without rupturing. From the limited tests performed on the rubber asphalt, it appears to have all the desirable properties, an observation that is supported by reports (1, 2) of its successful performance in practice.

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Attempts to Reduce Reflection Cracking of Bituminous Concrete Overlays on Portland Cement Concrete Pavements

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Studies of methods used in Virginia to reduce the incidence of reflection cracking when portland cement concrete pavements or bases are overlaid with asphalt concrete are reported. The methods discussed are (a) the use of sand to break the bond between the portland cement concrete pavement and the asphalt overlay and (b) the use of a fabric that has a high tensile strength as a stress-relieving layer between the asphalt layer and the concrete base. The studies showed that neither the sand bond breaker nor the high-strength fabrics are effective in reducing reflection cracking where differential vertical joint movements are a significant factor. Further studies showed that high-strength fabrics can delay the onset of reflection cracking but that such cracking will eventually develop under the application of repetitive wheel loadings.

The transverse joints in rigid pavements commonly reflect through bituminous concrete overlays in a short time. Many highway engineers believe that these reflection cracks are detrimental to pavement riding quality, and others believe that they are generators of future maintenance problems because they provide surface water ready access to subsurface pavement layers (1). Recent studies support this latter belief; it has been reported that a crack only 0.9 mm (0.035 in) wide will admit 70 percent of the surface water that falls on a pavement sloped 1.25 percent under a 50-mm/h (2-in/h) rate of precipitation (2).

METHODS USED

Numerous attempts to reduce reflection cracking have been reported in the literature. A good summary of those that have been at least partially successful is given in the National Cooperative Highway Research Program Synthesis on Pavement Rehabilitation (1). In that document, most of the methods attempted are grouped into four general classifications: (a) increased thickness of the asphalt concrete (AC) overlay, (b) special treatment of the existing PCC pavement, (c) special consideration of the AC overlay design, and (d) treatment of joints and cracks.

In Virginia, most of the methods in categories a through c have been rejected for economic or other reasons. The category d methods used in Virginia all consist of some method of breaking the bond or otherwise relieving the stress between the PCC and the bituminous concrete overlay. The first attempts to provide a bond breaker were reported by Hughes, who found that a thin layer of sand spread on either side of the PCC pavement joints before the application of a bituminous concrete overlay was partially successful in reducing reflection cracking. In his studies, an asphalt-emulsion tack coat was applied at a rate of 0.23-0.46 L/m^2 (0.05-0.10 gal/yd^2) for a distance of 225-300 mm (9-12 in) on either side of the transverse joints, and the class A sand sieved to pass a 9.5-mm (3/8-in) sieve was applied over the tack coat to a thickness of approximately 6 mm (1/4 in). A 59 to 95-kg/m^2 (100 to 175-lb/yd^2) AC overlay (85-100 penetration grade asphalt) was applied over the pavement surface and the sanded joints. Joint spacings were 9 m (30 ft). However, of the three projects treated in such a manner, only one showed any indication of fewer reflection cracks on the joints treated with sand. There was no apparent reason for any differences in performance among the three projects, and nine years later, some of the joints still had not reflected through the best-performing project, that located on US-13.

The next significant attempt to reduce reflection cracking, also reported by Hughes, involved the use of a nonwoven polypropylene fabric spanning the reflective cracks on a previously overlaid concrete pavement on US-460 (2). The polypropylene had a high tensile strength and was reported to prevent horizontal overstressing of the overlay. Supposedly, at points of stress concentration such as transverse joints or cracks, the material would prevent reflection cracking. Again, the joint spacing was 9 m; the fabric was applied by using approximately 1.1 L/m^2 (0.25 gal/yd^2) of cationic asphalt-emulsion tack coat. The fabric was applied in 0.9-m (3-ft) wide strips approximately centered on the cracks and running lengthwise with the cracks. A total of 99 joints, all of which had discernible cracking in the previous overlay, were treated in this manner. A 68-kg/m^2 (125-lb/yd^2) AC (85-100 penetration grade asphalt) overlay was applied after the fabric had been under traffic for about 12 hours.

The performance of the fabric-treated section, like that of the sanded sections, was disappointing. After three months under traffic, many of the joints were reflected through the second overlay (although there was somewhat more cracking in an adjacent section where no fabric had been used).

As a result of these partially successful experiments, field-test studies were undertaken in 1972 to determine the mechanism of reflection cracking on overlays of jointed PCC pavements. This paper summarizes these studies.

US-460 PROJECT

Horizontal Joint Movements

Before the second overlay on the US-460 project was placed, control and test sections were chosen for studies of horizontal joint movements. It was hoped that, by monitoring the horizontal hydrothermal movements of typical joints in both the section that had a fabric reinforcement and a control section that did not have such a reinforcement, it would be possible to determine the effect of such movement on the ability of the fabric to reduce reflection cracking. Five consecutive joints in both the control and the test sections were selected for monitoring. After the placement of the overlay on the control section and the fabric and overlay on the test section, gauge points were embedded in the overlay such that a nominal 250-mm (10-in) gauge length would span the area subject to reflection cracking. These gauge points were established at each of the 10 previously selected joints. Initial readings of the exact measurements between the gauge points were taken on August 25, 1971, the day after the overlay was placed. At the same time, readings were taken on reference (calibration) points embedded in the AC at places where no cracking was expected to occur. Thus, it would be possible to correct the measurements spanning the reflection cracks for the length change occurring in a 250-mm segment of uncracked pavement. A realistic measure of crack movement was anticipated through this adjustment.

Readings of both the test and calibration points were taken at monthly intervals for 30 months subsequent to the overlay. During the first 3 months, reflection cracks developed between the gauge points at three locations in each section. At one location in each section, a reflection crack developed outside the limits of the gauge points. At the end of the 30-month period, only one joint in each section had not reflected through the overlay. The results of these studies are shown in Figure 1; a positive number on the ordinate of this figure indicates joint opening and a negative number indicates joint closure. It is apparent that the fabric-reinforced test section and the control section behaved in a similar manner; there is no evidence from these tests that the stress-relieving layer provided any advantage in preventing reflection cracking. Once the cracks had formed, their behavior was generally as would be expected for the first year and seasonal movements were clearly evident. However, there is no ready explanation for the strange behavior of the measurements after the first year. Obviously, the indication that the cracks (which were clearly visible) took on negative widths is ridiculous. It is evident that, for unknown reasons, the distances between the gauge points became somewhat less than the nominal 250 mm originally established. This anomaly may be related to the humping effect noted at many transverse reflection cracks in Virginia. In such cases, a gradual upheaval or accumulation of AC at the reflection cracks results in noticeable roughness.

Vertical Joint Movements

The realization that most of the reflection cracking in the US-460 project had occurred during the first three months, when the measured horizontal movements had been minimal, led to the consideration of other factors that might contribute to the cracking. Because the pavement showed significant evidence of joint faulting and pumping, it was considered probable that vertical movement of the joints might be such a factor.

In April 1972, deflection tests were conducted at the joints on both the fabric-reinforced and the control sections. The procedure for these tests is indicated in Figure 2. A Benkelman beam (A in Figure 2) is placed on the shoulder of the road with its point near the edge of a reflection-cracked joint or of a joint that has not reflected through. A dump truck loaded to 80 kN (18 000 lbf) on its rear axle is positioned on the opposite side of the joint. At this point (point 1, Figure 2), an initial beam reading is taken. The truck is then driven slowly across the joint, and beam readings are taken as points 2 and 3 are traversed. The edge-deflection reading for point 2 (D_2) indicates the deflection when the wheel load is directly at the joint. The comparison between the reading for point 1 (D_1) and D_2 indicates the load-transfer efficiency, and the reading for point 3 is used to ensure that the Benkelman beam, still located at point 2, is no longer within the area of influence of the wheel load.

The results of these tests are shown below (1 mm = 0.04 in).

	Joints		Avg. Deflection (mm)		
Section	No.	%	D_2	D_1	$D_2 - D_1$
Fabric treated					
Cracked	57	58	0.35	0.23	0.12
Uncracked	42	42	0.23	0.20	0.03
Control					
Cracked	90	73	0.38	0.25	0.13
Uncracked	34	27	0.30	0.25	0.05

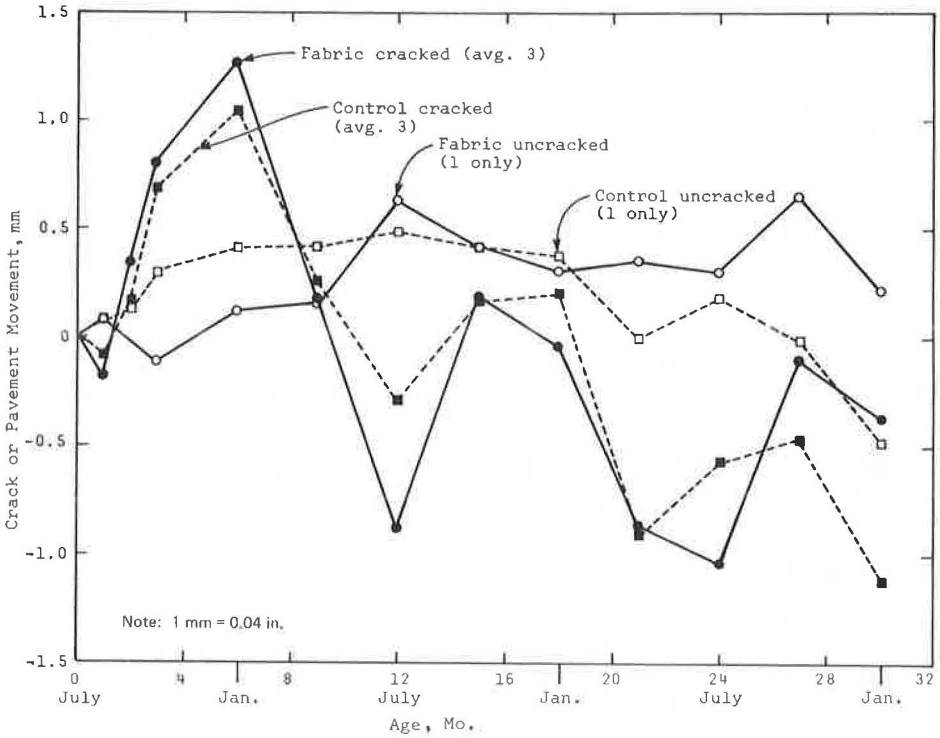
The differential joint deflection ($d = D_2 - D_1$) can be interpreted as a function of the load-transfer capability of the joint; i.e., if the load transfer is 100 percent, $d = 0$.

These tests were run when the overlay was approximately eight months old. Traffic records show that the test sections sustain an average of more than 600 vehicles/day in the 2-axle, 6-tire-or-larger truck and bus categories.

As shown above, the fabric-treated section had somewhat less reflection cracking than the control section (58 and 73 percent of joints cracked, respectively). A later survey (September 1974) showed 61 and 75 percent of joints cracked, respectively. The net joint deflection (D_2) may have some effect on the cracking; the average deflections of the uncracked joints are somewhat less than those of the cracked joints in both the fabric-treated and the control sections. More descriptive, however, is the differential joint deflection (d); the uncracked joints have very low average d-values [0.03-0.05 mm (0.001-0.002 in)] but the cracked joints average 0.13 mm (0.005 in) in both sections.

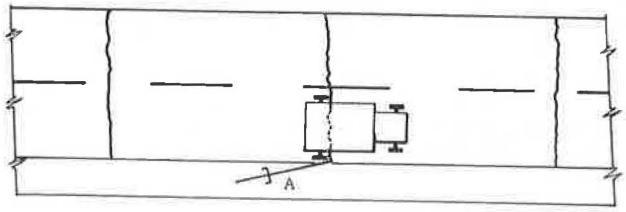
An analysis of the distribution of d-values is given in

Figure 1. Movement of cracks with age.

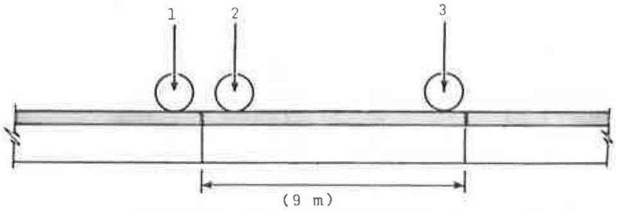


Note: 1 mm = 0.04 in.

Figure 2. Schematic of deflection-testing procedure.



Typical location of Benkelman Beam (A).



Typical wheel locations during tests.

Note: 1 m = 3.3 ft.

Table 1, where cracking frequency is given as a function of differential deflection in increments of 0.05 mm (0.002 in) (the smallest reading of the Benkelman beam used). When the differential deflection was 0 (load transfer = 100 percent), the fabric had a marked effect on reflection cracking; of 20 treated joints, none were cracked, although 4 of the 9 joints in the control section were cracked. Similarly, but less dramatically, when d was 0.05 mm, 29 and 54 percent of the fabric-treated and the control sections, respectively, had reflection cracks. Finally, when d was greater than 0.20 mm (0.008 in), all joints in both the control and the fabric-reinforced sections had reflection cracks.

Clearly, when joints have essentially 100 percent load-transfer capability, the reason for the absence of reflection cracking could be that the joints simply are not functioning. In such a case, no stress concentrations or cracking would be expected. This may well explain the absence of cracking at the 5 untreated joints where the differential deflection was 0. The 4 untreated joints where cracking did occur may be working joints where load transfer is fully effective. Thus, it is likely that many of the 20 fabric-treated joints that were uncracked and had a differential deflection of 0 were working joints where the fabric served its intended purpose of reducing overlay stresses to the point that no cracking occurred. Conversely, it is likely that, for those joints that had higher differential deflections, the fabric, a thin sheet, could not sufficiently distribute the sheer stresses and was thus unable to reduce reflection cracking significantly.

If this hypothesis is accepted, it follows that much, if not most, of the reflection cracking on the treated joints was the result of concentrations of sheer stress induced as wheel loads traversed the joints and caused differential deflections. Luther and others (3) have since established that reflection cracking of asphalt overlays is due to multimodal fatigue fracture. Their paper, based on laboratory-model studies, states in part:

> It was observed that these [reflection] cracks propagate from the surface under mixed mode conditions arising from compressive bending stresses and high sheer stresses induced by differential vertical movement between the underlying rigid concrete layer.

If, as seems to be the case, reflection cracking is fatigue in nature and differential vertical movements are a major cause, it is reasonable to assume that the rate of crack development will be a function of the frequency of wheel loadings and the magnitude of the vertical movements (differential deflection) caused by these loadings. This concept seems to have been substantiated on the US-460 project, where, with approximately 600 heavy loads/day, there was a 30 percent increase in cracking between April 1972 and September 1974, but the joints that had very low differential deflections in 1972 were still uncracked in 1974.

Table 1. Cracking and differential deflection: US-460.

Differential Deflection (mm)	No. of Joints Cracked		No. of Joints Uncracked		Percentage of Joints Cracked	
	Fabric Treated	Control	Fabric Treated	Control	Fabric Treated	Control
0	0	4	20	5	0	44
0.05	7	20	17	17	29	54
0.10	23	35	3	12	88	74
0.15	15	11	2	0	88	100
0.20	12	20	0	0	100	100

Note: 1 mm = 0.04 in.

Figure 3. Core through new overlay (top), polypropylene fabric, and old overlay.

Cores

During the September 1974 crack survey, five 100-mm (4-in) diameter cores were removed from the US-460 pavement. Each core was taken at a reflection crack in the fabric-treated section and was located so as to intercept the crack approximately as a core diameter. These five cores were returned to the laboratory for study. The results of these studies are indicated in Figure 3, where it can be seen that the core through both AC layers is held together by the polypropylene fabric. The reflection crack is plainly visible both above and below the fabric. Attempts to separate the AC from the fabric showed that all were firmly bonded together so that some effort was required to remove either AC layer. When the AC had been removed, the fabric showed no evidence of damage but had a slight wrinkle that corresponded to the location of the reflection crack.

The observation that there were no tears or other signs of elongation of the fabric was taken as further evidence that the reflection cracking had been caused primarily by vertical joint movements.

Joint Pumping

A coincidental observation of the 1972 and 1974 surveys was that the polypropylene fabric spanning the transverse joints might also have helped to reduce pumping. At both times about 15 percent of the joints in the control section were observed, on the basis of the ejection of fines from the subbase or subgrade, to be pumping, but no cases of pumping were observed in the fabric-treated section during either survey. It may be conjectured that the fabric, which had been asphalt-impregnated during its manufacture and applied with a heavy tack coat of liquid asphalt, served as a barrier to surface water entering the joints and thus prevented pumping. However, because joint pumping had not been a consideration early in the study, no data are available on the incidence of pumping before the fabric was applied and, thus, no firm conclusions can be offered on this matter.

US-13 PROJECT: VERTICAL JOINT MOVEMENTS

The apparent relationship between vertical joint movements and the effectiveness of the stress-relieving layer on the US-460 project led to speculation that such movements might also be significant where sand had been used as a bond breaker between an AC overlay and a jointed PCC pavement. Because, as noted above, the sand had been partially successful on the US-13 project, it was decided to conduct joint-deflection tests at that site. These tests were conducted, in the manner described above, in June 1972, when the test section was six years old. At that time, of 60 control or untreated joints, 100 percent exhibited reflection cracking and, of 232 sanded joints, 155 (66 percent) had such cracking. The results of the tests are summarized in Table 2.

Thus, although a sand layer can be effective in reducing reflection cracking, the degree of this effectiveness is strongly affected by the magnitude of the differential deflection. For example, after six years, the sand layer appears to have been 76 percent effective where there was no differential deflection but only 7 percent effective where the differential deflection was as much as 0.15 mm (0.006 in).

A more recent survey of this project showed that, after nine years, 93.5 percent of the sanded joints exhibited reflection cracking. Thus, it appears that the fatigue nature of reflection cracking is again shown on this project, where traffic volumes include an average of 335 vehicles/day in the 2-axle, 6-tire-or-larger truck and bus categories.

I-95 PROJECT

As a result of the studies described above, which indicated that stress-relieving layers could be effective in delaying reflection cracking where differential vertical joint movements were minimized, several test sections were placed on a segment of I-95 under construction in northern Virginia in July 1972. This project, called the Mixing Bowl, is a part of the multilane highway network near the Pentagon and has a composite pavement overlying a very rigid foundation. The pavement design

Table 2. Cracking and differential deflection: US-13.

Differential Deflection (mm)	No. of Joints Cracked		No. of Joints Uncracked		Percentage of Joints Cracked	
	Sand Treated	Control	Sand Treated	Control	Sand Treated	Control
0	4	1	13	0	24	100
0.05	58	15	43	0	57	100
0.10	66	28	19	0	77	100
0.15	27	14	2	0	93	100

Note: 1 mm = 0.04 in.

Table 3. Fabric-reinforced cracks available for study: September 1975.

Site	Location	Date Overlaid	No. of Cracks		
			Polypropylene Treated	Nylon Treated	Control
1	VA-27: northbound lane	9/18/72	22	0	0
2	I-95: southbound lane	9/18/72	25	25	8
3	I-95: southbound lane	10/31/72	0	0	29
Total			47	25	37

Figure 4. Core through bituminous layers and polypropylene fabric: I-95 project.

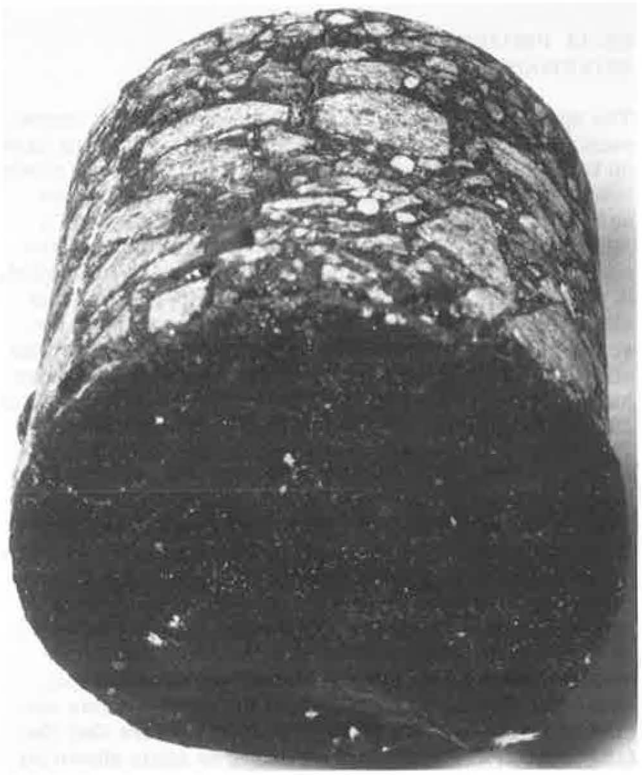


Figure 5. Core through bituminous layers and nylon fabric: I-95 project.

features are described below (1 kg/m = 1.85 lb/yd and 1 mm = 0.04 in).

Pavement Feature	Material	Thickness (mm)
Surface	54-kg/m² bituminous concrete	13
Binder	136-kg/m² bituminous concrete	19
Base	Plain PCC	200
Subbase	Cement-stabilized material	200

It was expected that the extremely rigid base and subbase layers would reduce vertical joint motions to a minimum so that the provision of a stress-relieving layer between the bituminous concrete layer and the PCC base would reduce the incidence of reflection of the shrinkage cracks in the concrete base. Plans called for the installation of two fabric stress-relieving materials, each on approximately 100 shrinkage cracks.

The details of the installation have been reported by McGhee and Hughes (4), and some of the more important features are summarized below along with the results of three years of performance studies.

Materials and Application

The materials applied were (a) an asphalt-impregnated,

Table 4. Cracking by lane: site 2—September 1975.

Land	Cracks Reflected					
	Polypropylene Treated		Nylon Treated		Control	
	Percentage	Function A[a]	Percentage	Function A[a]	Percentage	Function A[a]
Acceleration					100	8 of 8
Traffic	71	5 of 7	83	5 of 6		
Middle	55	5 of 9	67	6 of 9		
Passing	33	3 of 9	60	6 of 10		

[a] Function A = number of reflection cracks as function of total number of treated cracks in PCC base.

nonwoven polypropylene fabric and (b) a nonwoven, spunbonded nylon. After the concrete base was old enough to develop shrinkage cracks [which occurred at approximately 9-m (30-ft) intervals] but before the application of bituminous concrete layers, the cracks were located for installation of stress-relieving materials with respect to permanent reference points on the roadway or median. Before the materials were placed, each crack was tacked for its full length [a 3.6-m (12-ft) lane width] and for 0.45 m (18 in) on either side with approximately 1.1 L/m^2 (0.25 gal/yd^2) of cationic asphalt emulsion. After the tack had cured for 1-3 h, the fabric was broomed into place to ensure good adhesion; the polypropylene appeared to absorb the tack better and to adhere more uniformly to the base course than did the nylon.

Because of numerous problems, many of the fabric-treated cracks were not suitable for evaluation by the time the bituminous concrete layers had been placed. Since the overlay was placed, many of the treated cracks have been under traffic volumes of more than 40 000 vehicles/day, and no evaluation has been possible. The result is that at present only two test sections and one control (no fabric) section are available for evaluation. The results are summarized in Table 3.

Results

Periodic surveys of the three test sites showed an early difference in the number of reflection cracks. For example, in February 1973, when little traffic had used the sites, there were 0, 5, and 16 reflection cracks detected in the binder course on sites 1, 2, and 3, respectively. Thus, there was a clear indication that the fabric on sites 1 and 2 was being effective in reducing the incidence of reflection cracking at an early age of the overlay. In April 1973, soon after the final surface had been applied, no cracks could be detected in any of the three sections, and no significant cracking developed in the surface course during the summer of 1973. However, during the winter of 1973/74, when hydrothermal pavement movements could be expected to be most conducive to reflection cracking, numerous cracks began to develop in the control section and in site 2. It also became clear during this period that new cracks were developing in the unreinforced concrete base and were, in turn, being reflected through the AC surface. As a result, by July 1974, there were 32 reflection cracks in the control section (site 3) and 45 cracks in site 2, many of which were newly developed at the base-course level. At the same time, there were only 2 cracks in site 1.

Also, in July 1974, deflection measurements were made. Similar to the results for the US-460 project described above, the average differential deflection on visible cracks was 0.05 mm.

Cores removed from site 2 during July 1974 showed results similar to those described above for the US-460 project. For both the polypropylene- and the nylon-fabric-treated cracks, the cores showed that the cracks were directly above cracks in the PCC base and that the fabric was still intact and showed no signs of distress (see Figures 4 and 5).

Final surveys of the cracking on the I-95 project were conducted in September 1975. Again, there were a number of cracks that had developed in the base concrete and reflected through the bituminous layers after the installation of the test sections. However, as shown in the table below, which is based on the original cracking in the three test sites, both fabrics were somewhat effective in at least delaying the onset of reflection cracking.

Site	Traffic (vehicles per day)		Percentage of Cracks Reflected		
	Total	Large Trucks and Buses	Polypropylene Treated	Nylon Treated	Control
1	19 000	270	41		
2	42 500	3050	52	68	100
3	42 500	3050			90

There is also some evidence that the polypropylene was more effective than the nylon. The traffic characteristics given above are indicative of the service conditions but cannot be used to establish a relationship between traffic volume and reflection cracking. Although site 1 had been subjected to the indicated traffic for most of the 3-year period, because of construction-related detours, sites 2 and 3 had had only sporadic traffic.

However, the effects of traffic volume and fatigue on the rate of development of the reflection cracking are shown in a detailed study of site 2. The frequency of reflection cracking is greatest in the lanes subject to the most traffic, particularly trucks [see Table 4 (where the outermost lane has been designated as the acceleration lane, the second as the traffic lane, the third as the middle lane, and the innermost as the passing lane)]. Clearly truck traffic will be heaviest on the acceleration and traffic lanes. On this site, there was a marked decrease in reflection cracking on the lanes where there would be less truck traffic. There was also a significant difference in cracking between the polypropylene- and the nylon-fabric-treated cracks, although there is no explanation for this difference. Finally, all of the untreated cracks in the acceleration (control) lane have reflected through.

CONCLUSIONS

The following conclusions appear to be warranted from the studies reported above.

1. Neither sand as a bond breaker nor high-strength fabrics as stress-relieving layers are effective in reducing reflection cracking where vertical joint movement (differential deflection) is a significant factor.
2. At differential deflections greater than approximately 0.05 mm (0.002 in), reflection cracks from very early. Such cracking is delayed at lower differential deflections but will occur as the magnitude and frequency of wheel loadings increase.
3. When placed to span the joints in a PCC pavement or the cracks in a PCC base and then covered with an AC overlay, both asphalt-impregnated, nonwoven poly-

propylene and nonwoven, spun-bonded nylon fabrics can sustain the formation of reflection cracking in the overlaying layer without being damaged themselves.

4. An asphalt-impregnated, nonwoven polypropylene fabric spanning the joints in a PCC pavement and placed between the pavement and an asphalt overlay can be effective in reducing the infiltration of surface water to pavement sublayers. There is some evidence that pavement pumping may be reduced by this method.

5. Both asphalt-impregnated, nonwoven polypropylene and nonwoven, spun-bonded nylon fabrics can delay the formation of reflection cracking. There is strong evidence, however, that such cracking is fatigue in nature and will eventually develop under the application of repetitive wheel loadings.

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