EVALUATION OF THICKNESS DESIGN CONCEPTS FOR BLOCK PAVEMENTS

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SUMMARY

This paper reviews several basic concepts involved in the design of block pavements. Comparisons of block pavement test section performance to that predicted by conventional flexible pavement design theory shows that block pavements can be designed within conventional flexible pavement concepts. This requires use of an equivalent thickness or equivalent modulus for the block surfacing, and current recommendations for both are examined. Special block characteristics such as effect of laying pattern on performance must be considered, but two widely debated aspects (block shape and lock up) probably have relatively minor effects on thickness design.

INTRODUCTION

A variety of block pavement thickness design methods have been offered in the preceding three international block pavement conferences and in various other publications over the years. This paper will review and compare some of the basic behavior characteristics of block pavements that affect these different design procedures. Although this paper will concentrate on thickness design procedures, there is much more to pavement design than simply selection of a thickness for the pavement. Material strengths, especially in the subgrade, must be correctly estimated, appropriate materials for the base and subbase must be selected, appropriate bedding and jointing sands must be identified, drainage must be considered, and construction must be carried out. In conventional pavements, errors in thickness design are relatively seldom the cause of pavement failure in the field, but instead problems such as unexpected site conditions, improper selection or specification of materials, inadequate maintenance, or faulty construction are more likely to be the culprits [1]. Similar observations have been made for block pavements [2].

PAVEMENT BEHAVIOR

Investigators of block pavements have almost universally agreed that block pavements behave as flexible pavements rather than rigid pavements [e.g., 3, 4, 5, or 6]. in flexible pavements, the load applied to the pavement surface is distributed by a relatively thin wearing surface, such as asphaltic concrete, and the underlying base and subbase layers

to the natural soil subgrade. When the stresses on the subgrade from the traffic loads are sufficiently large, the subgrade will shear and displace causing rutting in the subgrade which appears as a surface rut. Classic failure of flexible pavement is rutting due to shear deformations in the subgrade, and all flexible design procedures consider this failure mode. In the last few years, other failure modes such as fatigue cracking of the asphaltic concrete surface or stabilized base layers have been added to some design procedures, but subgrade shearing remains as the most crucial element. While a complete discussion of flexible pavement design philosophy is outside the scope of this paper and is available in standard texts [e.g., 7], the basic design concepts can be summarized as providing:

- Sufficient pavement thickness to protect the subgrade
- Quality base and subbase material to carry applied loads
- Stable surface to provide wearing course for traffic
- Compaction to provide strength and resist densification

It is well established now that the paving block surface behaves as a coherent, interacting structure rather than as an assemblage of independent rigid bodies loosely linked by sand filled joints. The ability of blocks to develop interaction and effectively distribute loads has been established by a wide variety of plate load tests [e.g., 8 or 9], pullout tests [e.g., 10 or 11], observations of in situ pavements [e.g. 12 or 13], and accelerated trafficking tests of specially constructed block test sections [e.g., 3, 5, or 6]. As with all flexible pavements, the primary failure mode observed for block pavements is rutting. Block breakage and spalling are a secondary problem usually associated with large ruts.

COMPARISON WITH COB CRITERIA

In order to evaluate how block pavement performance compares to conventional flexible pavement design criteria, block accelerated traffic tests were reanalyzed and compared to the Corps of Engineers (COE) CBR flexible pavement design criteria. The Corps of Engineers conventional CBR flexible pavement design criteria was selected for this comparison because it is one of the best documented and widely used approaches for design of flexible pavements. Complete descriptions of this design approach and its background) can be found in a number of references [7, 14, and 15]. Tliis criteria selects a thickness of pavement (surface, base, and subbase) that will prevent shearing in the subgrade that would develop a 25 mm rut. This system evaluates the subgrade strength in terms of its CBR and treats the pavement system as an elastic half space (i.e., no differentiation is made between the relative stiffness of the different layers) . The block pavement test sections used in this analysis include those described in references 3, 4, 5, 16, and 17. Only test sections that reported all required parameters in sufficient detail to allow analysis, that used good quality base materials so that rutting was limited to the subgrade, and that trafficked the sections with a single sized traffic load were included in the analysis. Failure for this analysis was defined as a 25 mm rut. Other investigators have proposed rutting

failure criteria for block pavements varying from 10 mm [18] to 40 mm [19]; however, 25 mm is consistent with the COE CBR criteria and is widely used for flexible pavements.

Figure 1 shows the block test section data plotted with the COE CBR criteria. The CBR criteria is the solid line. Points plotting below and to the right of the line would not be expected to fail while those points plotting to the left and above the line would be expected to fail according to the Corps criteria. The plot in Figure 1 includes the effects of total pavement thickness (sum of subbase, base, sand bedding layer, and block, "t"), size of the load (square root of tire contact area, "SQRa"), subgrade soil strength (CBR), and intensity of load in terms of tire pressure and equivalent single wheel load (ESW tire pressure, "P^"). Complete descriptions of the ESW tire pressure concept and details of calculation can be found in reference 7 or 15. Essentially the ESW concept, as used here, replaces multiple wheel gears with an equivalent single wheel that would cause equal deflection at the subgrade surface according to Boussinesq elastic half space theory. This allows the data from tests such as the WES tests [5] that trafficked the test sections with a tandem axle with dual tires to be analyzed with the data from tests such as the South African tests [4] that trafficked test sections with a single tire.

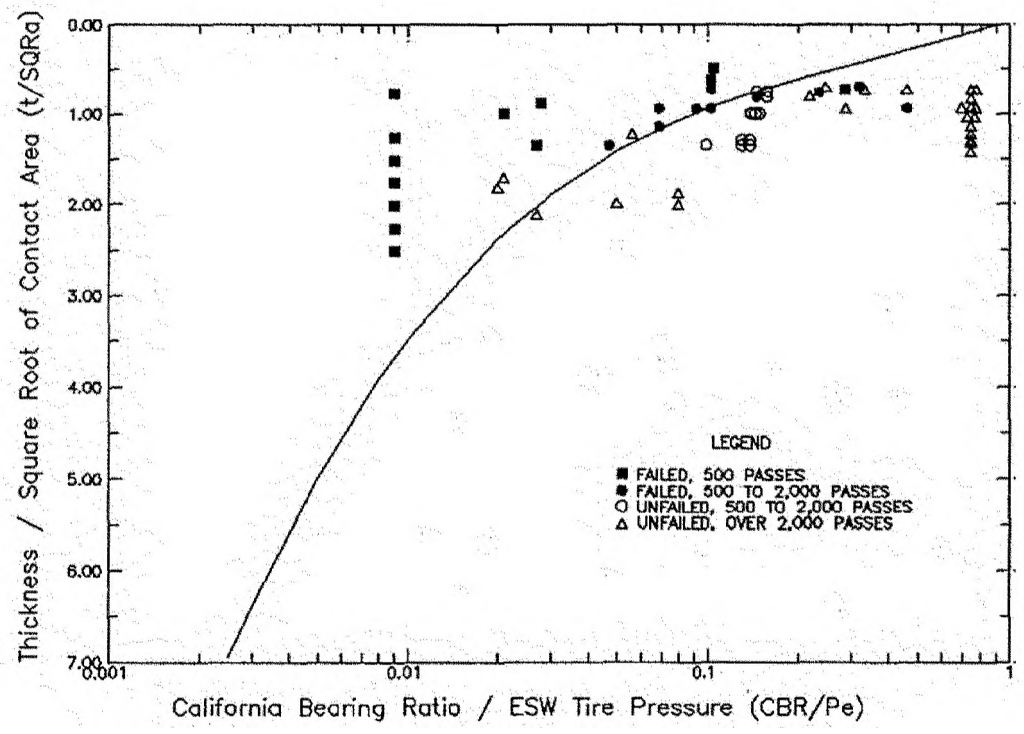


Figure 1. Comparison of Block Test Section Data with Conventional COE Design Criteria.

The data in Figure 1 agree reasonably well with the existing COE flexible pavement criteria. There are four failing points that are significantly below the COE criteria line. Two of these points failed at relatively high traffic levels (1,500+). The base course for these four tests was poor quality, more

representative of a subbase than a base course material [4]. Consequently, rutting and failure could have been occurring in the base rather than in the subgrade. As mentioned before and as should be clear in considering the axes parameters in Figure 1, rutting in the base is not handled by this type of analysis. Base course load carrying capacity is normally addressed in the material specification rather than in the design analysis.

The result of the analysis shown in Figure 1 strongly supports the general contention that block pavements behave and can be designed as flexible pavements. This type of analysis clearly shows that block pavements are a conventional load carrying pavement and that the block surface fits within the parameters of conventional flexible pavement theory.

EQUIVALENT THICKNESS CONCEPTS

One approach to block pavement design is to determine the equivalent thickness of conventional paving material that would provide the same equivalent performance as the block and sand surfacing layer. Several investigators have done this by equating the stress distribution measured by pressure cells under block pavements to that predicted by elastic theory. From such results the block and sand surface can be equated to an equivalent thickness of asphaltic concrete, base course, or combination of these that would reduce stresses to the same level as measured under the block and sand bedding layer. Also trafficking tests can be used to develop an equivalent thickness for the blocks based on block performance under traffic. Table 1 shows several such equivalent thickness relations. All of the investigators listed in Table 1 agree that the block surface is equivalent to some greater thickness of conventional flexible pavement material, however the specific ratio varies.

These equivalent thickness relations are a convenient method of adapting existing flexible pavement design methods to include block pavements (e.g., 5 and 8). The pavement is first designed using the existing flexible design method. Then the block surface and sand bedding layer are converted to an equivalent thickness of conventional flexible pavement material. The required thickness of pavement under the blocks is then simply the difference between the conventional design thickness and the block surface's equivalent thickness. While this is a convenient design expedient, it is not a theoretically rigorous approach.

EQUIVALENT MODULUS CONCEPTS

No conventional pavement material (e.g., asphaltic concrete, portland cement concrete, crushed stone, or natural sands and gravels) is truly elastic. However, these materials are often treated as elastic in pavement design theory so that analytical solutions can be formulated for calculating engineering functions such as stress, strain, or displacement. Like other pavement materials, paving blocks are not truly elastic; they are composed of relatively rigid bodies with flexible sand-filled joints. However, if an effective or equivalent modulus of elasticity can be determined for the block and sand bedding layer, conventional pavement theory can be used to design block pavements.

Table 1. Block Equivalent Thickness Relations

Reference	Material	Ratio Block to Material Thicknesses	Basis
20	Granular Base	2.5	Experimental
8	Asphaltic Concrete	1.24	Plate Tests & Elastic Theory
4	Asphaltic Concrete	1.1 to 1.5	Tr. Tests
	Crushed Rock Base	2.1 to 2.9	Tr. Tests
19	Asphaltic Concrete	1.02 to 1.08	Static Tests & Elastic Theory
5	Flexible Pavement (Asphaltic Concrete and Base)	1.6	Ref. 8 plus Tr. Tests
21	Asphaltic Concrete	1.50	80 mm Block
		1.61	65 mm Block
		1.67	60 mm Block
		1.80	50 mm Block

The data from failed test sections in Figure 1 were analyzed to determine the equivalent modulus of elasticity that would predict the coverage level at which failure occurred for the test section. The pavement and loading was modeled using layered elastic theory. To use this analytical model each layer of the pavement must be characterized by a modulus of elasticity. The subgrade modulus of elasticity was estimated from a common CBR correlation [22] which is most appropriate for relatively soft, fine grained soils. The modulus of elasticity for granular materials such as those used in base and subbase courses is highly dependent on the state of stress that is acting on the material. For this analysis, the modulus values for base and subbase materials were assigned according to the procedures in reference 23 which are used by the Corps of Engineers and Federal Aviation Administration for their layered elastic analysis of flexible pavements.

The critical engineering parameter for rutting in flexible pavements is the vertical subgrade compressive strain. For this analysis, the allowable vertical subgrade strain was calculated using a procedure proposed in reference 23. This relation determines the allowable subgrade strain as a function of the subgrade modulus of elasticity and the number of load cycles. This relation is consistent with the 25 mm rut failure definition for flexible pavement [23].

The allowable vertical strain for each failed test section was calculated by substituting the number of traffic passes at failure for the number of load cycles in the allowable strain relation. The effective modulus of elasticity for the block and sand layer that corresponded to the failure traffic was then calculated by varying the modulus of elasticity for the block and sand layer until this allowable subgrade strain was reached. In eleven of the twenty-seven cases, the limiting subgrade strain was not reached even at very low block modulus values, and an effective modulus could not be determined. These cases either had high CBR subgrades, thick base courses, or were the South African tests with the low quality base course. Deformations may

have been occurring in the bases rather than in the subgrade for these tests.

Table 2 shows range and mean values for these calculated effective modulus values from failed test sections. Block shape had a negligible influence on the results, but subgrade strength had a major impact on the effective block modulus values. As subgrade strength decreases the calculated effective modulus increases. Previous plate load tests [8 and 24] found the resistance of blocks to deflection increased as the subgrade support decreased which is consistent with results in Table 2.

Table 2. Mean Effective Modulus Values from Failed Test Sections

	Effective Modulus of Elasticity (MPa)	
	Range	Mean
All Results	214 - 2,585	1,172
Shaped Blocks	214 - 2,585	1,179
Rectangular Blocks	296 - 1,648	1,151
Subgrade CBR 2 -4	1,027 - 2,337	1,648
Subgrade CBR 5-10	214 - 2,585	889
Subgrade CBR >10	593 - 641	613

Other investigators listed in Table 3 have also proposed effective modulus values for the block and sand bedding layer based on matching measured surface deflections with theoretical calculations while others are based on field tests or experience. The values in Table 3 range from 214 to 12,400 kPa, and no clear consensus exists between different investigators on appropriate modulus values. An effective block modulus value in the range of 1,100 to 4,500 kPa would appear to be consistent with the mean test values or recommendations of most of the investigators. Further precision in estimating the modulus value is not possible with the data currently available. The use of an equivalent modulus of elasticity with other conventional flexible pavement design criteria has been the basis of several recommendations for design based on layered elastic theory (e.g., 26, 29, and 32).

SPECIAL BLOCK CHARACTERISTICS

The block factors such as shape, thickness, laying pattern, and strength can all affect design. These topics were discussed extensively in previous conferences, and there is probably a general consensus that (1) thicker blocks do better than thinner with most improvement being seen as thickness increases from 60 to 80 mm, (2) herringbone laying patterns do better than others, and (3) block strength within the ranges normally encountered does not affect performance under traffic but may have a major impact on durability. The importance of block shape and the concept of "lock up" remain topics of sharp debate, however.

Past debate over block shape can be divided into two diametrically opposed groups: those who believe shaped blocks perform better than rectangular [e.g., 4] and those who believe

Table 3. Equivalent Modulus of Elasticity Values for Paving Block

Reference	Block Shape	Block Thick. (mm)	Equiv. Modulus (MPA) Range	Equiv. Modulus (MPA) Mean	Basis
3	Rect.	80	— —	900	For Design
19	Shaped	80	——	1,620	Deflection
13	Shaped	80	——	4,330	Deflection
25	Shaped	80	——	410	Defl. Bowl
26	——	——	—	7,600	For Design
27	——	— —	290 - 1,160	—	Deflection
	——	— —	58 - 290	—	For Design
28	——	80	— —	800	FWD
	—• —	100	450 - 950	--	FWD
29	Shaped	——	1,570 - 12,495	3,400	FWD
	Rect.	——	500 - 7,000	2,975	FWD
	— —	——	2,800 - 3,400	— —	Tr. Tests
30	Shaped	80	214 - 620	—	FWD
31	— —	80	— —	4,480	For Design
Table 2	All	— —	214 - 2,585	1,172	Tr. Tests
	Shaped	—	214 - 2,585	1,179	Tr. Tests
	Rect.	— —	296 - 1,648	1,151	Tr. Tests
	Low Str. Subgrade, CBR 2-4		1,027 - 2,337	1,648	Tr. Tests

FWD - Falling Weight Deflectometer
For Design - Recommended by Reference for use in Design

rectangular blocks perform better than shaped [e.g., 26]. There has always been some question if the data clearly supported either camp in this debate [32], and tests by researchers not associated with the debate have failed to find conclusive support for either side [6 and 19].

Figure 2 shows the data from Figure 1 replotted to reflect block shape. This type of plot includes the effect of block shape, subgrade strength, load severity, and pavement thickness, and no clear superiority of one block shape over another is apparent. There are two possible exceptions to this at x, y coordinates of approximately (0.15, 0.78) and (0.33, 0.73). At the first location, a type A block (Uni-Stone) failed, and three Anchorlock pavements did not under similar loading and subgrade conditions. This supports findings by Shackel that Anchorlock pavements perform better than other block pavements although he noted that data was insufficient to quantify this difference [15]. At the second point, a type C block (rectangular) failed when a type A Uni-Stone did not under similar conditions. However, the rectangular block had been laid in stretcher bond while the shaped block had been laid in herringbone pattern which is generally recognized as the superior laying pattern. Consequently, the effects of shape cannot be separated out from the effects of laying pattern. Otherwise, blocks that plot close together in Figure 2 behave similarly regardless of shape. Consequently, the block shape does not appear to be sufficiently important to cause a noticeable effect on thickness design, and its effect may be masked by other more important parameters.

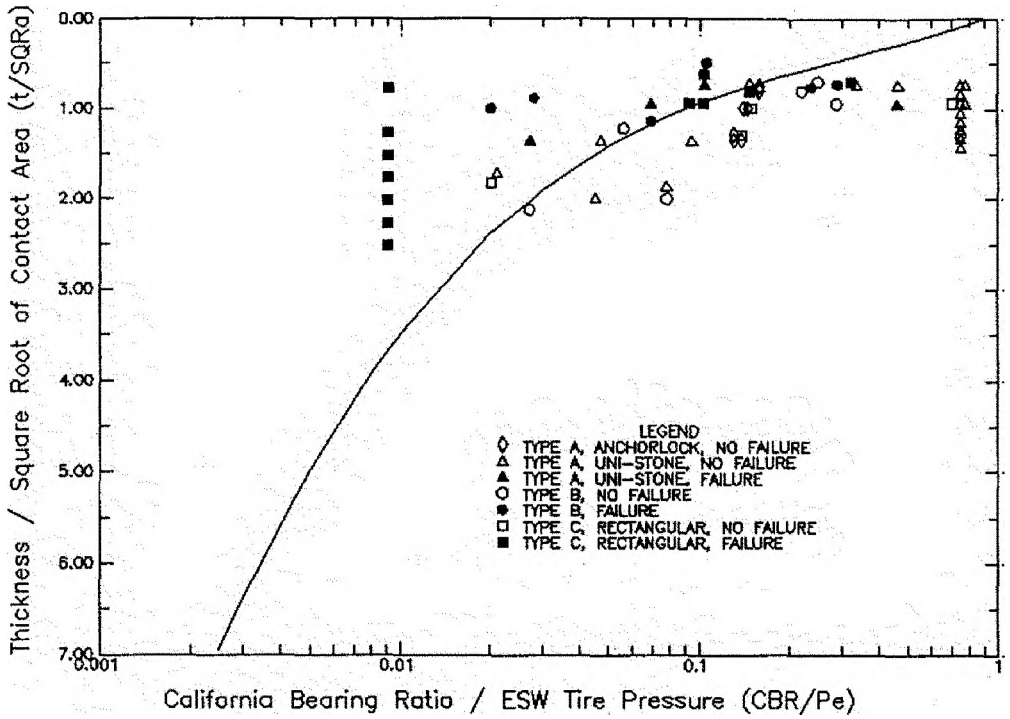


Figure 2. Effect of Block Shape on Test Section Results

Numerous investigators have noted the tendency of block pavements to progressively stiffen under traffic, and this has been referred to as "lock up." This stiffening or lock up has led to some proposals that after a block pavement locks up, it is essentially unaffected by further applications of traffic or increases in wheel load. This is overly optimistic, since regardless of how stiff the blocks become, the stresses do not disappear and they must ultimately be carried by the subgrade.

Metcalf and Sharp [33] first raised the question "do we take the term (lock up) too seriously?" This is probably a valid question, and Rollings [32] showed that conventional flexible asphaltic concrete pavements showed the same range of behavior as block pavement including lock up. Stiffening of the block under initial traffic does occur and is beneficial. This occurs relatively rapidly, and it is probably sufficient to design block pavements on the basis of an average modulus value after this stiffening has occurred. An exception to this may be pavements that are designed for only a few repetitions of load.

CONCLUSIONS

Block pavements are flexible pavements, and comparisons of their behavior with that expected of conventional flexible pavements indicates that block pavements can comfortably be designed within the framework and philosophy of conventional flexible pavement design. In order to accomplish this design, the block layer must be represented as some equivalent thickness of conventional material or it must be assigned some equivalent

modulus value. Table 1 shows several relations for equivalent thickness of the block pavement surface that have been proposed. The concept of an equivalent block modulus is more complex, and as seen in Table 3, there is considerable scatter in suggested values. At present, a selection of a modulus value in the range of 1,100 to 4,500 kPa is probably as specific guidance as is justified by the current data. This range in possible values is not as significant as it at first appears because small variations in subgrade modulus values have much greater impact on the results of mechanistic flexible pavement design methods than do relatively large changes in surface layer modulus value [6]. The special details of block design must be addressed (e.g., laying pattern) , but the two special block characteristics of shape and lock up have probably only a small impact on actual thickness design under most circumstances.

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