Friction Studies in Bonded Cement Concrete Pavement Slabs

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A smooth base is desirable for a prestressed concrete pavement so that losses in prestress due to frictional restraint at the interface below can be reduced to minimum. In the case of non-prestressed rigid pavements, opinion is varied regarding the efficacy of a smooth base.

In Indian highway practice, where the stage construction method is common, the concrete slab is bonded to a well consolidated water-bound macadam base below. This bonding increases the effective thickness of the slab. Furthermore, the force of adhesion at the interface is extremely high and in the case of restrained contraction of the slab, the failure takes place well inside the base and the slab simply acts as a bonded surcharge initiating the deformations. In other words, the classical "drag" theory does not seem to be valid for bonded slabs.

THE GENERALLY accepted "drag" theory based on simple laws of friction developed by Bradbury (1) assumes that the expansion or contraction of a cement concrete pavement due to the variation in its average temperature is resisted by the friction at the interface between the slab and the support below. A value of 1.5 to 2.0 is generally assumed (2) for this coefficient and the slab is supposed to slide freely over the support after failure.

A high friction base is undoubtedly undesirable for a prestressed concrete pavement, and the studies by Timms (3), and Stott (4) were primarily concerned with developing details of construction to reduce the interface friction. In the case of ordinary concrete pavements, plain or reinforced, the role of frictional restraint at the interface is not clearly understood. European highway engineers (5) have expressed doubts about the advocacy of a minimum friction coefficient. They are of opinion that a very high frictional value may serve to distribute stresses caused by expansion and contraction more evenly, and thereby reduce the incidence of cracking. The case histories reported by Walker (6), a British engineer who has had extensive experience in India with thin concrete road slabs bonded to a strong water-bound macadam base, have indicated the advantages of bonding the slab to the base.

BONDING OF SLABS TO BASE

Bonding of the slab to the base is a particular method of increasing the forces of resistance at the interface, and is in principle the same as the American concept (7) of providing terminal lugs or anchors to restrain the movements of the terminal areas in long pavements where the frictional resistance is not fully mobilized. These lugs are analogous to the key trenches used in the construction of rolled-filled earth dams. The success of these lug anchors in restraining the terminal movements greatly depends on the nature of the soil to which it is anchored, especially its shearing strength. While in the case of slabs with terminal lugs, the shearing resistance is highly mobilized in

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the immediate neighborhood of the anchors, it is evenly spread throughout the bonded slab.

Stage construction is the common highway practice in India, and the concrete road slab is generally well bonded to a consolidated water-bound macadam base. This is done by thoroughly cleaning the macadam base with wire brushes and removing all the dust and the loose particles. The rugged face of the cleaned surface with small protrusions of the stones provides good bonding to the concrete. The thickness of the slab is much less than that of a slab designed by conventional methods. Their satisfactory performance is due to the bonding of the slab to the water-bound macadam base which is really a sort of prepacked mud concrete. Data presented by Childs (8) have confirmed the beneficial effects of bonding on wheel-load stresses. The Indian experience of bonding the slab to the macadam base has stood the test of time and is favored in Indian highway practice; however, there are practically no experimental data under controlled conditions to help understand rationally the interaction between the base and the bonded slab. This paper attempts to study the resistance offered by the different types of bases to the horizontal movement of the slabs.

GENERAL TEST PROCEDURE

The test procedure adopted was similar to that employed at the Arlington tests (9) in the United States.

CONSTRUCTION DATA

A masonry tank with inside dimensions 4.5 ft long, 2.5 ft wide and 1.0 ft deep was constructed in the basement of the Civil Engineering department where the air temperature variation was negligible. Within this tank, the different types of base courses were constructed and tested. The slabs were either 4 or 6 in. thick and their dimensions were 4- by 2-ft or 3- by 1-ft. The concrete was of 1:1½:3 mix and was hand-rodded and finished. No vibration was done to guard against mortar being forced into the base and thereby vitiating the results. A 4-ft high mass concrete bulkhead of dimensions 3- by 3-ft, constructed on either side of the test tank, and taken 1 ft below the concrete floor level, provided the necessary reactions for the mechanical jacks used in pushing the slabs.

DETAILS OF INSTRUMENTATION

A 3-ton hydraulic load cell, calibrated to 20 kg, was used to measure the total thrusting force. The horizontal movement of the slab was recorded on four dial gages (0.001 in.) set at each corner of the slab; the average of the four values was taken as the displacement of the slab. While testing the 1-ft wide slabs, only two dial gages were used, set at diagonally opposite corners. No attempt was made to measure the vertical displacement of the slab due to the dilatancy of the base, a common phenomenon reported in British tests (10). The dilatancy of the support below caused by the slab movements is not mentioned at all in American literature. The general setup of the test is shown in Figure 1.

The horizontal load was applied in increments corresponding to a displacement of 0.02 in. at a time till a total displacement of about 0.1 in. was reached. The load was then released in steps until completely removed, and was then applied from the opposite direction in a similar manner until 0.10 in. movement was recorded in the reverse direction. This cycle was repeated, and generally it did not exceed 5.

DETAILS OF TEST SLABS AND BASE SUPPORTS

Ten slabs were tested, using different base course conditions. In the first series, brown tar paper 0.006 in. thick was used as an insulating medium on the base before the slab was laid. It actually consisted of two thin papers with a fine layer of hard bitumen between them. Two slabs were laid in the open on the natural subgrade over the paper, the other three slabs were cast over the paper on prepared foundations in the tank mentioned earlier. In the second series, the five slabs were laid directly on the prepared bases inside the tank. The details of the slabs are as follows.

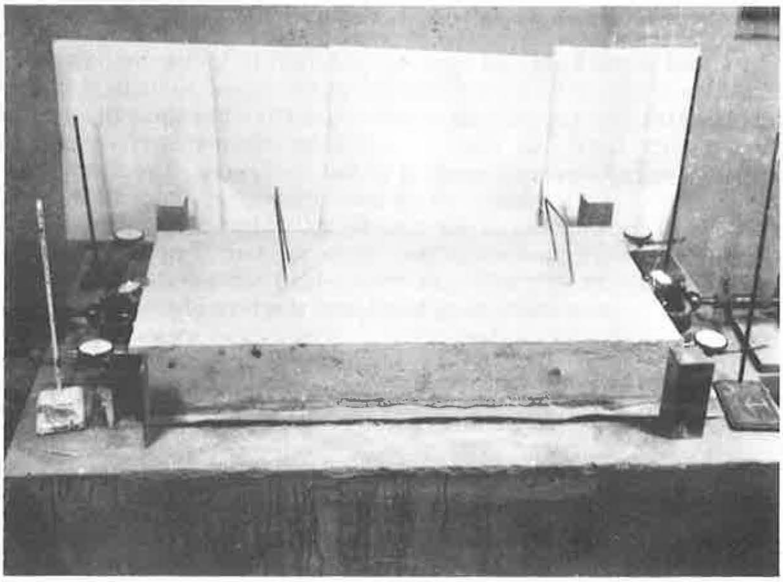

Figure 1. General setup of test to measure resistance of base to horizontal movement of slab, showing 4-ft by 2-ft by 6-in. slab on insulated paper over prepared soil base.

Series 1

1. Slab, 5 ft by 4 ft by 6 in., cast on the natural subgrade with top vegetation removed.
2. Slab, 5 ft by 4 ft by 4 in., cast on the natural subgrade with the top vegetation removed.
3. Slab, 4 ft by 2 ft by 6 in., on prepared soil subgrade.
4. Slab, 4 ft by 2 ft by 6 in., on prepared sand base.
5. Slab, 4 ft by 2 ft by 6 in., on water-bound macadam base.

Series 2

1. Slab, 3 ft by 1 ft by 6 in., on compacted damp sand base.
2. Slab, 4 ft by 2 ft by 4 in., on saturated water-bound macadam base.
3. Slab, 3 ft by 1 ft by 6 in., on saturated water-bound macadam base.
4. Slab, 4 ft by 2 ft by 6 in., on dry water-bound macadam base.
5. Slab, 3 ft by 1 ft by 6 in., on dry water-bound macadam base.

The two field slabs were originally laid for temperature measurement studies previously reported (11). The natural subgrade soil on which these were cast over insulation paper, is a fine silty sand with a classification of A-7-6. A similar procedure was adopted to push these field slabs.

Slab No. 3

The tank was filled with the subgrade soil borrowed from the site near slabs 1 and 2. The soil was compacted in two 6-in. layers at the optimum moisture content. Before casting the 4-ft by 2-ft by 6-in. slab, the insulation paper was spread on this smooth compacted soil.

Compacted Sand Base

Locally available river sand was compacted in layers to the full depth of the tank by tamping, followed by repeated flooding and draining. The surface was smoothed, and the slab cast over the insulation paper, or directly on the sand base as in the case of slab No. 4 in series No. 1 and No. 6 in series No. 2, respectively.

Water-Bound Macadam Base

The tank was filled with a 2-in. layer of compacted sand, on which a 6-in. thick laterite stone subbase was constructed. The stones were handpacked in the usual manner with smaller pieces wedged in between the larger ones. On this a 4-in. thick water-bound macadam base was constructed using 1½-in. broken stones. Locally available disintegrated gravel, known as "moorum," was used as filler material. Hand-tamping by steel rammers was employed for consolidation. For the subsequent tests the laterite subbase was not disturbed; only the water-bound macadam layer was removed and relaid with fresh materials. The top of the macadam base was cleaned with wire brushes to remove the dust and loose particles before laying the slabs.

To saturate the macadam base in the case of slabs 7 and 8 24 hr after the slabs were cast, the base was flooded with about ½-in. standing water and this condition was maintained for 10 days, after which the slabs were tested. It was presumed that this procedure represented the worst condition that can be expected during the service behavior of the slab. Figure 2 shows the base of the bonded 3-ft by 1-ft by 6-in. slab subjected to flooding by ponding before the test.

To simulate the condition of the dry water-bound macadam base for slabs 9 and 10, apart from the water used in preparing the base and the concrete no extra water was added, and the condition of the base after 10 days of air curing was arbitrarily assumed to represent a reasonably dry condition. The moisture contents of the filler material in the bases varied from 5 to 7 percent immediately after the tests. In actual field conditions in tropical areas having heavy rainfall and high relative humidity, it is reasonable to expect that the base course will always be damp due to subgrade moisture movements.

PRESENTATION OF RESULTS

The relationships between the thrusting force applied in pounds per square foot and the horizontal displacement in inches for slabs laid on the insulation paper are shown in Figures 3 to 7. It is evident that during the first test, much greater force is necessary to produce a given displacement than during the subsequent cycles; and the thrust-displacement relationship becomes stable in about 6 cycles. Such a pattern of behavior appears true even in the case of macadam base when insulation paper is provided. The paper, which adheres to the slab tenaciously (Fig. 8), provides a smooth plane for the slab to slide over the base. However, the conditions appear different when the paper is not provided. The results of the tests without insulation are shown in Figures 9 through 13.

As in the previous cases, for the bonded slabs much larger force is necessary during the first test and the initial curve is parabolic. After about 2 cycles, the force displacement curves do not indicate much variation, and equilibrium conditions appear established. The continuous thrust-displacement curves for the complete cycles in the case of the slabs bonded to saturated macadam base are shown in Figures 14 and 15. After the initial peak curve, the upper right-hand portion and the lower left-hand portion of the subsequent cycles both give forces that do not vary markedly with displacement from each other; hence in the case of bonded slabs, the testing is limited to 5 cycles.

The 4-ft by 2-ft by 6-in. slab (slab No. 9) bonded to the dry macadam base was initially subjected to repeated tests with deformations not exceeding 0.005 in., before pushing it to failure. The results of these tests are shown in Figure 16. For small displacements the macadam base and the slab bonded to it behave as an elastic and composite structure.

After the tests were completed, the slabs were lifted from their beds, and their bottom surfaces examined. Figures 17 through 21 show the bottom surfaces of the bonded slabs after test. Tables 1 and 2 give the values of the coefficients of base resistance computed for the different base course conditions. When the insulating tar paper is provided, the coefficients are considerably lower and are within the generally

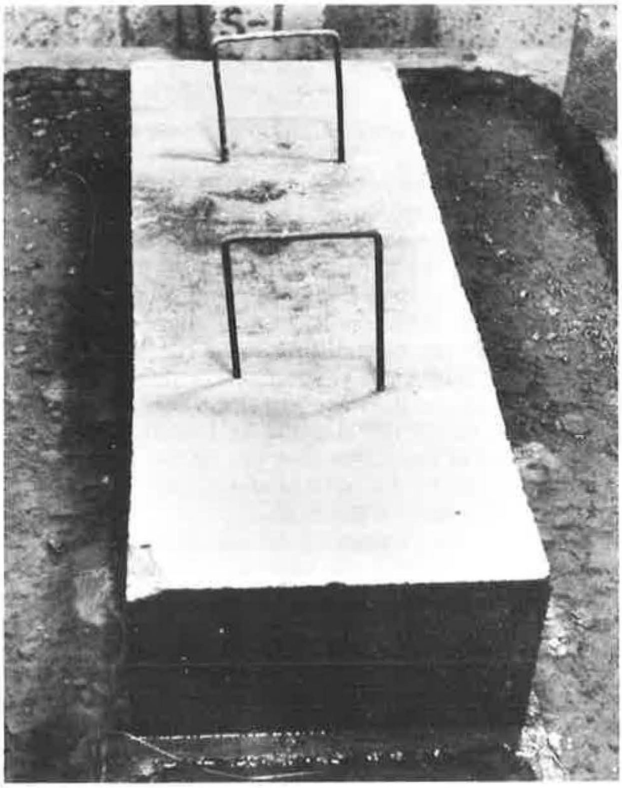

Figure 2. Slab 3 ft by 1 ft by 6 in. bonded to water-bound macadam base, before test, with base saturated by ponding.

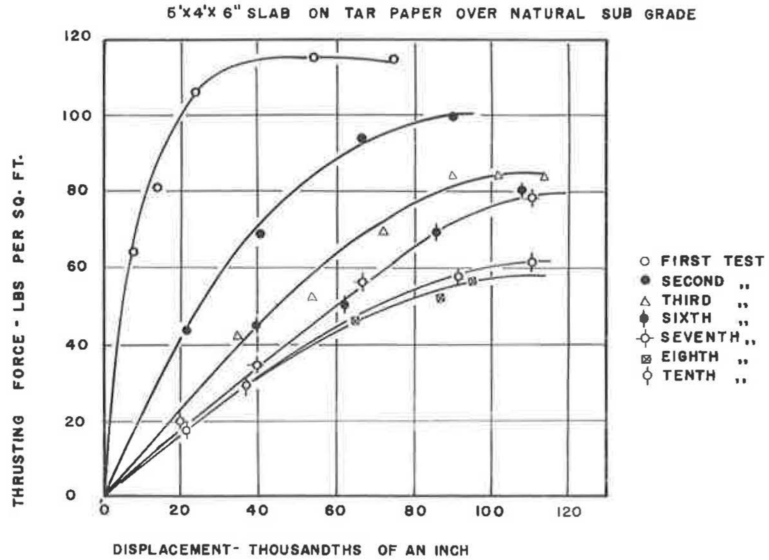

Figure 3. Force-displacement curves for repeated tests on 6-in. field slab.

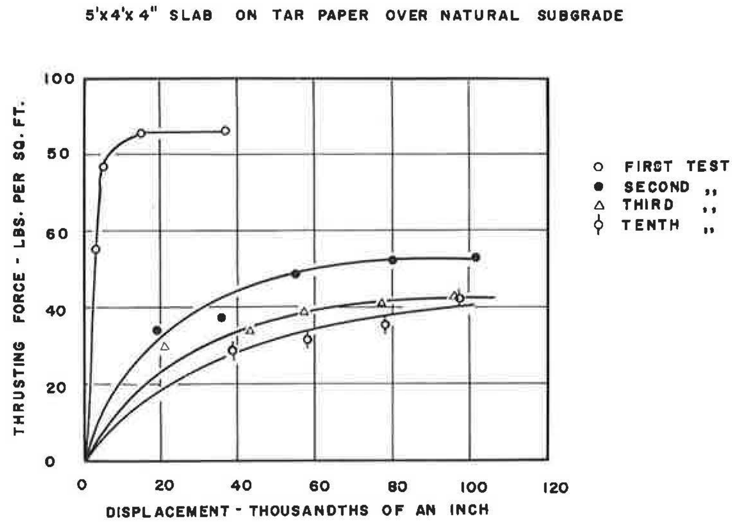

Figure 4. Force-displacement curves for repeated tests on 4-in. field slab.

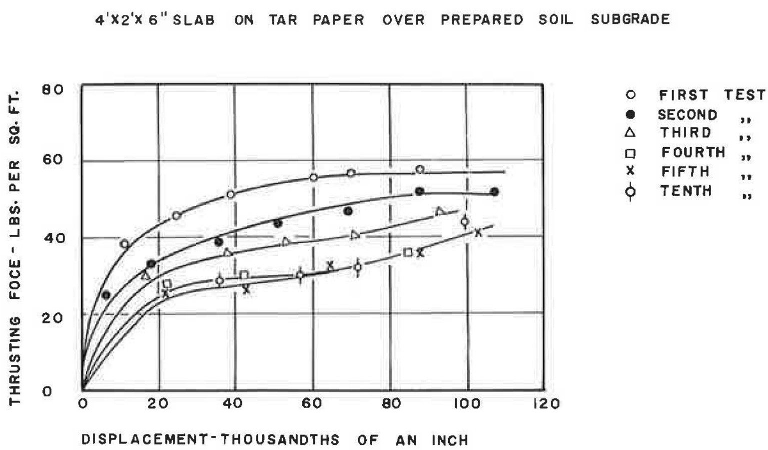

Figure 5. Force-displacement curves for repeated tests on 6-in. slab.

recommended values. In the case of slabs bonded to water-bound macadam bases, they are very much higher than the values reported by Kelly (12). Even after failure, when the slab with a portion of the base adhering to it moves over the remaining part of the base, the coefficient of resistance is greater than 1.5 for displacements larger than 0.06 in.

DISCUSSION

The data presented in this paper indicate that when the tar paper insulation is provided, the coefficients of base resistance are less than 2.0 for displacements less than 0.02 in. for the first cycle, and for the second and subsequent movements this value

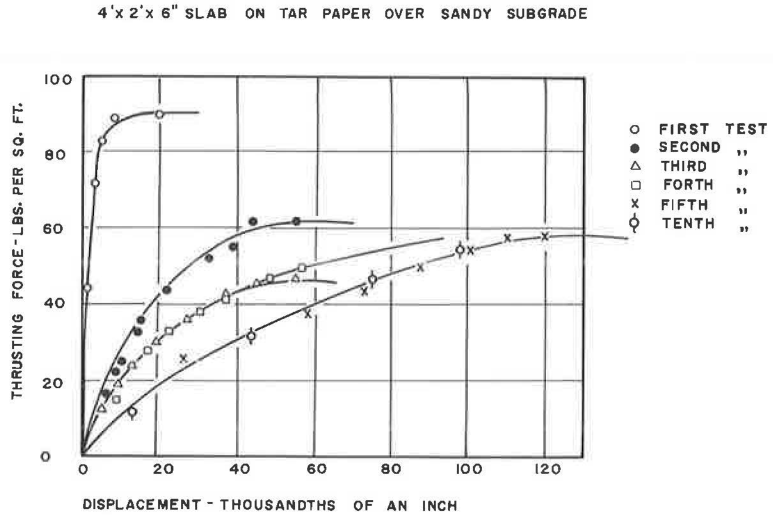

Figure 6. Force-displacement curves for repeated tests on 6-in. slab.

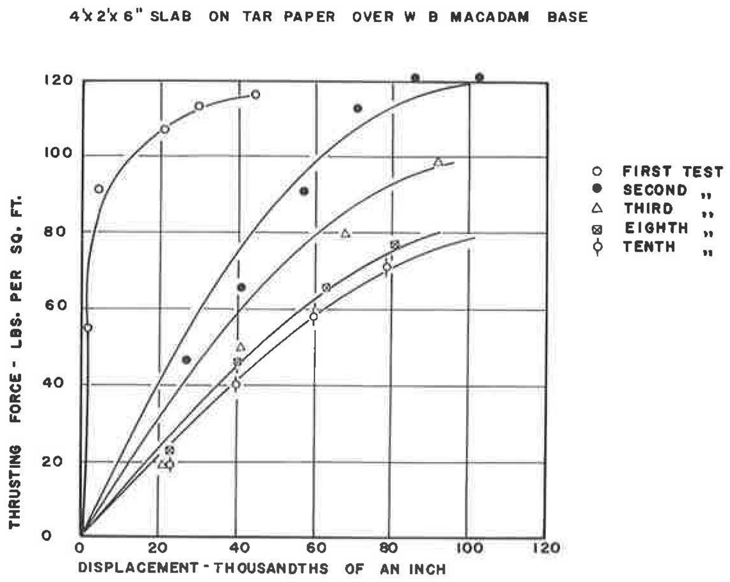

Figure 7. Force-displacement curves for repeated tests on 6-in. slab.

is further reduced and is generally less than 1.0. In the case of the slab in direct contact with the compacted damp sand base, the coefficient does not exceed 1.23 in the first test, and is less than 1.0 for subsequent displacements up to 0.06 in. The low value of the resistance may be because the locally available sand is poorly graded with subrounded particles and a fineness modulus of not more than 1.92.

In the case of bonded slabs on saturated water-bound macadam bases, for 0.05-in. displacements, the coefficients of base resistance are of the order 6.9 and 4.5 for the

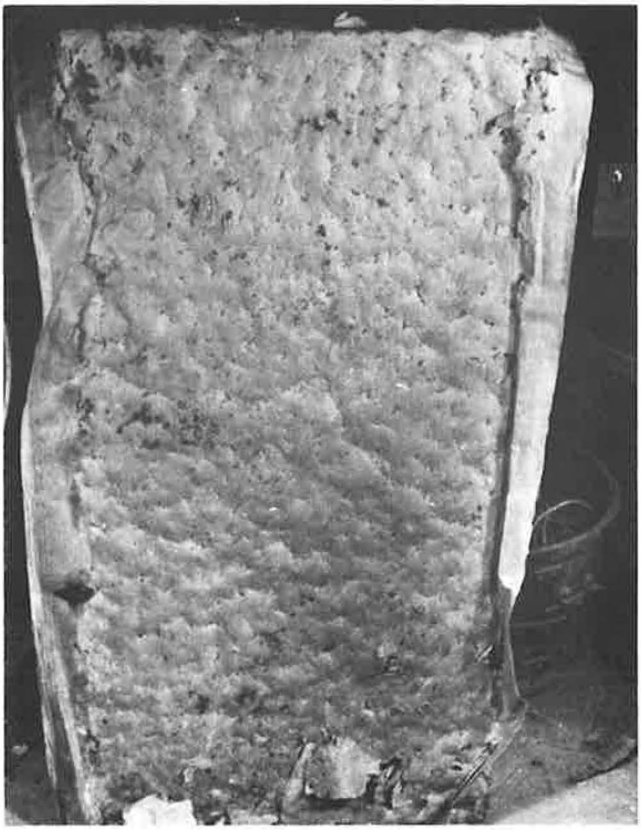

Figure 8. Underside of 4-ft by 2-ft by 6-in. slab on insulation paper over water-bound macadam base, showing scratches on paper due to pushing of slab.

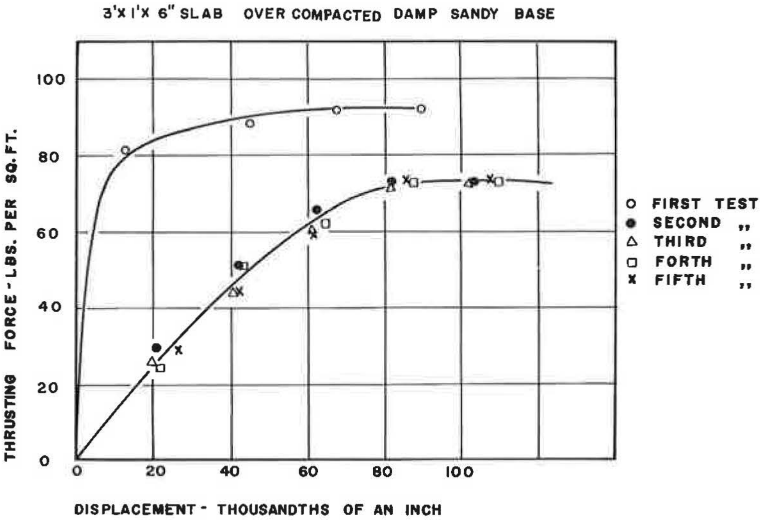

Figure 9. Force-displacement curves for repeated tests on 6-in. slab.

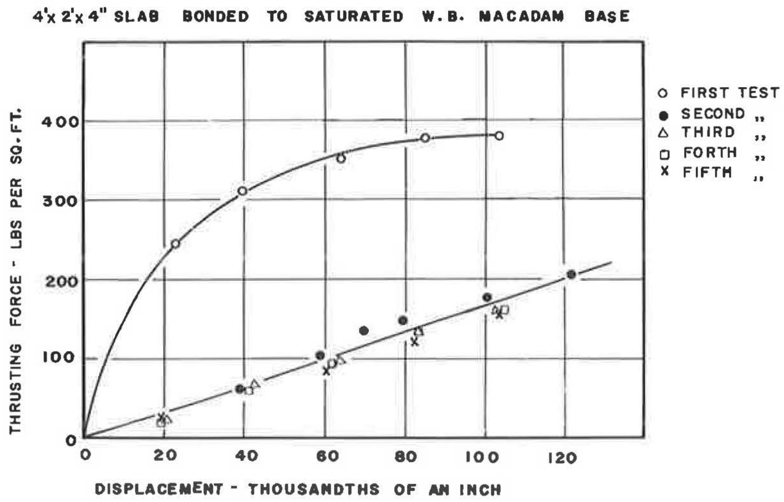

Figure 10. Force-displacement curves for repeated tests on 4-in. slab.

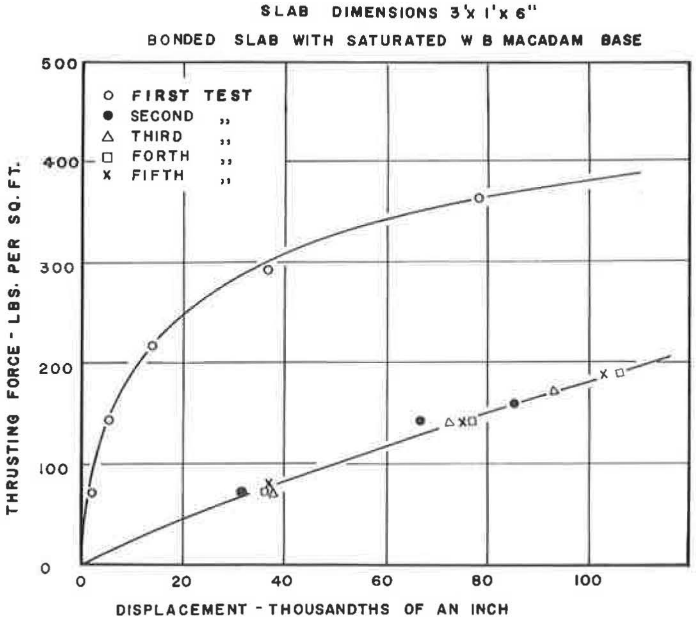

Figure 11. Force-displacement curves for repeated tests on 6-in. slab.

4- and 6-in. slabs, respectively. In other words, the thrusting force on the slabs or the restraint offered by the base for 0.05-in. displacement amounts to 330 and 324 psf, respectively. These values are in close agreement with the British recommendations (13). On dry bases, the thrusting forces vary from 550 to 600 psf. These values are higher than any known recommendations at present. It appears that for slabs laid on water-bound macadam base, the British recommendations represent the minimum values that can be expected under adverse field conditions. In actual practice, where stage construction techniques are adopted as in India, the base will be further consolidated

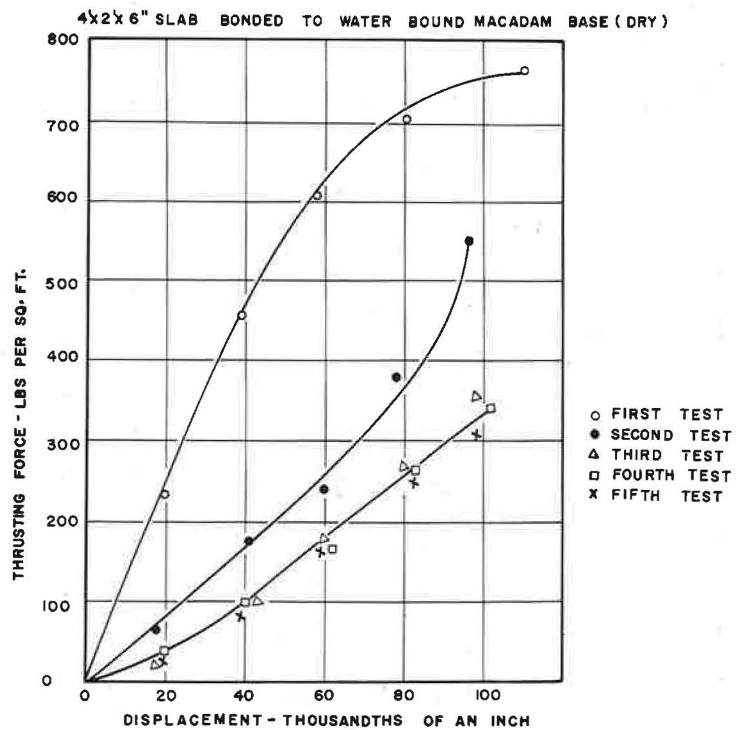

Figure 12. Force-displacement curves for repeated tests on 6-in. slab subjected to repeated tests within elastic range before this series.

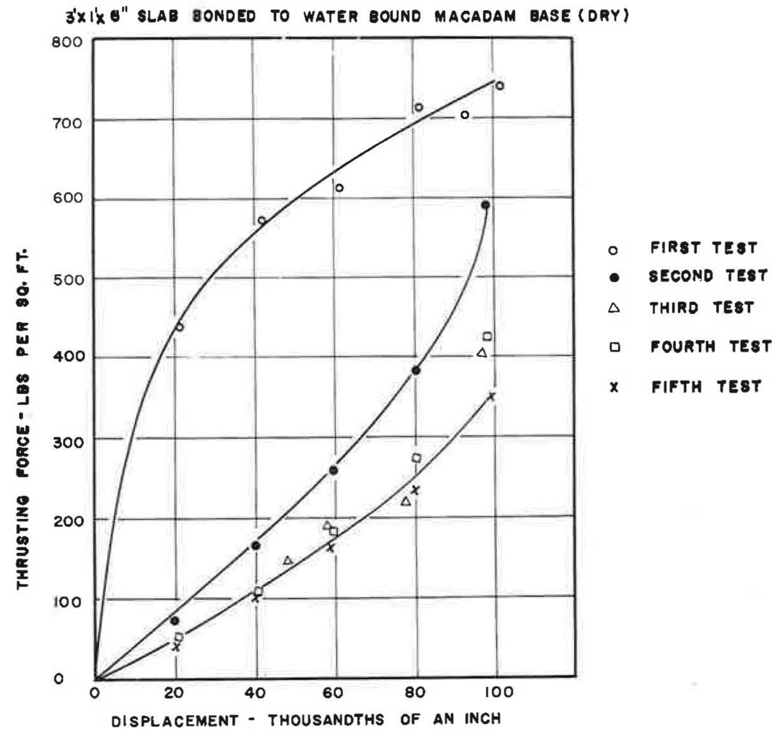

Figure 13. Force-displacement curves for repeated tests on 6-in. slab.

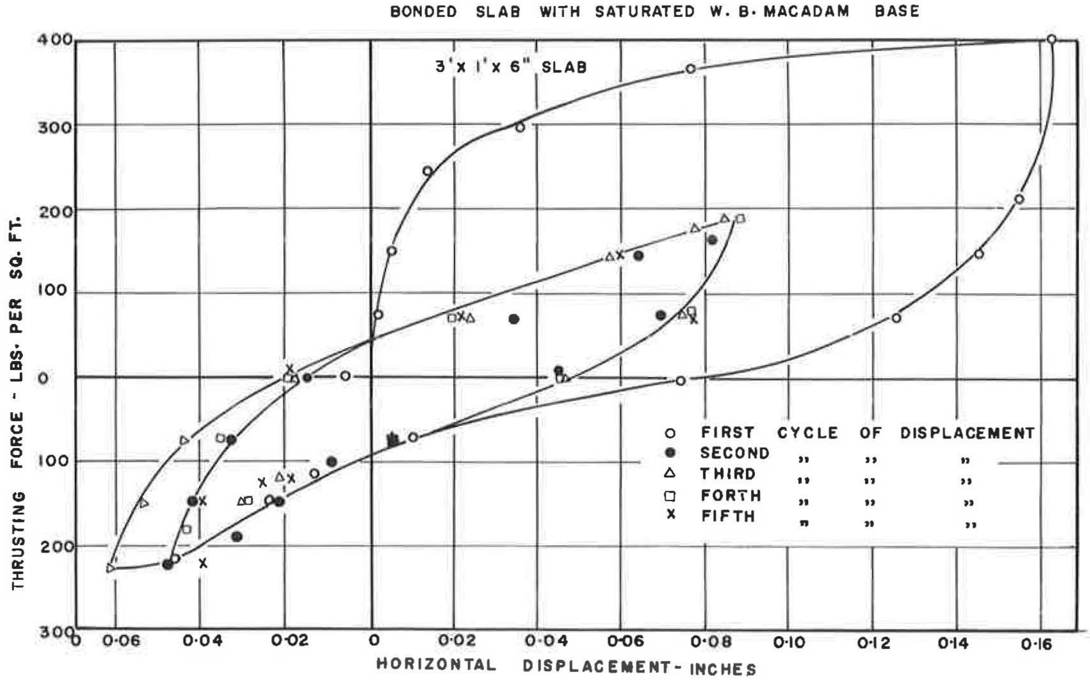

Figure 14. Cycles of force-displacement curves.

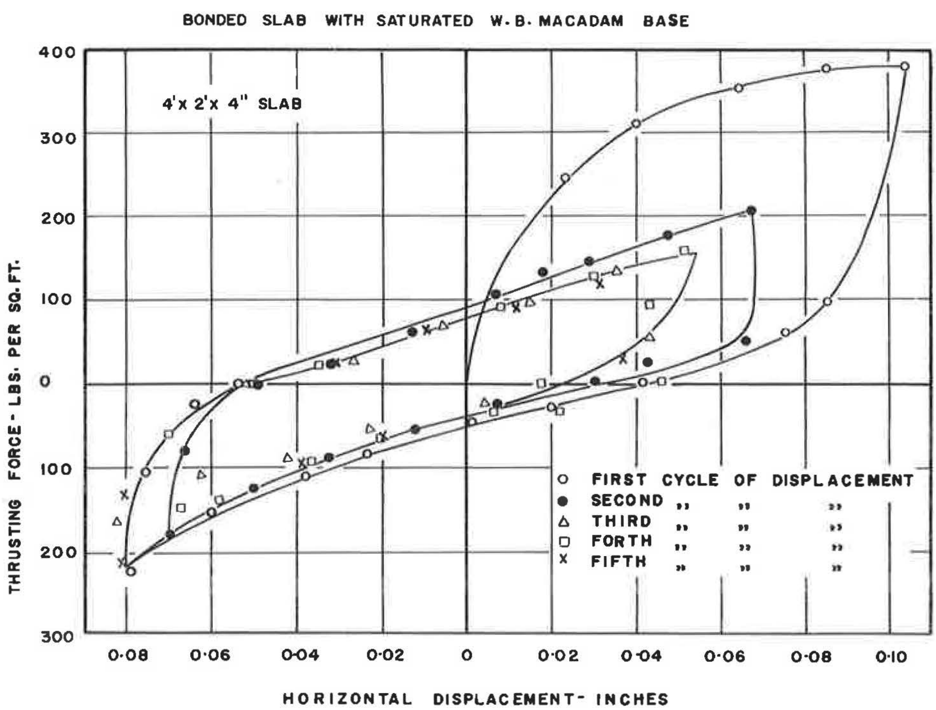

Figure 15. Cycles of force-displacement curves.

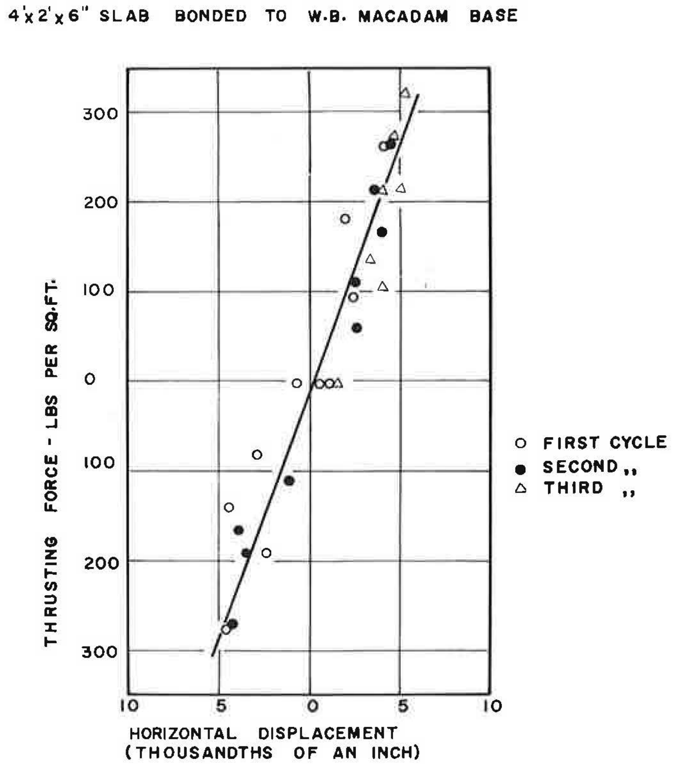

Figure 16. Force-displacement curves for repeated tests on 6-in. slab.

Figure 17. Underside of 3-ft by 1-ft by 6-in. slab bonded to a dense sand base, with masses of sand sticking to surface.

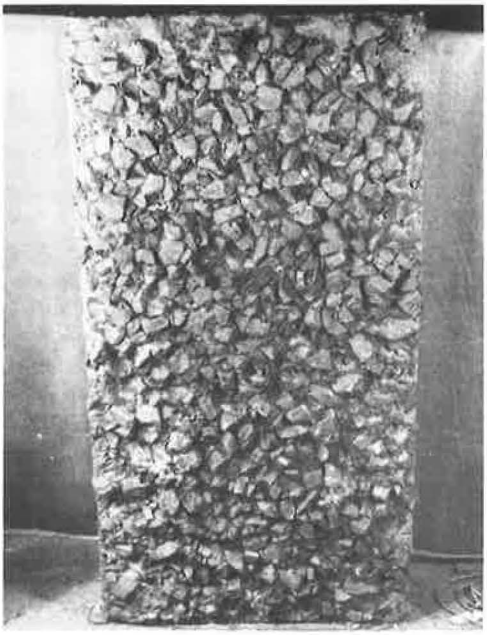

Figure 18. Underside of 4-ft by 2-ft by 4-in. slab bonded to saturated water-bound macadam base after test.

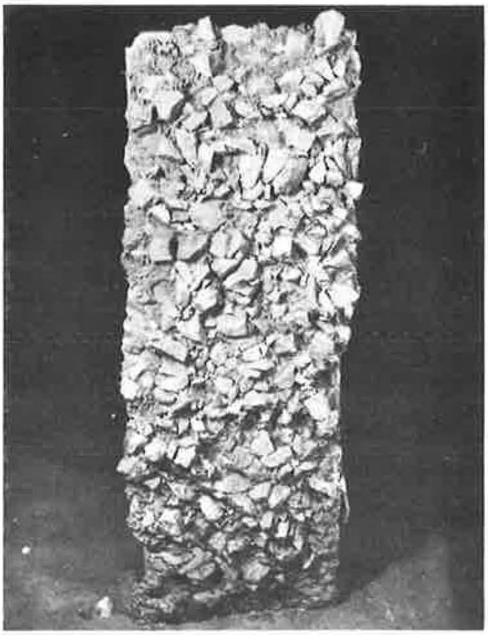

Figure 19. Underside of 3-ft by 1-ft by 6-in. slab bonded to saturated water-bound macadam base after test.

Figure 20. Underside of 4-ft by 2-ft by 6-in. slab bonded to water-bound macadam base (dry) after test.

Figure 21. Underside of 3-ft by 1-ft by 6-in. slab bonded to water-bound macadam base (dry) after test.

TABLE 1

COEFFICIENTS OF BASE RESISTANCE FOR SLABS LAID ON TAR PAPER OVER DIFFERENT BASES

Slab and Base	Coeff. of Resistance for Displacement									
	0.02 In.		0.04 In.		0.06 In.		0.08 In.		0.10 In.	
	1st Test	After Failure	1st Test	After Failure	1st Test	After Failure	1st Test	After Failure	1st Test	After Failure
5-ft by 4-ft by 6-in. field slab	1.39	0.22	2.43	0.44	2.43	0.61	2.43	0.72	2.43	0.80
5-ft by 4-ft by 4-in. field slab	1.76	0.37	1.76	0.58	1.76	0.71	1.76	0.79	1.76	0.83
4-ft by 2-ft by 6-in. slab on prepared subgrade	0.61	0.32	0.72	0.39	0.76	0.41	0.79	0.48	0.79	0.57
4-ft by 2-ft by 6-in. slab on compacted damp sand base	1.25	0.29	1.25	0.43	1.25	0.65	1.25	0.66	1.25	0.73
4-ft by 2-ft by 6-in. slab on water-bound macadam base	1.88	0.28	2.44	0.56	2.44	0.82	2.44	1.00	2.44	1.11

TABLE 2

COEFFICIENTS OF BASE RESISTANCE FOR BONDED SLABS ON VARIOUS BASES

Slab and Base	Coeff. of Resistance for Displacement									
	0.02 In.		0.04 In.		0.06 In.		0.08 In.		0.10 In.	
	1st Test	After Failure	1st Test	After Failure	1st Test	After Failure	1st Test	After Failure	1st Test	After Failure
3-ft by 1-ft by 6-in. slab on compacted damp sand base	1.17	0.34	1.23	0.62	1.26	0.86	1.28	1.00	1.28	1.00
4-ft by 2-ft by 4-in. slab on saturated water-bound macadam base	4.70	0.52	6.46	1.45	7.30	2.10	7.81	2.71	7.81	3.33
3-ft by 1-ft by 6-in. slab on saturated water-bound macadam base	3.47	0.69	4.30	1.17	4.72	1.67	5.14	2.08	5.27	2.50
3-ft by 1-ft by 6-in. slab on dry water-bound macadam base	6.11	0.70	7.64	1.51	8.70	2.43	9.58	3.47	10.14	4.86
4-ft by 2-ft by 6-in. slab on dry water-bound macadam base[a]	3.48	0.55	6.53	1.38	8.68	2.44	10.00	3.61	10.44	4.58

[a]Slab subjected to repeated cycles of initial displacements not exceeding 0.01 in. before test.

by traffic and time, and under reasonably well-drained conditions will offer strong restraint to the failure of the base by shear.

Cracks in Base

During the tests with the bonded slabs, for a displacement of about 0.05 in., a small horizontal crack began to develop in the base course about 1 in. from the edge of the face on which the jack was applied, and it extended to the full width of the tank. The disposition of these surface cracks is shown in Figures 22 and 23. They became wider with further pushing of the slab. A few cracks were also seen along the direction of movement, at an angle of about 45 F and extending away from the longitudinal edges of the slab. When the direction of the thrust was reversed, the cracks in the base previously formed closed themselves, and a fresh set of cracks, similar in pattern, occurred on the pushing side. With repeated tests the cracks at the farther end did not disappear as they did in the initial stages. The result was that at the end of the five cycles cracks approximately ⅛ in. wide extending to the full width of the base inside the tank near the transverse faces of the slabs could be clearly seen. In other words, the repeated tests revealed that with the bonded slabs, all the distress that occurred took place in the base course, and the slab simply served as a bonded surcharge initiating the movements leading to the final failure by shear inside the base.

DILATANCY OF BASE

Sparkes (10) mentions that the base course below the slab dilates or increases in volume whether the slab expands or contracts. It is well known that in direct shear tests, dense soils expand and loose soils reduce in volume (14), and this dilatancy is maximum for sandy soils and minimum for clays. Concrete roads are rarely laid directly on clayey soils, and since only compacted granular material is commonly used

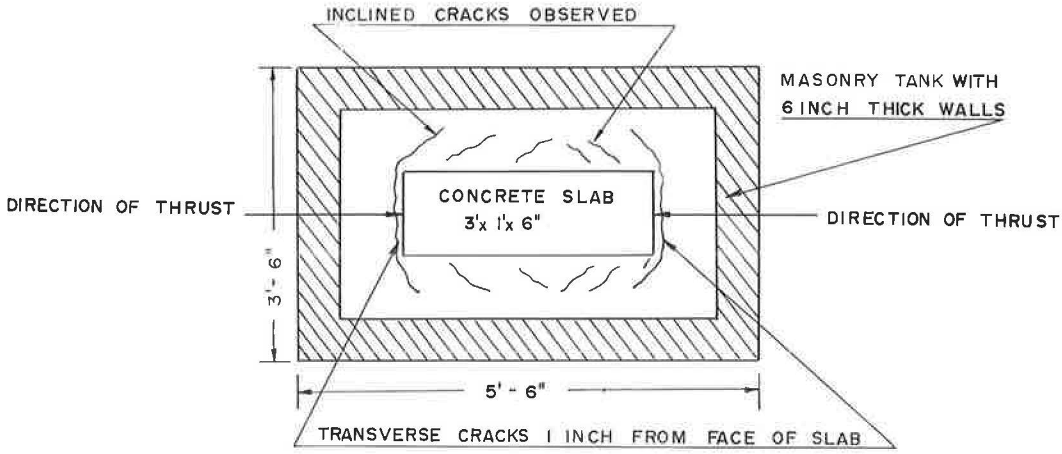

Figure 22. Disposition of surface cracks in the base of bonded slab.

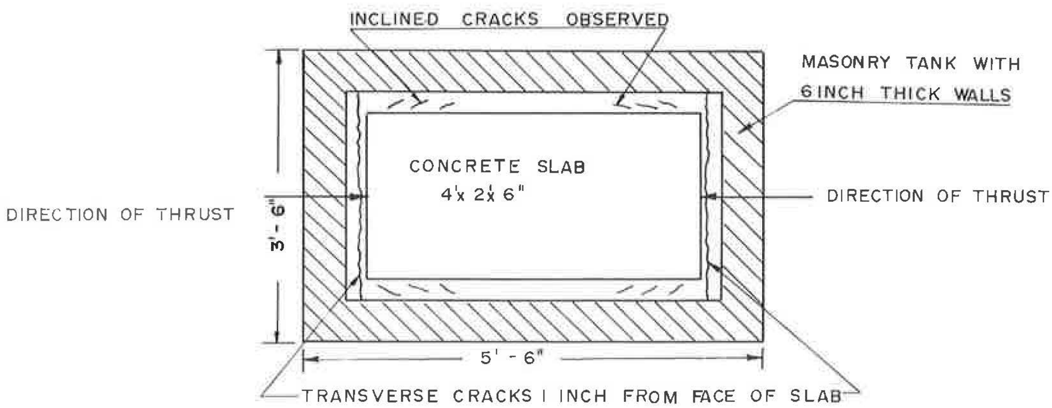

Figure 23. Disposition of surface cracks in the base of bonded slab.

under a concrete pavement, the shear deformation initiated by the expanding or contracting slab causes dilatancy. These observations along with the data presented herein indicate that it is the shear resistance of the soil immediately below the slab that has to be reckoned with in resisting the horizontal strains induced by the slab due to variation in its average moisture and temperature. Contrary to what is generally accepted, the actual plane of failure is inside the base, and not at the interface between the slab and the support below.

ACKNOWLEDGMENT

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