Design Practices for Paved Shoulders

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This paper presents the results of a study to develop improved methodology for designing paved shoulders adjacent to portland cement concrete pavements. A survey of 1975 shoulder practices was conducted as a part of National Cooperative Highway Research Program Project 14-3. The results indicate that most shoulder pavement sections are underdesigned. Truck traffic encroaching on the shoulder, together with water entering the longitudinal joint, and severe climatic conditions are the most important causes of early shoulder deterioration. A major recommendation is that the shoulder in the vicinity of the joint be structurally designed to withstand the wheel loadings from encroaching truck traffic. Alternate designs are developed for a range of traffic, soil, and environmental conditions by using the American Association of State Highway Officials Interim Guide for Design of Pavement Structures. These structural sections should be supplemented with subsurface drainage or sealed longitudinal shoulders based on environmental conditions or subgrade conditions or both.

The highway system in the United States is composed of a large number of portland cement concrete (PCC) pavements having asphalt concrete shoulders. The resulting joint formed between the pavement and shoulder has proved to be one of the weakest parts of the pavement-shoulder system (1, 2). Although the rate of deterioration of the pavement and shoulder at the joint varies widely with respect to locality, materials used, and construction practices, the basic mechanisms of joint deterioration are generally the same. If the transverse and longitudinal pavement-shoulder joints are not completely sealed, surface water will infiltrate into the subbase, subgrade, and shoulder. This water, together with repeated traffic loads, can cause the subbase material to be pumped from beneath the concrete slab and beneath the shoulder resulting in faulting of the slab (3, 4) and cracking or settlement of the asphalt concrete shoulder (5, 6, 7) or both. In the northern parts of the United States, infiltration of water beneath the pavement can lead to frost heave, cracking, and early deterioration of the shoulder.

Because pavement and shoulder deterioration is often related to the infiltration of water into the subbase and the underlying subgrade, attempts have been made to prevent infiltration by sealing the longitudinal joints. However, it has generally been conceded that watertight pavement-shoulder joints cannot last the life of the pavement. Therefore, consideration should be given to (a) minimizing the amount of water passing through the joint and (b) designing a stronger pavement-shoulder structure by using, for example, concepts of drainage and base treatment to minimize the effects of water that does eventually pass through the joint. This paper deals primarily with one aspect of the project—developing structural shoulder designs to resist deterioration due to encroaching traffic. The complete findings of this study (including improved drainage and joint sealing) are given elsewhere (8).

CURRENT DESIGN PRACTICES

When considering the structural design of pavement shoulders, one must carefully consider the functions of the shoulder. One purpose of a shoulder is to provide a safe all-weather refuge for vehicles that must leave the main traffic stream (1). Paved shoulders reduce the amount of infiltration of surface runoff and provide some degree of lateral support of the pavement.

Asphalt Concrete Shoulder Sections

The performance of the shoulder with or without a sealed longitudinal joint depends to a considerable degree on the structural strength and design of the shoulder and how it acts with the pavement. During their early development, paved shoulder sections used on Interstate pavements tended to be relatively thin. As the detrimental effects of traffic loading and the environment became apparent, considerably heavier shoulder sections gradually gained relatively widespread use.

Table 1 gives a summary of typical shoulder sections used in 1975 and how they performed. The information reported is based on field inspections made in 15 states and on a questionnaire mailed to each state highway organization. In Table 1, Arkansas, Colorado, Delaware, Iowa, Maryland, Manitoba, Mississippi, Nebraska,

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Table 1. Current asphalt concrete shoulder sections.

	Surface Course		Base Course		Subbase	
State	Material	Thickness (cm)	Material	Thickness (cm)	Material	Thickness (cm)
Alabama	AC	~2.5	AC	~7.6	Select soil	11.4
Arizona	AC	10.2	AB	12.7	ASB	10.2 to 15.2
California	AC	7.6 to 14.0	AB	15.2	ASB	Variable
Connecticut	AC	7.6	SSB	15.2	Not specified	15.2 to 57.2
Georgia	AC	3.8	CTB	15.2	Select borrow	
Florida	AC	2.5	SA	12.7	Sand-clay	15.2
Idaho	AC	9.1	AB	21.3	ASB	6.1
Illinois	AC	3.8	CTB	16.5	ASB	10.2
			LTB	16.5		
			ATB	16.5		
Indiana	ST		ATB	15.2	ATSB	10.2
Kentucky	AC	5.1	AB	Variable		
Kansas		22.9 tapered	AB	10.2	LTS	15.2
Louisiana	AC	20.3 to 25.4	AC	8.9	LTS	
Maine	AC	7.6	AB	22.9	ASB	22.9
Michigan	AC	3.8	ATB	16.5 to 19.1	ASB	35.6
Missouri	AC	5.1	ATB	12.7	ASB	12.7 to 17.8
			CTB	12.7		
Minnesota	AC	3.8 to 5.1	AB	7.6	ASB	22.9 to 27.9
New York	AC or ST	~2.5	Emulsion-stabilized gravel	7.6	ASB	43.2
North Carolina	ST or AC	2.5	AB	20.3	ASB	10.2
North Dakota	AC	10.2	ATB	10.2	LTS	
		5.1	Emulsion or cutback treated	15.2		
Ohio	AC	7.6	ATB	12.7 to 15.2	ASB	15.2
Oregon	AC	Full pavement depth	CTB	10.2 to 15.2	LTS	15.2
					CTS	
Pennsylvania	AC or ST	10.2	AB	15.2	ASB	30.5
South Carolina	AC		ATB			
South Dakota	AC	5.1	ATB	15.2	AC	5.1
			LTB	15.2		
Texas	AC	20.3	ATB	10.2	LTS	
Utah	AC	7.6	AB	15.2	ASB	20.3
Washington	AC	5.1	AB	7.6	ASB	17.8
West Virginia	PM	7.6	AB	15.2	ASB	15.2
Wisconsin	AC	7.6	AB	15.2	ASB	38.1

Note: 1 cm = 0.394 in.

Nevada, New Jersey, New Mexico, Virginia, Wisconsin, and Wyoming did not provide sufficient information, and Alberta, British Columbia, and Vermont had little or no experience with PCC pavements. Also the following codes appear in Table 1:

Code	Definition	Code	Definition
AB	Aggregate base	LTB	Lime-treated base
AC	Asphalt concrete	LTS	Lime-treated subgrade
ASB	Aggregate subbase	PM	Penetration macadam
ATB	Asphalt-treated base	SA	Sand asphalt
ATSB	Asphalt-treated subbase	SSB	Salt-stabilized base
CTB	Cement-treated base	ST	Surface treatment

Full-Depth Asphalt Concrete

Eleven states indicated that they have used full-depth asphalt concrete shoulder sections varying from about 17.8 to 25.4 cm (7 to 10 in) in depth. Arizona and California are considering use of full-depth sections in the future. Illinois, Texas, North Dakota, Louisiana, Michigan, and Ohio were visited to evaluate the field performance of full-depth asphalt concrete shoulders. Use of full-depth shoulders is found to eliminate or greatly reduce cracking near the longitudinal joint and limit separation at the joint to approximately 3.2 mm ($\frac{1}{8}$ in).

A comprehensive study in Illinois (9) showed that a full-depth bituminous aggregate shoulder section performed better than either cement-aggregate or a pozzolanic aggregate base shoulder. The bituminous aggregate base tapered in thickness from 20 cm (8 in) at the pavement to 15.2 cm (6 in) at the outer edge. A 3.8-cm ($1\frac{1}{2}$-in) bituminous concrete surfacing was placed over a 13.9-cm-thick ($5\frac{1}{2}$-in-thick) cement aggregate base and over a 16.5-cm ($6\frac{1}{2}$-in) pozzolana-aggregate base. In the sections having cement and lime-fly ash bases, longitudinal cracks were found to form approximately 20.3 to 50.8 cm (8 to 24 in) from the joint; random cracks occurred in between. A significant amount of the deterioration observed in the lime-fly ash and cement-aggregate bases was found to be caused by the loss of durability due to freeze-thaw cycles and the presence of brine. The bituminous aggregate bases performed well.

In Michigan (10), considerable settlement of the shoulder occurred and longitudinal cracks usually formed during the first year or two about 15.2 to 30.5 cm (6 to 12 in) from the edge; the shoulder problem was similar to that observed in Illinois. The shoulder section consisted of 3.81 cm ($1\frac{1}{2}$ in) of asphalt concrete with an 11.4-cm ($4\frac{1}{2}$-in) gravel base. Select stone extended from the main-line pavement 0.6 m (2 ft) under the shoulder. Because of the poor performance of this shoulder section, the following stronger shoulder sections are now used in Michigan:

1. A deep asphalt concrete section equal to the slab thickness at the inside edge and tapering to 16.5 cm ($6\frac{1}{2}$ in) at the outside edge placed over a 35.6-cm (14-in) sand subbase and
2. Concrete shoulders conforming to the main-line slab thickness and tapering to 15.9 cm ($6\frac{1}{4}$ in) at 0.9 m (3 ft) from the outside edge and remaining constant to the edge of the shoulder.

The performance of these two sections has been a considerable improvement over the thinner granular base sections.

Full-depth bituminous pavement shoulders in North Dakota are found to perform quite well considering the presence of expansive soils and a very severe climate.

Transverse temperature cracks do occur in the shoulder because of the extreme temperature variations. The shoulders used in North Dakota consist of 10.2 cm (4 in) of asphalt concrete over a 10.2-cm (4-in) liquid or emulsified asphalt-treated base. Important factors contributing to the good performance in North Dakota appear to be the use of a continuously reinforced concrete pavement bituminous stabilized base, and sealed longitudinal pavement-shoulder joints. The sealed longitudinal joints are generally well maintained, and the system appears to be relatively effective in keeping surface water from beneath the pavement. By means of an increase in density requirements from American Association of State Highway and Transportation Officials (AASHTO) [formerly American Association of State Highway Officials (AASHO)] T-99 to T-180, most of the shoulder settlement problems formerly existing in the granular base section have been eliminated.

Texas uses thick asphalt concrete sections consisting of 20.4 cm (8 in) of asphalt-stabilized material over a 10.2-cm (4-in) asphalt-stabilized subbase. The upper 15.2 cm (6 in) of the subgrade beneath this section is frequently treated with lime. Local materials are used extensively in the asphalt-stabilized bases and subbase. Several districts in Texas seal the longitudinal joint to try and keep water from expansive clay subgrades. Use of the deep asphalt sections has greatly minimized the problem although transverse and vertical movements up to approximately 6.35 mm ($^1/_4$ in) are still found to occur at the joint. Considerably larger movements are caused by expansive clay subgrades.

Cement-Treated Bases

From the survey, five states indicated that they use a cement-stabilized base under an asphalt concrete surface course. All of these states except Oregon use a relatively thin asphalt concrete surfacing varying from 3.81 to 5.08 cm ($1^1/_2$ to 2 in) in thickness. Oregon uses an asphalt concrete surface equal in thickness to that of the PCC slab. Of the states in which field inspections were made, only Georgia continues to use cement-stabilized bases on Interstate pavements. Illinois, Pennsylvania, and Louisiana have discontinued their use on at least Interstate pavements because of poor performance. Field inspections in Illinois, Pennsylvania, Louisiana, Georgia, and Texas showed that their cement-stabilized bases tend to pump, which causes faulting of the main-line slab. Erosion of base material also results in settlement and subsequent cracking and deterioration of the shoulder and main-line slab in the vicinity of the transverse joint. In many instances, a depression forms in the shoulder immediately adjacent to the longitudinal joint and is followed by cracking in this area. The pumping problem is particularly severe in both Georgia and Louisiana where the average annual rainfall is about 127 to 139 cm (50 to 55 in). Georgia uses a 15.2-cm-thick (6-in-thick) cement-treated base with a 3.8-cm ($1^1/_2$-in) asphalt concrete surfacing. The base is usually a cement-treated aggregate overlaying a layer of select borrow material. In Louisiana, extensive use is made of local soils for the cement-stabilized bases for shoulders constructed on primary highways. These shoulders consist of 3.8 to 5.2 cm ($1^1/_2$ to 2 in) of asphalt concrete over a 20.3-cm (8-in) soil and cement base. Louisiana now uses 20.3 cm (8 in) of asphalt concrete over an asphalt concrete base on Interstate pavements.

Granular Bases

Twelve states reported the use of aggregate bases or subbases. Of these twelve, field inspections were conducted in Arizona, California, Minnesota, Ohio, Pennsylvania, and Utah. In general, shoulders constructed with typically 3.8 to 5.1 cm ($1^1/_2$ to 2 in) of asphalt concrete and 15.2 cm (6 in) of granular base have performed poorly at least partly because this section in most instances is grossly underdesigned. Furthermore, sections having deep granular bases have been found to experience settlement problems. Maximum settlements of typically 2.5 to 3.8 cm (1 to $1^1/_2$ in) appear to be caused primarily by a combination of factors, including some or all of the following: (a) low compaction, (b) use of frost susceptible material, (c) poor gradation or small maximum size aggregate or both, and (d) use of low-quality uncrushed gravel aggregate often having an excessive amount of fines.

In California, the shoulder sections in the valley areas were observed to perform quite well. A relatively small amount of separation at the longitudinal joint [approximately 3.20 to 6.35 mm ($^1/_8$ to $^1/_4$ in)] and some surface cracking and faulting were observed in the shoulder although the severity is much less than that found in states such as Illinois and Michigan. Some problems with faulting of the main-line pavement are also experienced in the valley areas where there is a mild climate and average annual rainfall of only 38.1 to 50.8 cm (15 to 20 in). Extension of the stabilized subbase under the main-line pavement 0.3 m (1 ft) beyond the edge has been found to significantly reduce the shoulder problems in the valley areas. In contrast, pavements in the mountain areas (near Donner Pass where the winters are quite severe) exhibited extensive shoulder cracking near the longitudinal joint similar to that found in Michigan, Illinois, and Minnesota. California uses 7.6 to 14 cm (3 to $5^1/_2$ in) of asphalt concrete surfacing over a 15.2-cm (6-in) aggregate base.

Deep granular bases and subbases are used in Minnesota, New York, Ohio, Pennsylvania, and Utah and vary from approximately 25.4 to 45.7 cm (10 to 18 in) in thickness. New York uses approximately 10.2 cm (4 in) of asphalt-treated surfacing, Minnesota uses 3.81 cm ($1^1/_2$ in), and the other states use 7.6 cm (3 in) of asphalt concrete. Maximum settlements from approximately 1.3 to 3.8 cm ($^1/_2$ to $1^1/_2$ in) have been found to occur in these shoulders, which are underlaid by deep layers of granular materials. Shoulder sections with granular bases are found to perform reasonably better in Ohio than in other states using this type of section. The better performance may be at least partly due to sloping the pavements so that water flows to the inside rather than the outside shoulder. The most serious problem in Ohio appeared to be associated with frost heave during the first winter, which leads to longitudinal cracking about 0.3 m (1 ft) from the edge of the pavement. In the future Ohio plans to use full-depth asphalt concrete shoulders tapering from the PCC slab thickness at the shoulder joint to 15.2 cm (6 in) at the outer edge. In New York, settlement of the shoulder appears to be the most severe type of distress although some cracking also occurs. In Minnesota and Utah, both settlement and cracking of the shoulder near the longitudinal joint are found to be important. Because of current shoulder deterioration, Minnesota plans to use a 10.2-cm (4-in) asphalt concrete surfacing in the future and wait until the shoulder settlement has occurred before sealing the longitudinal joint. Some of the excessive settlement experiences in Minnesota could be caused by compacting the granular materials to only 100 percent of AASHTO T-99 density. Utah and Georgia currently plan to use concrete shoulders on future Interstate pavements.

Pennsylvania has studied the performance of the following four bases: (a) bituminous concrete, (b) soil cement, (c) bituminous soil, and (d) lime fly ash.

Shoulder sections using the asphalt concrete base course have been found to give the best performance and are currently used by Pennsylvania. This section consists of 10.2 cm (4 in) of asphalt concrete, 15.2 cm (6 in) of aggregate base, and a variable thickness subbase. The required subbase thickness, which is typically 30.5 cm (12 in), is determined from frost considerations by using the U.S. Army Corp of Engineers method.

PCC Shoulders

Portland cement concrete shoulders adjacent to main-line concrete pavements have been constructed for the past 12 years. Between 1970 and 1974, approximately 4.77 million m^2 (5.7 million yd^2) of concrete shoulder contracts have been awarded in a total of 21 states (11, 12). The states that have planned or constructed PCC shoulders are shown in Figure 1. Figure 1 is patterned after data in the California Highway Design Manual (16). Table 2 gives a summary of the different shoulder sections used or planned by the various states. Only sections constructed in Illinois, Texas, and Michigan have had traffic for a sufficient length of time to fully evaluate their performance.

In Illinois, the PCC shoulders are found to perform as well as or better than asphalt concrete sections. From the comprehensive study performed in Illinois, five significant conclusions were reached (13):

1. A plain concrete shoulder 15.2 cm (6 in) thick gives good performance.
2. The shoulder should be tied to the main-line pavement by 76.2-cm-long (30-in-long) tie bars spaced 76.2 cm (30 in) on center.
3. Spacing of transverse joints of about 6.1 m (20 ft) is desirable for control of the intermediate cracking.
4. Use of a 15.2-cm (6-in) granular subbase under the concrete shoulder is found to reduce the amount of shoulder cracking by approximately 50 percent. However, the cracks that did develop in the sections not underlaid by a subbase remained closed and did not significantly affect shoulder performance.
5. Sealing the longitudinal edge joint did not improve shoulder performance.

Several states have also followed the recommendations of the Illinois study, and others have increased the slab thickness to equal that of the main-line pavement. The Federal Highway Administration (14) has recommended use of either a straight or tapered concrete shoulder having a minimum thickness of 15.2 cm (6 in). They also recommended a stabilized base. Further, when the inside and outside shoulders are integrally placed in one pass of a slip-form paver with a 7.32-m-wide (24-ft-wide) main-line pavement, a longitudinal joint should be placed between the main-line pavement and the shoulder. When the jointed main-line pavement is used, steel reinforcement is not required in the shoulder. For continuously reinforced pavements, the same percentage of longitudinal steel should be used in the shoulder as is used in the main-line pavement.

E. C. Lokken (11) has prepared recommendations that follow reasonably closely to those of Illinois.

SHOULDER ENCROACHMENT STUDY

Truck encroachment appears to be a major cause of observed cracking and settlement in the vicinity of the shoulder joint. The term encroachment is restricted to continuous movements of truck traffic and does not apply to movements for stopping. Despite the apparent relationship between traffic loading and shoulder distress, little has been done to develop a formal approach for designing structural shoulder sections. Early studies concerned with transverse placement of trucks used the data only for the design of the main-line pavement.

The objectives of this study were twofold: (a) to determine, on the basis of actual observations, the amount and extent of shoulder encroachment by trucks and (b) to develop criteria that pavement designers can use to arrive at an optimal structural design of the paved shoulder. This study consists of summarizing observations of transverse truck placement on rural freeways with free-flow characteristics. All observations relate to rural freeways and should not be considered applicable to other types of facilities.

Procedure

For the study performed in Georgia (15), trucks were selected at random and followed by observers for 16.1 km (10 miles). Those trucks not completing a full 16.1-km (10-mile) trip were dropped from the analysis. Records were made of the time on the shoulder to determine the longitudinal distance for each encroachment. Estimates of transverse encroachment with respect to the shoulder joint were made based on the dimensions obtained for different types of trucks at several terminals in the Atlanta, Georgia, area.

A total of 205 trucks were followed for the 16.1-km (10-mile) distance in nine states. Sixty percent of the trucks followed were on PCC main-line paving, and 40 percent were on asphalt concrete main-line paving. A comparison in truck classification between the randomly selected samples and two continuous count stations in Georgia was made to ensure a representative sample. As shown by the data given in Table 3, the comparison is reasonably close except for the two-axle, single-unit trucks.

Results

Table 4 gives a summary of information on outside shoulder encroachments by type of shoulder. Sixty-five percent of all trucks encroached on the shoulder sometime during the 16.1-km (10-mile) study length. The percentage was similar for asphalt concrete and bituminous surface treatment shoulders, which indicates that rough-textured shoulders do not necessarily discourage encroachment on the shoulder. A total of 677 encroachments were observed, or an average of approximately 3.3 encroachments/vehicle for the 16.1-km (10-mile) study length.

Table 5 gives a summary of the number of outside shoulder encroachments by type of truck; Table 6 gives encroachments by type of terrain. The results indicate that certain types of trucks and terrain are more likely to contribute to a higher incidence of shoulder encroachments. For example, 83 percent of the four-axle, multiple units encroached on the shoulder an average of 4.7 encroachments/vehicle. Although 60 percent of the three-axle, multiple units encroached, they did so an average of 8.5 times. Types of terrain also had a significant effect on the number of encroachments. The higher incidence of horizontal curves in rolling and hilly terrain appears to have contributed to the high encroachment ratio.

The following tabulation gives a summary of frequency, time, longitudinal distance, and transverse placement of encroachments (1 km = 0.621 mile; 1 m = 3.28 ft):

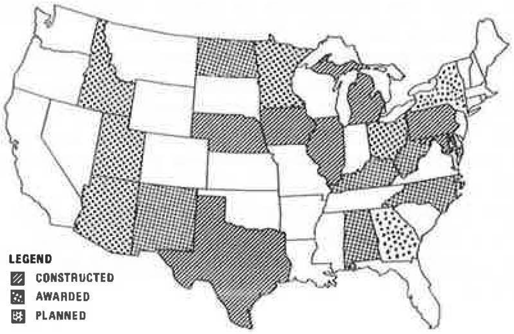

Figure 1. States having concrete shoulder projects by end of 1974.

Item	Outside Shoulder	Median Shoulder
Avg. encroachments per truck in 16.1 km	3.30	0.25
Avg. time on shoulder per encroachment, s	4.5	3.4
Avg. longitudinal distance on shoulder per encroachment, m	117	104.9
Avg. transverse distance on shoulder per encroachment, m	0.18	0.015

For the outside shoulder, average transverse encroachment was 17.7 cm (0.58 ft). Actual distribution for the outside shoulder is shown in Figure 2. A considerable amount of traffic is found to operate on the outside shoulder to a distance of approximately 30.5 cm (12 in) from the longitudinal joint.

Table 2. Summary of PCC shoulder designs.

State	Type of Pavement	Slab Thickness (cm)	Base Type	Base Thickness (cm)	Tie Bars Size Number	Tie Bars Spacing (cm)
Alabama	Continuously reinforced concrete	20.3	Aggregate	15.2		
Georgia	Plain	27.9 taper to 15.2	Subgrade		10.2	76.2
Illinois	Plain	15.2	Subgrade		10.2	76.2
Iowa	Plain	15.2				
Kentucky	Plain, reinforced	12.7 to 17.8				
Maryland	Reinforced	17.8			10.2	76.2
Michigan	Plain	22.9 taper to 15.9	Aggregate	10.2	Hook bolt	101.6
Nebraska	Plain	14.0	Subgrade			
New Mexico	Plain	20.3	Cement stabilized base			
New York	Plain	15.2	Aggregate	20.3 min.		
North Carolina	Plain	17.8				
North Dakota	Continuously reinforced concrete	20.3	Aggregate	5.1	12.9	121.9
Pennsylvania	Plain	15.2	Aggregate	30.5	Hook bolt	
Texas	Continuously reinforced concrete	20.3	Cement stabilized base	15.2	10.2	91.4
Utah	Plain	22.8	Cement stabilized base	12.7	12.7	91.4
West Virginia	Plain	20.3	Cement stabilized base	15.2		

Notes: 1 cm = 0.394 in.
Design details not available on Arizona, Idaho, and Minnesota.

Table 3. Comparison of truck classification from study trucks and two continuous-count stations.

Truck Class	Study Trucks Number	Study Trucks Percent	Station Trucks[a] (%)
2 axle, single unit	45	21.9	13.7
3+ axle, single unit	8	3.9	3.0
3 axle, multiple unit	10	4.9	4.7
4 axle, multiple unit	31	15.1	21.5
5+ axle, multiple unit	111	54.1	57.1
Total	205	100	100

[a] One station on I-85, 129 km (80 miles) northeast of Atlanta, and one station on I-75, 161 km (100 miles) south of Atlanta.

Table 4. Summary of outside shoulder encroachments by type of shoulder pavement.

Item	Asphalt Concrete	Bituminous Surface Treatment	Total
Number of samples	129	76	205
Number of trucks encroaching	83	50	133
Percent of trucks encroaching	64.3	65.8	64.9
Number of encroachments	398	279	677
Avg. encroachments per truck encroaching	4.8	5.6	5.1
Avg. encroachments per truck	3.1	3.7	3.3
Avg. vehicle speed, km/h	—	—	103

Note: 1 km/h = 0.621 mph.

Table 5. Encroachments on outside shoulder by type of truck.

Type of Truck	Trucks in Sample	Trucks Encroaching Number	Trucks Encroaching Percent	Encroachments	Avg. Encroachments per Truck Encroaching	Avg. Encroachments per Truck
2 axle, single unit	45	30	66.7	133	4.4	2.96
3+ axle, single unit	8	3	25.0	21	7	2.63
3 axle, multiple unit	10	6	60.0	51	8.5	5.1
4 axle, multiple unit	31	26	83.9	123	4.7	3.97
5+ axle, multiple unit	111	68	64.0	349	1.6	3.14
All trucks	205	133	64.9	677	5.1	3.30

Design Criteria for Shoulders

The data on shoulder encroachment can be used to develop a design traffic number in terms of percent of main-line traffic. For example, consider the traffic conditions existing on I-75 at Perry, Georgia, and the previously observed 3.3 outside shoulder encroachments per truck for 16.1 km (10 miles) (1 km = 0.621 mile):

Item	Calculation
1973 avg. annual daily traffic	22 966
Design trucks, %	19.5
Design trucks, one way	2239
Outside shoulder encroachments per day in 16.1-km segment	7389
Total encroachment distances in 16.1-km segment, km	865
Encroachments for given point	54
Trucks encroaching on shoulder, %	2.4

On the average, each of these encroachments resulted in a traveled distance of 117 m (384 ft) on the shoulder. For this example, there are 54 encroachments each day by the 2239 trucks, or 2.4 percent of the trucks that use the outside shoulder. Because the truck wheels are concentrated primarily within about 30.5 cm (12 in) of the longitudinal joint, use of the full percentage of truck traffic for structural design appears justified.

STRUCTURAL DESIGN STUDY

Structural shoulder pavement designs have gradually developed more through experience than from rational pavement design analyses. Apparently only California uses a formal design procedure for shoulders (16). In California, shoulder sections are designed for 1 percent of the main-line traffic index (TI); TI is 5 [approximately 10^4 equivalent 80.1-kN (18-kip) axle loads]. The results of the encroachment of main-line truck traffic onto the shoulder presented in this paper, however, have shown that 1 percent encroachment is low for at least some traffic flow conditions. This study indicates that, for free-flow traffic conditions in at least rural areas of the South, shoulder pavement within 0.3 m (1 ft) of the joint should be designed for at least 2 to 2.5 percent of the truck traffic.

The purpose of the study presented in this section is to determine, by using an AASHO procedure (17), shoulder sections designed for the anticipated traffic. Both asphalt and PCC shoulder designs were developed for 1, 2.5, and 5 percent shoulder encroachment.

Asphalt Concrete Shoulder Design

The required structural number (SN) of the shoulder section was calculated by using the AASHO equation for flexible pavements (17). A computer solution of the equation was used for the variables given in Table 7 for terminal serviceability indexes (P_t) of 2.5 and 3.0. To illustrate for flexible shoulders the structural sections required by the AASHO equation (17), three alternative sections were

Figure 2. Distribution of outside shoulder encroachments.

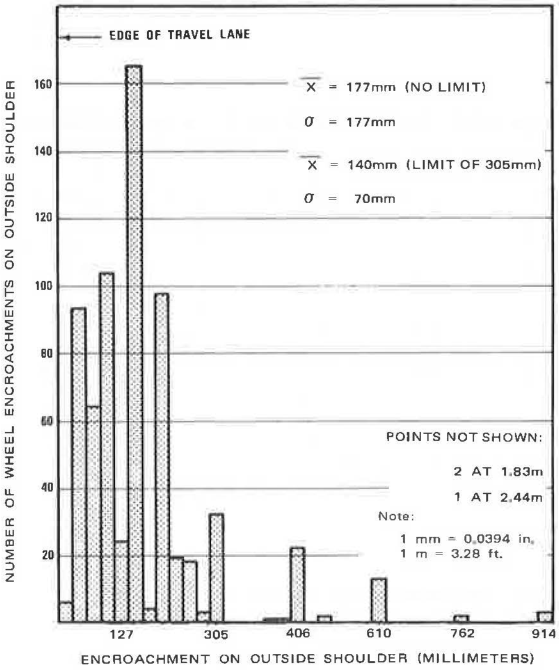

Table 6. Encroachments on outside shoulder by type of terrain.

Type of Terrain	Total Trucks	Trucks Encroaching	Encroachments	Avg. Encroachments per Truck Encroaching	Avg. Encroachments per Truck
Flat	67	43	190	4.42	2.84
Rolling	134	87	480	5.52	3.58
Hilly	4	3	7	2.33	1.75
All terrain	205	133	677	5.09	3.30

Table 7. Structural numbers for flexible pavements.

Traffic Number	P_t	Regional Factor 0.5			Regional Factor 1.0			Regional Factor 5.0		
		SS 3	SS 5	SS 10	SS 3	SS 5	SS 10	SS 3	SS 5	SS 10
10^6	2.5	4.11	2.86	1.27	4.69	3.31	1.45	6.06	4.61	1.95
	3.0	5.56	3.50	1.28	6.25	4.45	1.47	7.84	6.15	2.02
10^5	2.5	2.54	1.84	0.76	2.92	2.09	0.90	4.11	2.85	1.27
	3.0	2.85	1.90	0.76	3.64	2.20	0.90	5.56	3.50	1.28
10^4	2.5	1.65	1.18	0.38	1.88	1.36	0.48	2.54	1.84	0.76
	3.0	1.68	1.20	0.38	1.94	1.38	0.48	2.54	1.90	0.76
10^3	2.5	1.05	0.70	—	1.21	0.83	0.16	1.65	1.19	0.38
	3.0	1.01	0.70	—	1.22	0.38	0.16	1.69	1.20	0.38

Note: SS = soil support.

Table 8. Examples of design thickness for flexible shoulder.

Shoulder Traffic Number	Equivalent Main-Line Traffic Number	Truck Usage of Inside Edge of Shoulder (%)	Material	Thickness (cm) Conven-tional	Cement-Stabilized Base	Full-Depth Asphalt Concrete
1 × 10^4	1 × 10^6	1	AC	7.6	5.1	7.6
	4 × 10^5	2.5	ATB	—	—	5.1
	2 × 10^5	5	CTB	—	12.7	—
			AB	10.2	—	—
			Total	17.8	17.8	12.7
1 × 10^5	1 × 10^7	1	AC	10.2	7.6	7.6
	4 × 10^6	2.5	ATB	—	—	14.0
	2 × 10^6	5	CTB	—	15.2	—
			AB	21.6	—	—
			ASB	—	10.2	—
			Total	31.8	33.0	21.6
1 × 10^6	1 × 10^8	1	AC	12.7	12.7	7.6
	4 × 10^7	2.5	ATB	—	—	29.2
	2 × 10^7	5	CTB	—	15.2	—
			AB	45.8	—	—
			ASB	—	30.5	—
			Total	58.4	58.4	36.8

Notes: 1 cm = 0.394 in.
a_1 = 0.44 for AC; a_2 = 0.30 for ATB; a_2 = 0.20 for CTB; a_2 = 0.14 for AB; a_3 = 0.11 for ASB.

Table 9. Design slab thicknesses in centimeters for a rigid pavement with a terminal serviceability index of 2.5.

Traffic Number	Modulus of Elasticity (6 Pa)	FS[a] = 2.8 MPa[b] SR[c] = 0.41 MPa	SR[c] = 0.69 MPa	SR[c] = 2.76 MPa	FS[a] = 4.8 MPa[b] SR[c] = 0.41 MPa	SR[c] = 0.69 MPa	SR[c] = 2.76 MPa	FS[a] = 6.9 MPa[b] SR[c] = 0.41 MPa	SR[c] = 0.69 MPa	SR[c] = 2.76 MPa
10^6	6.9	24.1	23.4	18.3	16.8	15.2	—[d]	21.2	10.2	—[d]
	29.0	25.7	25.2	23.4	19.1	18.3	15.5	14.5	14.0	10.4
	41.4	25.9	25.7	23.9	19.3	18.8	16.5	15.0	14.5	11.9
10^5	6.9	15.0	13.5	—[d]	9.4	—[d]	—[d]	—[d]	—[d]	—[d]
	29.0	17.3	16.8	13.7	11.9	11.2	—[d]	9.4	8.9	—[d]
	41.4	17.8	17.3	19.7	12.2	11.7	8.9	9.7	9.1	—[d]
10^4	6.9	7.9	—[d]	—[d]	—[d]	—[d]	—[d]	—[d]	—[d]	—[d]
	29.0	10.9	10.4	—[d]	7.9	7.1	—[d]	6.1	4.8	—[d]
	41.4	11.2	10.7	—[d]	8.1	7.6	—[d]	6.6	5.8	—[d]

Note: 1 cm = 0.394 in. 1 Pa = 0.000 145 lbf/in^2.

[a] FS = flexural strength. [b] Working stress = 75 percent of flexural strength. [c] SR = subgrade reaction. [d] Did not converge.

Table 10. Required concrete shoulder thickness with and without a 15.2-cm subbase.

Shoulder Traffic Number	Equivalent Main-Line Traffic Number	Truck Usage of Inside Edge of Shoulder (%)	Shoulder Slab Thickness (cm) On Subgrade	On Subbase
1 × 10^4	1 × 10^6	1	7.6	—
	4 × 10^5	2.5		
	2 × 10^5	5		
1 × 10^5	1 × 10^7	1	12.7	—
	4 × 10^6	2.5		
	2 × 10^6	5		
1 × 10^6	1 × 10^8	1	19.1	15.2
	4 × 10^7	2.5		
	2 × 10^7	5		

Note: 1 cm = 0.394 in.

studied. The thickness of the asphalt concrete surface is fixed at 7.6 cm (3 in) for the conventional asphalt concrete shoulder section; the asphalt surface is fixed at 5.1 cm (2 in) for cement-treated base sections; cement-treated base thicknesses are fixed at 15.2 cm (6 in). The full-depth asphalt concrete sections had a surface course thickness of 7.6 cm (3 in). The calculated thickness of the remaining layers is determined by using the AASHO equation (17):

$$SN = a_1D_1 + a_2D_2 + a_3D_3 \tag{1}$$

where

a_1, a_2, and a_3 = layer coefficients and
D_1, D_2, and D_3 = layer thickness.

Examples of design thickness for flexible shoulders are given in Table 8 for a regional factor of 1.0, soil support of 3.0, and a P_t of 2.5. The material codes used in Table 8 are the same as those used in Table 1. Consider, for example, the results given in Table 8 for a main-line design traffic of 4 × 10^6 equivalent 80.1-kN (18-kip) axle loads and a 2.5 percent truck usage of the inside edge of the shoulder. For these design considerations, a 7.6-cm (3-in) asphalt concrete surfacing and 14-cm ($5\frac{1}{2}$-in) asphalt-treated base would be required. The theoretically equivalent aggregate and cement-treated base sections from the AASHO procedure (17) are also given in Table 8 and could be used as alternate designs. The 21.6-cm ($8\frac{1}{2}$-in) full-depth asphalt concrete shoulder section required for a main-line traffic of 4 × 10^6 axle loadings compares favorably with the shoulder designs now used by Illinois, North Dakota, Texas, and Louisiana that were gradually developed through field experience. For higher design traffic volumes, stronger shoulder sections than those currently used would be required, which is also illustrated by the data given in Table 8.

PCC Shoulder Design

The required design slab thickness obtained by using the AASHO rigid pavement equation (17) is given in Table 9 for the indicated range of variables and a terminal serviceability index of 2.5. The AASHO rigid pavement equation (17) was solved by using a computer. The concrete slab was assumed to be supported either directly on a subgrade having a Winkler modulus of 1661 kg/dm^3 (60 lb/in^3) or by a 15.2-cm (6-in) high-quality subbase with an overall effective Winkler modulus of 11 072 kg/dm^3 (400 lb/in^3).

Table 10 gives a summary of the required slab thickness by using the rigid equation with and without a 15.2-cm-thick (6-in-thick) high-quality subbase. From this table, a 19.1-cm-thick (7½-in-thick) slab is required when placed directly on the subgrade and a 15.2-cm-thick (6-in-thick) slab is required for a 15.2-cm (6-in) high-quality subbase for a main-line design traffic of 4×10^7 axle loadings and a shoulder encroachment of 2.5 percent. These theoretically required slab thicknesses are quite similar to sections currently used by many states as shown by the data given in Table 2. In Table 10, $P_t = 2.5$, modulus of elasticity of concrete = 29 GPa (4.2×10^6 lbf/in^2), and flexural concrete strength = 4.8 MPa (690 lbf/in^2).

DESIGN IMPLICATIONS

The field observations have shown that shoulder distress is primarily concentrated within approximately 61 cm (24 in) of the longitudinal pavement-shoulder joint. Longitudinal cracking of shoulders having relatively thin structural sections in areas of severe winters is likely to occur during the first winter that traffic is on the pavement. For similar shoulders constructed in the fall and left untrafficked through the first winter, little or no cracking develops. Furthermore, the distribution of truck traffic found to encroach on the shoulder very closely coincides with the usual location of primary shoulder cracking. These findings indicate that a significant part of the structural damage occurring near the longitudinal joint is the result of the application of heavy truck traffic to the edge of the shoulder. In general, cracking of the outer two-thirds of the shoulder is not a significant problem. Premature cracking in the vicinity of the outside edge of the shoulder for asphalt concrete surface thicknesses less than about 5.1 cm (2 in) in several instances is found to be the result of the surface thickness being significantly less than the specified value.

SHOULDER DESIGN PROCEDURE

The shoulder in the vicinity of the longitudinal joint should be structurally designed to carry the anticipated truck traffic. Little information is currently available on the actual usage by truck traffic of the shoulder in the vicinity of the longitudinal joint. The California Department of Transportation currently uses 1 percent of the main-line traffic for shoulder design. This study indicates, however, that, for at least rural Interstate pavements in the Southeast, truck encroachment on the shoulder due to wandering is about 2.4 percent. The mean distance of encroachment is about 17.8 cm (7 in), and almost all of the encroachments are within approximately 61 cm (24 in) of the pavement edge. In the absence of more reliable usage data, shoulders in rural areas with free-flowing traffic characteristics should probably be designed for at least 2 to 2.5 percent of the main-line truck traffic. No data were collected for truck encroachments in heavily congested urban areas.

Use of the AASHO equations (17) and 2.5 percent truck encroachment is found to give realistic structural shoulder sections based on observed field performance for both flexible and rigid pavements. The AASHO equations (17) are used in this study for illustration only; other suitable design methods could be used, depending on established practice and experience. Design methods developed for the main line, however, should only be used until suitable procedures are available for the shoulder.

When 2 to 2.5 percent of the main-line truck traffic is encroaching on the shoulder, the AASHO equations (17) show that many currently used asphalt concrete shoulder sections are underdesigned in the vicinity of the longitudinal pavement-shoulder joint. Use of full-depth asphalt concrete and PCC shoulder sections has greatly reduced distress near the longitudinal joint. These sections generally satisfy or almost satisfy the theoretically required structural numbers given by the AASHO equations (17). These theoretical results help to at least partially explain the good performance of portland cement and full-depth asphalt concrete shoulders and the relatively poor performance of weaker conventional or cement-stabilized shoulder sections.

After studying these results, we recommend that the structural shoulder section be designed for the expected amount of truck traffic due to encroachment by using currently accepted design methods. In general, construction of shoulders with sufficient structural strength to carry the expected traffic should greatly reduce the amount of distress currently experienced at the longitudinal joint. Problems with excessive water, shoulder settlements, expansive clay subgrades and frost-susceptible bases, subbases, or subgrades should be provided for separately.

Because virtually all truck encroachment apparently occurs within 61 cm (24 in) of the longitudinal joint, the potential exists for significant savings in construction costs if a shoulder design having a variable structural strength is used. Tapered sections or special, variable strength structural shoulder designs can be used to strengthen the shoulder in the critical area of heavy loading.

SUMMARY

The longitudinal pavement-shoulder joint problem is complex and the cause of a considerable amount of shoulder distress. The severity of deterioration of the shoulder in the vicinity of the longitudinal joint appears to be significantly influenced by a number of factors including the following: (a) the strength and type of the structural shoulder section, (b) traffic use of the shoulder, (c) environmental factors, (d) subgrade conditions, and, in some instances, (e) the design features of the main-line pavement.

Most of the distress is located within approximately 61 cm (24 in) of the joint and appears to be directly related to the encroachment of heavy truck traffic on the shoulder. The most important measure to minimize the observed distress is to structurally design the shoulder in the vicinity of the joint by using currently available design methods (for main-line traffic) to carry the truck traffic expected to encroach on the shoulder. In the absence of more reliable data, shoulders in rural areas with free-flowing traffic characteristics should probably be designed for at least 2 to 2.5 percent of main-line truck traffic. Additional investigations are necessary to determine design values of truck encroachment for other conditions. Further, additional work is required in the development of pavement design procedures for shoulders. Until then, procedures developed for main-line pavements, such as the AASHO equations (17), or other suitable methods should be used.

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