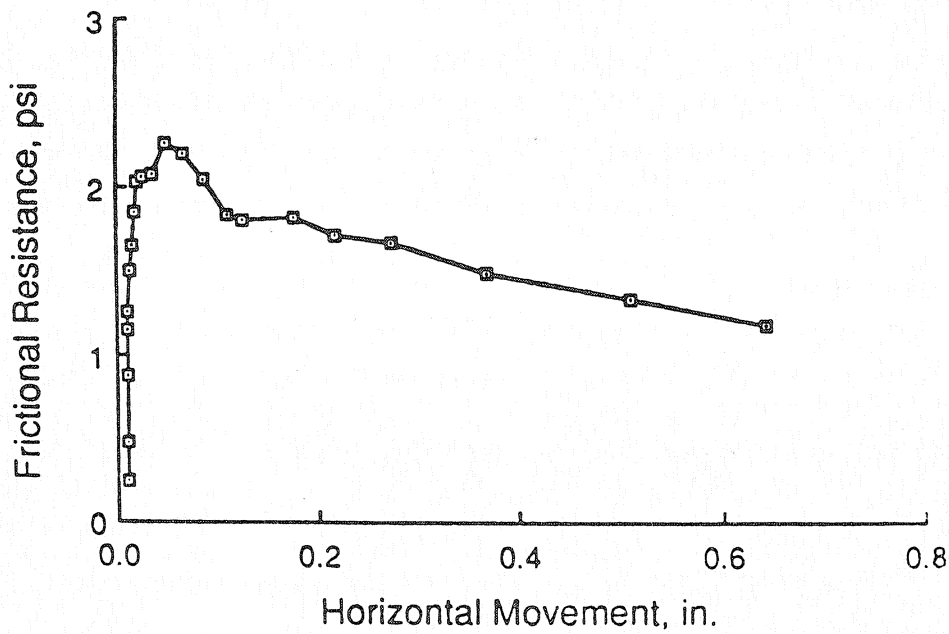


Fig 7. Horizontal movement for push-off tests on simulated 7-inch asphalt stabilized subbase (2).

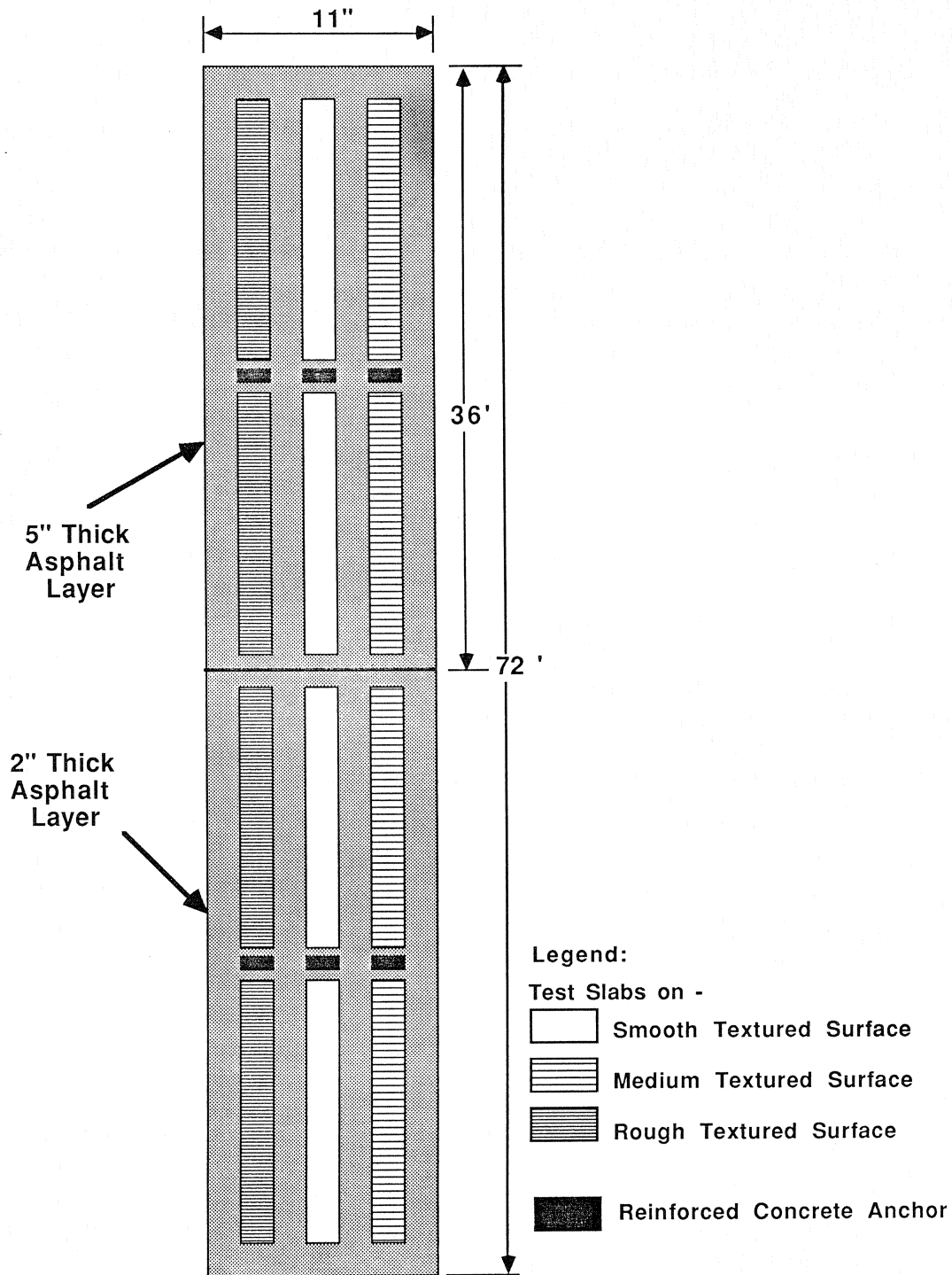


Fig 8. Plan view of test site (6).

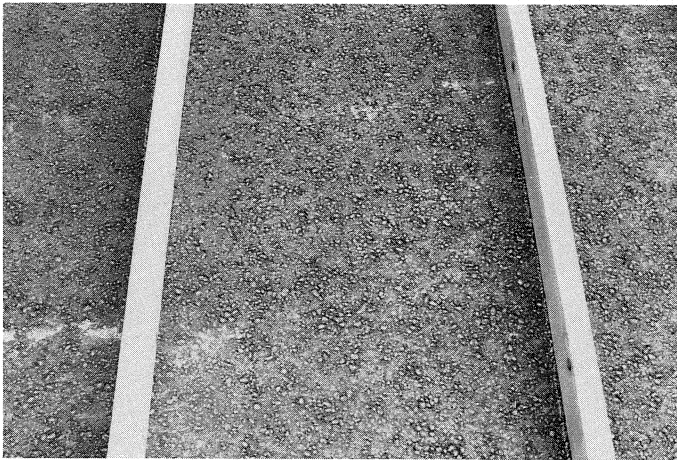


Fig 9. Smooth, medium, and rough textures (6).

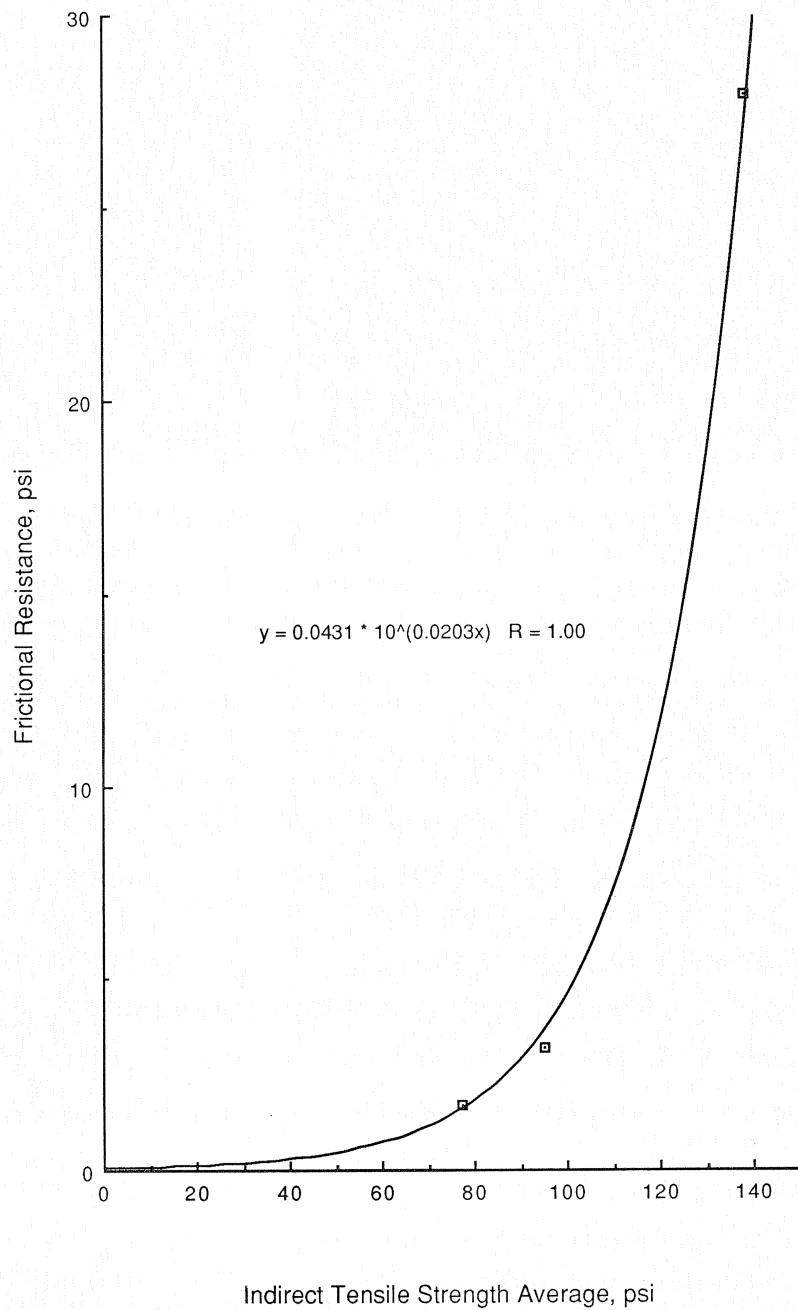


Fig 10. Frictional resistance versus CTR Project 98 average values (6).

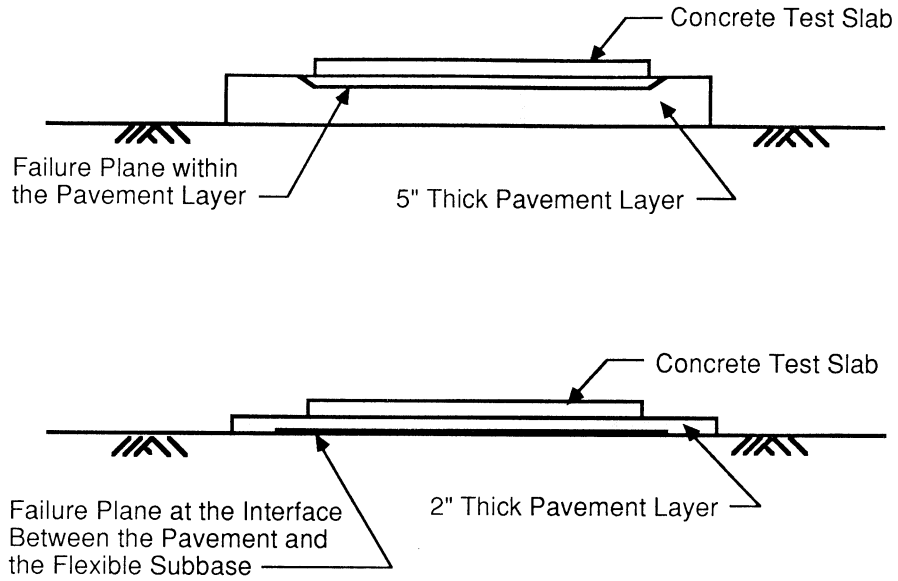


Fig 11. Resulting failure planes within the layers (6).

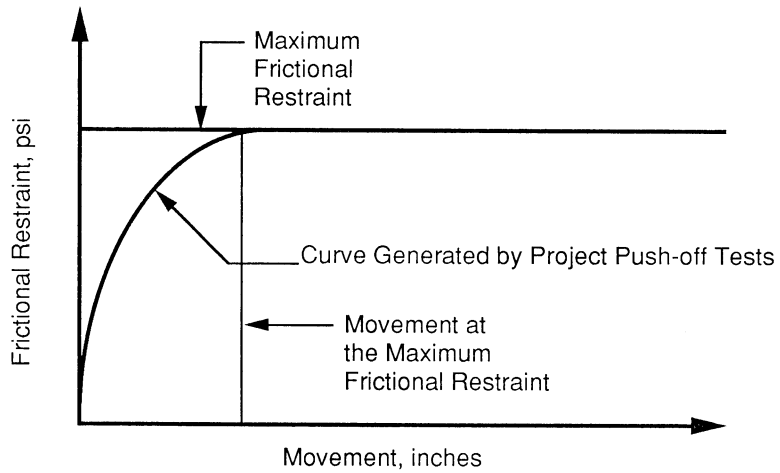


Fig 12. Conceptual frictional restraint movement curve for the subbases entered into the PCPI program (6).

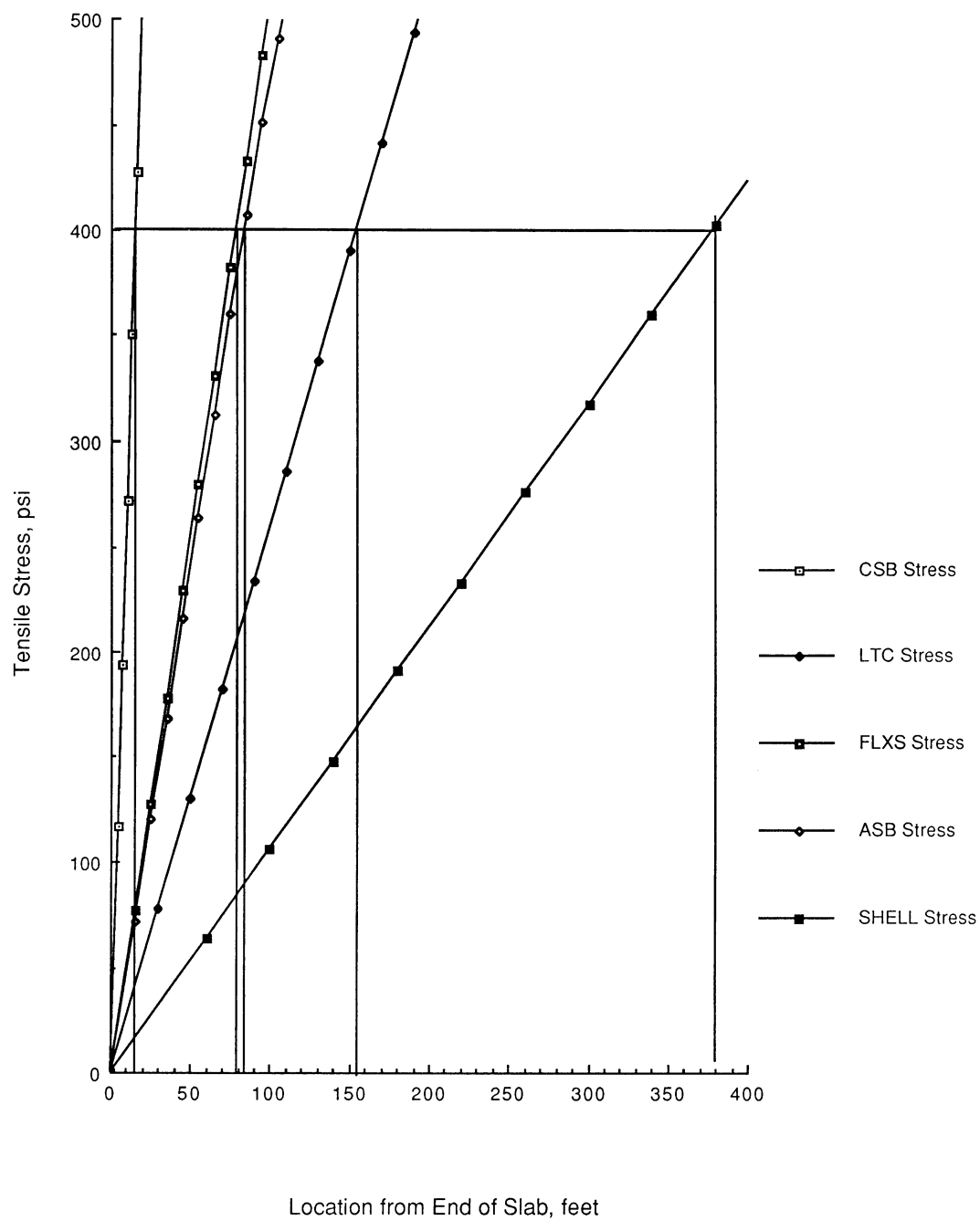


Fig 13. Tensile stress versus slab location (6).

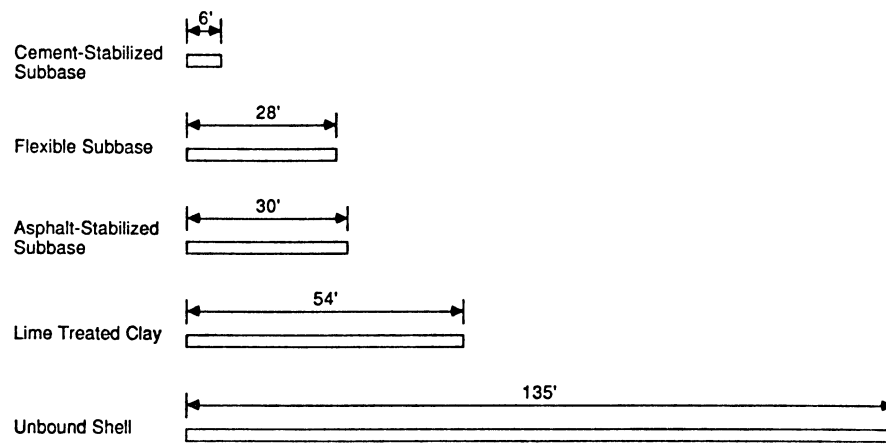


Fig 14. Comparative joint spacings from the computed results (6).

Kind of Base	Movement	Force	Coefficient	Movement	Force	Coefficient	Movement	Force	Coefficient
Level clay	0.001	480	0.55	0.01	1130	1.3	0.05	1800	2.07
Uneven clay	0.001	500	0.57	0.01	1120	1.29	0.05	1800	2.07
Loam	0.001	300	0.34	0.01	1030	1.18	0.05	1800	2.07
Level sand	0.001	600	0.69	0.01	1080	1.24	0.05	1200	1.38
3/4-in. gravel	0.001	450	0.52	0.01	960	1.10	0.05	1100	1.26
3/4-in. broken stone	0.001	380	0.44	0.01	800	0.92	0.05	950	1.09
3-in. broken stone	0.001	1060	1.84	0.01	1550	1.78	0.05	1900	2.18

TABLE 1. FRICTIONAL RESISTANCE OF CONCRETE ON VARIOUS SUBBASES (DAMP BUT VERY FIRM) (3)

Kind of Base	Movement	Force	Coefficient	Movement	Force	Coefficient
Level clay	0.001	120	0.14	0.01	300	0.35
Uneven clay	0.001	200	0.23	0.01	460	0.53
Loam	0.001	150	0.17	0.01	260	0.3
Level sand	0.001	140	0.16	0.01	280	0.32
3/4-in. gravel	0.001	510	0.58	0.01	640	0.73
3/4-in. broken stone	0.001	400	0.46	0.01	660	0.76
3-in. broken stone	0.001	240	0.28	0.01	630	0.73
Oiled clay	0.001	150	0.17	0.01	410	0.47
Clay and cobblestones	0.001	140	0.16	0.01	410	0.47
Concrete base	0.000	2500+	2.9+	0.00	2500+	2.9+
Sand, oiled	0.001	180	0.21	0.01	280	0.32
Concrete, oiled	0.000	2500+	2.9+	0.00	2500+	2.9+

Kind of Base	Movement	Force	Coefficient	Movement	Force	Coefficient
Level clay	0.05	500	0.58	1.5	950	1.09
Uneven clay	0.05	620	0.71	1.4	925	1.06
Loam	0.05	410	0.47	0.75	925	1.06
Level sand	0.05	400	0.46	0.75	875	1.00
3/4-in. gravel	0.05	950	1.1	0.5	1050	1.2
3/4-in. broken stone	0.05	940	1.08	2.0	1160	1.33
3-in. broken stone	0.05	900	1.04	0.875	1625	1.87
Oiled clay	0.05	850	0.98	1.25	1425	1.64
Clay and cobblestones	0.05	710	0.82	1.75	1260	1.45
Concrete base	0.00	2500+	2.9+	0.00	2500+	2.9+
Sand, oiled	0.05	480	0.55	0.375	800	0.92
Concrete, oiled	0.00	2500+	2.9+	0.00	2500+	2.9+

TABLE 2. FRICTIONAL RESISTANCE OF CONCRETE OF VARIOUS SUBBASES, EXTREMELY WET AND SOFT) (3)

Friction Reducer	Subbase Texture	Maximum Coefficient of Friction					Sliding Coefficient of Friction				
		Push	Pull	Push	Pull	Ave.	Push	Pull	Push	Pull	Ave.
1/4" Sand + Poly.	Medium	0.56	0.58	0.55	0.56	0.56	0.56	0.58	0.55	0.56	0.56
1/4" Sand	Smooth	0.55	0.55	0.54	0.56	0.55	0.55	0.55	0.54	0.55	0.55
	Medium	0.59	0.59	0.58	0.58	0.59	0.59	0.59	0.58	0.58	0.59
	Rough	0.52	0.50	0.56	0.52	0.53	0.51	0.50	0.56	0.52	0.52
1/16" Sand skin + Poly.	Smooth	0.93	0.75	0.86	0.70	0.81	0.51	0.56	0.74	0.61	0.61
	Medium	0.76	0.77	0.65	0.70	0.72	0.65	0.67	0.65	0.65	0.65
	Rough	0.94	- - - -	0.76	0.70	0.80	0.78	- - - -	0.71	0.65	0.71
Double Poly.	Smooth	0.63	0.58	0.63	0.74	0.65	0.59	0.58	0.63	0.70	0.62
	Medium	0.68	0.81	0.66	0.75	0.72	0.67	0.65	0.65	0.68	0.66
	Rough	0.98	0.76	0.71	0.69	0.79	0.89	0.68	0.65	0.63	0.71
1/16" Sand skin	Smooth	13.83*	0.81	1.06	1.05	0.97	0.85	0.81	1.06	1.05	0.94
	Medium	44.47*	1.24	1.13	1.40	1.26	1.04	0.93	1.00	1.07	1.10
	Rough	51.15*	1.45	1.44	1.72	1.54	1.14	1.23	1.29	1.24	1.23
No friction reducer (CTB coated with curing compound)	Smooth			> 13.5**							
	Medium			> 44.0**							
	Rough			> 51.0**							
No friction reducer (CTB uncoated)	Medium			> 8.0**							

* Not included in average.

** Values are based on the maximum load that could be applied to the slab with our testing equipment.

TABLE 3. COEFFICIENTS OF FRICTION FROM THE CEMENT-STABILIZED SUBBASE TESTING (1)

Reducer	Subbase Texture	Size, ft	Movement	Maximum Coefficient of Friction					Sliding Coefficient of Friction					Slab Weight
				Push	Pull	Push	Pull	Ave.	Push	Pull	Push	Pull	Ave.	
1/4" Sand + Poly.	Medium	4x4x0.5	0.11	0.30	0.31	0.30	0.30	0.31	0.30	0.31	0.30	0.30	0.31	1240
1/4" Sand	Smooth	4x4x0.5	0.16	0.31	0.30	0.30	0.31	0.30	0.30	0.30	0.30	0.30	0.30	1273
	Medium	4x4x0.5	0.03	0.33	0.33	0.32	0.32	0.33	0.33	0.33	0.32	0.32	0.33	1279
	Rough	4x4x0.5	0.07	0.29	0.28	0.31	0.29	0.29	0.28	0.28	0.31	0.29	0.29	1269
1/16" Sand skin + Poly.	Smooth	4x4x0.5	0.24	0.52	0.42	0.48	0.39	0.45	0.28	0.31	0.41	0.34	0.33	1275
	Medium	4x4x0.5	0.25	0.41	0.42	0.35	0.38	0.39	0.35	0.36	0.35	0.35	0.35	1249
	Rough	4x4x0.5	0.11	0.52	0.63**	0.42	0.39	0.44	0.43	0.50**	0.39	0.36	0.39	1271
Double Poly.	Smooth	4x4x0.5	0.17	0.35	0.32	0.35	0.41	0.36	0.33	0.32	0.35	0.39	0.35	1273
	Medium	4x4x0.5	0.27	0.38	0.45	0.36	0.42	0.40	0.37	0.36	0.36	0.38	0.37	1279
	Rough	4x4x0.5	0.21	0.54	0.42	0.39	0.38	0.43	0.49	0.38	0.36	0.35	0.39	1269
1/16" Sand skin	Smooth	4x4x0.5	7.55	7.55**	0.44	0.58	0.57	0.53	0.46	0.44	0.58	0.57	0.51	1257
	Medium	4x4x0.5	24.4	24.4**	0.68	0.62	0.77	0.69	0.57	0.51	0.55	0.59	0.55	1265
	Rough	4x4x0.5	28.3	28.3**	0.80	0.80	0.95	0.85	0.63	0.68	0.71	0.69	0.68	1276
No friction reducer on Bit. Curing Compound	Smooth	4x4x0.5						>7.4					>7.4	1266*
	Medium	4x4x0.5						>24.3					>24.3	1266*
	Rough	4x4x0.5						>28.2					>28.2	1266*
No friction reducer	Medium	4x4x0.5						>4.3					>4.3	1266*
1/16" Sand Skin + Poly.	Medium	2x4x0.5	0.22	0.41	0.39	0.40	0.43	0.41	0.38	0.36	0.38	0.43	0.39	649
	Medium	4x8x0.5	0.33	0.50	0.34	0.30	0.40	0.39	0.44	0.28	0.29	0.38	0.35	2552
	Medium	4x4x1	0.22	0.69	0.86	0.67	0.78	0.75	0.69	0.86	0.67	0.78	0.75	2524
	Medium	4x8x1	0.41	0.86	0.35	0.79	0.76	0.80	0.86	0.78	0.79	0.76	0.80	5076

Frictional Restraint values are in lbs per square inch (psi) * Average weight for 4x4x0.5 slabs ** Not used in average

TABLE 4. FRICTIONAL RESTRAINT VALUES (POUNDS/SQUARE INCH) OBTAINED FROM TABLE 3

Subbase Type	Peak Frictional Resistance (psi)	Horizontal Movement at Sliding (inch)	Slab Depth (inches)
Flexible	3.0, 3.4	0.024, 0.020	4, 8
Asphalt Stabilized	1.6, 2.2	0.030, 0.038	3.5, 7
Cement Stabilized	15.4 +	0.001 +	3.5
Lime-treated Clay	1.6, 1.7	0.011, 0.012	3.5, 7
Untreated Clay	0.6, 1.1	0.030, 0.052	3.5, 7

TABLE 5. RESULTS OF TESTING - CTR RESEARCH REPORT 459-1 (2)

Subbase Depth (inches)	Texture	Concrete Thickness	
		3.5 inches	7 inches
2	Smooth	1.65 psi* (0.03 in.)**	2.54 psi (0.04 in.)
	Medium	2.31 psi (0.06 in.)	2.56 psi (0.02 in.)
	Rough	2.30 psi (0.05 in.)	2.42 psi (0.03 in.)
5	Smooth	2.53 psi (0.07 in.)	- -
	Medium	2.90 psi (0.03 in.)	- -
	Rough	2.85 psi (0.06 in.)	3.23 psi (0.04 in.)

* Maximum frictional restraint.

* * Movement at sliding.

TABLE 6. RESULTS OF PUSH-OFF TESTS ON TYPE D ASPHALT-PAVEMENT (6)

Test Slab Depth (inches)	Maximum Frictional Resistance (psi)	Corresponding Horizontal Movement (inches)
3.5	1.11	0.04
8.0	1.06	0.04

TABLE 7. RESULTS OF THE HOUSTON IH45 UNBOUND SHELL PUSH-OFF TESTS (6)

Type of Specimens	Number of Test Specimens	Mean (psi)	Standard Deviation (psi)	Maximum Observed Tensile Strength (psi)	Minimum Observed Tensile Strength (psi)
Asphalt Treated	68	94.8	54.2	231.3	7.6
Cement Treated	180	138.2	96.8	497.1	13.1
Lime Treated Clay	34	77.1	56.2	318.0	24.0

TABLE 8. RESULTS FROM CTR RESEARCH REPORTS 98-2 (8), 98-3 (9), AND 98-4 (10)