EFFECT OF SERVICEABILITY AND ROUGHNESS AT TRANSVERSE JOINTS ON PERFORMANCE AND DESIGN OF PLAIN CONCRETE PAVEMENT

M. P. Brokaw, Portland Cement Association

This paper covers the author's activities during the past 16 years in plain pavement evaluation. The studies include measurement of faulting by hand method, conversion of these data to slope variance, appraisal of highway user reaction to faulting roughness, measurement of cracking and patching, and survey of serviceability indexes by the PCA road meter. These performance features were related to wide spectra of pavement thicknesses, traffic, subgrade soil classification, joint spacing, and age of pavement in Minnesota, Wisconsin, North Dakota, and Iowa. Results have been expressed in a design model for the plain pavement system. Components are explained, data sources are cited, and suggestions are made for additional research and construction of test sections meeting the criteria established.

•CONCRETE pavements with closely spaced transverse joints, but without dowels and distributed reinforcement, have been in use for many years. Performance features have ranged from very good to very poor, yet the simplicity and economy of the system suggest that a method of design is needed so that the system can perform adequately in all situations.

The method finally adopted must account for the main weakness in the system, which is faulting or vertical dislocation of short pavement sections at transverse joints, and then for eventual serviceability indexes during an assigned analysis period.

Many field and laboratory studies have been reported. None has compared results of field measurements of faulting with highway user dissatisfaction, thickness of pavement, volume and weight of traffic loading, types of subgrade soil, transverse joint spacing, and age of pavement. None has attempted to relate findings to the concept of present serviceability index (PSI) developed at the AASHO Road Test.

In 1955, the Minnesota Department of Highways initiated a comprehensive, statewide survey of transverse joint faulting and pavement cracking in 74 projects having 15- and 20-ft joint spacing and 2 levels of pavement thickness. The survey was repeated in 1961 and 1967 for the purpose of establishing trends in faulting related to time and traffic loading (2).

Analysis of the 1955 data by the Portland Cement Association disclosed that faulting of Minnesota pavements was a function of average daily traffic of tractor semitrailer and combination vehicles and the square of the age of the pavement. In addition, ratings of pavement riding comfort suggested that the magnitude of tolerable faulting could be represented by statistics such as 100 percent of joints faulted 0.15 in. and more, or an average fault of about $^{6}/_{32}$ in. These factors were combined in an expression that enabled determination of the traffic level requiring joint reinforcement (3).

In 1960, the Portland Cement Association prepared a report setting forth methods of design for both plain and reinforced pavements in Minnesota (3). Pavement thicknesses were designed by load-stress analysis and by the additional requirement of joint and crack reinforcement when traffic exceeded 300 tractor semitrailer and combination

Publication of this paper sponsored by Committee on Pavement Condition Evaluation.

vehicles per day during a 35-year life to first resurfacing. The 35-year period was justified by concrete pavement survivor analysis. The method was subsequently adopted by the Minnesota Department of Highways and is contained in current concrete pavement design standards.

Research of the performance characteristics of plain pavements has continued in Minnesota and has been extended to Wisconsin, North Dakota, and Iowa to include the serviceability index concept developed at the AASHO Road Test (6, 7, 8, 9). Results were combined in a report (1) presented at a 7-state highway conference sponsored by the Minnesota Department of Highways in 1971.

The 1971 report showed that 5- and 6-in. plain pavements have greater capacity for load than previously expected and that the system can be designed for traffic levels greater than 300 tractor semitrailer and combination vehicles per day during a 35-year analysis period, but pavement thicknesses must be greater than those established for reinforced pavements by load-stress analysis. The reports also indicated that the pavements resting on subgrade soils having excellent internal drainage have substantially greater capacity for traffic load than can be attributed to customary increases in subgrade reaction (k).

PERFORMANCE MODEL

Plain pavements have a very short transverse joint spacing, usually 15 to 20 ft. Traffic and age effects are represented by deterioration (faulting and hinging) at joints. Additional breaks at intermediate points are limited if the joint spacing does not exceed about 20 ft. Therefore, the main source of pavement roughness is at joints, but with some addition from slopes in uncracked slabs between joints.

The additional slopes occur with and without faulting and contribute to total pavement roughness, depending mostly on frost effects and recovery, volume changes in subgrade, consolidation in subgrades and subbases, and time.

This hypothesis suggested that total pavement roughness (slope variance) might be the sum of uncorrelated parts such as initial constructed roughness, roughness at joints, and roughness between joints. In that event, PSI of a plain concrete pavement could be expressed by a modified AASHO equation (6), as follows:

$$\text{PSI} = 5.41 - 1.80 \log (\text{SVC} + \text{SVF} + \text{SVO} + 1) - 0.09 (\text{C} + \text{P})^{0.05}$$

where

PSI = present serviceability index,
SVC = part of slope variance due to construction,
SVF = part of slope variance due to displacement at joints,
SVO = part of slope variance between joints, and
C, P = cracking and patching according to AASHO definition.

EVALUATION OF SERVICEABILITY COMPONENTS

Constructed Roughness

Initial serviceability indexes of the 138 projects included in the study were not measured in situ. However, time-related components of pavement roughness and serviceability were extrapolated to give reasonable estimates of probable initial serviceability (1).

Errors from this method are of little consequence when pavements reach maturity and approach serviceabilities that indicate need for resurfacing. For example, a pavement constructed to an initial PSI of 4.50 might serve for a number of years before reaching a PSI of 2.50. If the same pavement was constructed to an initial PSI of 4.00 and was subjected to the same traffic loading for the same number of years, the small increase in initial slope variance reduces the terminal PSI to 2.42. This disparity in PSI numbers is a result of the unique AASHO Road Test semilogarithmic equation dealing with slope variance that tends to exaggerate serviceability indexes when roughness inputs are low. However, the disparity rapidly diminishes when initial serviceability drops below 4.0, and this points to the need for vigilant construction controls.

Once the initial serviceability index has been selected, the corresponding constructed roughness can be computed, as follows:

$$SVC = 1{,}014/10^{0.56P_o} - 1$$

where P_o = initial serviceability index.

Roughness at Transverse Joints

Eventual roughness at transverse joints has been the main deterrent to greater use of the plain pavement system. When joints are placed at a constant spacing (say, 15 or 20 ft), faulting causes a cyclical roughness input to some vehicles that creates an adverse highway user reaction that was not recognized or measured in the AASHO Road Test. In effect, this means that customary terminal serviceability indexes might not be applicable and that design should also be a function of some limitation on joint roughness.

The portion of total slope variance attributable to joint roughness was computed for each project in the study by converting manual measurements of joint faulting to slope variance at joints only (1). These, in turn, were related to traffic of tractor semitrailer and combination vehicles, age of pavement, thickness of pavement, and 2 levels of subgrade soil classification. The relations are as follows: For A-1, A-2, and A-3 subgrade soils,

$$SVF = 1.94\ TA^2/D^{5.47}$$

and for A-4, A-5, A-6, and A-7 subgrade soils,

$$SVF = 1.11\ TA^2/D^{4.60}$$

where

T = average 2-way ADT of tractor semitrailer and combination vehicles;
A = age of pavement, years; and
D = thickness of pavement, in.

Studies of terminal serviceability indexes and limitations on slope variance at transverse joints are also given in an earlier report (1). It appears that faulting creates an incipient stage of highway user dissatisfaction when SVF is greater than 12 and joints are spaced at constant 15- to 20-ft intervals. If joints are spaced at random intervals (say, 13, 19, 18, and 12 ft) and are skewed, adverse roughness input to susceptible vehicles is reduced. In that case, the terminal limit of SVF might be increased to 14. It then becomes a design factor equal in importance to terminal serviceability index.

Roughness Between Joints

In a plain pavement system, roughness between joints is caused by slopes in uncracked panels. Although some transverse cracking may develop, it is usually at long intervals if the basic joint spacing does not exceed about 20 ft. The magnitude of slopes in the panels is small if the only source of roughness is faulting at transverse joints. For example, a $\frac{1}{4}$-in. fault in a 15-ft panel could account for about $\frac{1}{80}$-in. deviation in a profilometer 9-in. gauge length. Surface texturing for skid resistance can exceed this amount. Therefore, meaningful roughness between joints must be spatial in character, probably erratic, and related mostly to profile distortions from frost effects, volume changes in subgrade, consolidation in subgrades and subbases, and exposure time.

Pavement roughness between joints ought to be influenced by pavement thickness and traffic weight and frequency of application, especially when pavement thickness is grossly inadequate for the imposed loads. In fact, this situation was observed at the AASHO Road Test where pavements less than 8-in. thick were rapidly destroyed when subjected to extreme overload. In these cases, pavement slabs were eventually shattered and slope measurements were increased by tilting and vertical displacement of segmented parts. Serviceability indexes also reached an unusual level of 1.5.

Analysis of data in 138 projects in Minnesota, Wisconsin, and North Dakota showed that roughness between joints had great variability and was not related to pavement thickness and rate of loading as long as the thickness was reasonably adequate for the rates imposed and serviceability index remained above 2.5. However, SVO did increase with time, but at a diminishing rate, for all levels of thickness regardless of the rates of loading. The analysis was extended to pavements with thicknesses of 8 to 12½ in. in the AASHO Road Test and to 6 in. in the Iowa county road system (10). The same phenomenon was observed (1), and this led to a general equation for slope variance between joints, as follows: For A-1, A-2, and A-3 subgrade soils,

$$SVO = (A + 1)^{0.58} - 1$$

and for A-4, A-5, A-6, and A-7 subgrade soils,

$$SVO = (A + 1)^{0.70} - 1$$

where A = age of pavement in years.

The idea that pavements can develop significant roughness without traffic, but at increased age, is a distinct departure from most design models. However, those familiar with the gradual increase in roughness of minor structures such as sidewalks and residential driveways or segments of heavy-duty pavement occasionally transferred to local traffic are aware of age effects alone.

Cracking and Patching

The plain pavement system is basically designed to minimize reductions in serviceability index caused by cracking of pavement slabs between transverse joints. To accomplish the objective, joint spacings have to be limited to a maximum of about 20 ft.

Pavements included in this report had both 15- and 20-ft transverse joint spacings, but both spacings were not equally represented in all variables of thickness, traffic, subgrade class, and age. Therefore, joint spacing was not differentiated in the analysis.

Composite data showed that cracking and patching increased with age of pavement and decreased with thickness of pavement. Departures from the design model indicate that projects with 15-ft joint spacing had an average serviceability index about 5.5 percent higher than those with 20-ft joint spacing.

Reduction of serviceability index for cracking and patching is

$$0.09\ (C + P)^{0.5} = 0.62 + 0.01\ A - 0.65 \log D$$

where

A = age of pavement, years; and
D = thickness of pavement, in.

DESIGN MODEL AND STATISTICAL SIGNIFICANCE

Design Model

The design model for plain concrete pavement is the summation of performance components developed in previous sections of the paper. Limitations are as follows: Faulting slope variance should not exceed 14; terminal serviceability index should not be lower than ordinary values, such as 2.0 to 2.2 for residential streets, 2.2 to 2.4 for county roads or lightly traveled secondary state routes, and 2.4 to 2.6 for important Interstate and primary highways; pavements should be constructed with random spacing and skewed joints; subgrade and subbase material should meet established criteria for resistance to pumping; and time, represented by age of pavement, should be the interval between construction and first resurfacing.

The design model is as follows: For A-1, A-2, and A-3 subgrade soils,

$$PSI = 5.41 - 1.8 \log \left[1{,}014/10^{0.56P_o} + 1.94\ TA^2/D^{5.47} + (A + 1)^{0.58} - 1\right] - 0.01A + 0.65 \log D - 0.62$$

and for A-4, A-5, A-6, and A-7 subgrade soils,

$$PSI = 5.41 - 1.8 \log \left[1{,}014/10^{0.56P_o} + 1.11\ TA^2/D^{4.60} + (A + 1)^{0.70} - 1\right] - 0.1A + 0.65 \log D - 0.62$$

where

PSI = serviceability index following years of service A after construction;
P_o = serviceability index constructed;
T = 2-way average ADT of tractor semitrailer and combination vehicles during years of service A;
A = years of service after construction and to reaching PSI; and
D = thickness of pavement, in.

Sample solutions of the model for a wide range of conditions are given in Table 1.

Statistical Significance

Measures of statistical significance are made possible by comparing observed serviceability indexes with those computed by use of the design model. Two methods were used. The first involved transformation of differences to a percentage increase or decrease from model serviceability index. This method simplifies comparisons among the various levels of thickness, joint spacing, traffic, subgrades, and age and also facilitated graphical representation of the data (4). A summary of percentage differences between observed and model serviceability indexes is given in Table 2.

Average differences and standard deviations of the averages were computed and subjected to null hypothesis to determine whether the differences were a result of sample variation or whether the model did not fully account for variations in each level. The following conclusions were drawn.

1. For 138 projects, including 2 levels of joint spacing, 4 levels of pavement thickness, 2 levels of subgrade soils, combination traffic ranging from 0 to 1,000 vehicles per day, ages ranging from 10 to 21 years, and serviceability indexes ranging from 2.51 to 3.91, the model is able to predict serviceability indexes with a mean error of +0.9 percent. Standard deviation of the differences amounts to 7.2 percent, and the standard error of the group mean is 0.6 percent. Null hypothesis indicates that the mean error of 0.9 percent can be attributed to sample variation and that the model equation is dependable.

2. Effects of the 2 levels of joint spacing are important. When these are analyzed separately, pavements with 15-ft joint spacing showed a mean serviceability index 3.7 percent greater than the model and those with 20-ft spacing had a mean serviceability 1.8 percent lower than the model. Null hypothesis indicates that the differences are greater than sample error, and the model does not account for either extreme in the best possible way. The discrepancy was expected because all joint spacings were pooled. Furthermore, the data point out superior performance of joints spaced at 15-ft intervals, and they do not preclude use of the model in a plain pavement system having random joint spacings ranging from about 12 to 20 ft.

3. Other items, tested by null hypothesis, showed differences beyond sample error when joint spacings were not equally divided. For example, 8-in. pavements performed significantly better than the model, and 10-in. pavements were lower than the model. In these cases, 8-in. pavements were represented by 62 percent of projects with 15-ft spacing, and 10-in. pavements all had 20-ft spacing. The same disparity to 15-ft joint spacing appeared in analysis of 105 projects carrying less than 300 combinations per day and in the group of projects that were more than 16 years of age.

Table 1. Design for plain pavement based on random-spaced and skewed joints, terminal SVF of 14, and initial PSI of 4.5 to 4.0.

Subgrade Soil[a]	Pavement Thickness (in.)	Design Life (years)	Final PSI	Initial TST-ADT and Growth/Year[b] 0 Percent	1 Percent	3 Percent	5 Percent
A-1, A-2, A-3	6	25	2.6 to 2.4	200	175	145	120
		30	2.5 to 2.3	140	120	95	80
		35	2.5 to 2.3	105	90	70	55
	7	20	2.8 to 2.7	750	680	575	500
		25	2.7 to 2.6	480	425	350	295
		30	2.6 to 2.5	335	290	230	190
		35	2.6 to 2.5	245	210	160	130
	8	20	2.8 to 2.7	1,450	1,320	1,190	965
		25	2.8 to 2.7	925	820	670	570
		30	2.7 to 2.6	690	600	475	395
		35	2.7 to 2.6	510	435	335	270
	9	20	2.9 to 2.8	2,960	2,690	2,290	1,970
		25	2.8 to 2.7	1,900	1,690	1,380	1,170
		30	2.7 to 2.6	1,320	1,150	910	755
		35	2.7 to 2.6	970	825	635	515
	10	20	2.9 to 2.8	5,290	4,800	4,060	3,520
		25	2.8 to 2.7	3,390	3,020	2,460	2,090
		30	2.7 to 2.6	2,340	2,040	1,610	1,340
		35	2.7 to 2.6	1,730	1,470	1,135	925
A-4, A-5, A-6, A-7	6	25	2.6 to 2.4	75	65	55	45
		30	2.5 to 2.3	50	45	35	30
		35	2.5 to 2.3	40	35	25	20
	7	20	2.7 to 2.6	245	225	190	165
		25	2.6 to 2.5	155	140	115	95
		30	2.5 to 2.4	110	95	75	65
		35	2.5 to 2.4	80	70	50	45
	8	20	2.7 to 2.6	450	410	345	300
		25	2.6 to 2.5	290	260	210	180
		30	2.6 to 2.5	200	175	140	115
		35	2.6 to 2.5	150	130	100	80
	9	20	2.8 to 2.7	775	705	595	515
		25	2.7 to 2.6	500	445	365	310
		30	2.6 to 2.5	345	300	240	195
		35	2.6 to 2.5	255	220	165	135
	10	20	2.8 to 2.7	1,260	1,145	970	840
		25	2.7 to 2.6	805	715	585	495
		30	2.6 to 2.5	555	480	385	320
		35	2.6 to 2.5	415	355	270	220
	11	20	2.8 to 2.7	1,960	1,780	1,370	1,310
		25	2.7 to 2.6	1,240	1,100	900	765
		30	2.6 to 2.5	860	745	595	490
		35	2.6 to 2.5	640	545	420	340
	12	20	2.8 to 2.7	2,910	2,640	2,240	1,940
		25	2.7 to 2.6	1,820	1,620	1,325	1,120
		30	2.7 to 2.6	1,300	1,130	895	740
		35	2.7 to 2.6	955	810	625	510
	13	20	2.8 to 2.7	4,220	3,840	3,250	2,820
		25	2.7 to 2.6	2,700	2,400	1,960	1,660
		30	2.7 to 2.6	1,880	1,640	1,300	1,070
		35	2.7 to 2.6	1,385	1,180	910	740

[a]Classes according to AASHO M 145.
[b]Initial TST-ADT is the maximum permissible volume of tractor semitrailer and combination vehicles at the beginning of the analysis period, which corresponds to design life. These amounts have been adjusted to account for 3 exemplary rates of annual growth during the analysis period.

Table 2. Statistical summary.

Item	Compare	Projects	Mean Difference Between Observed and Model PSI (percent)	Standard Deviation of Group Mean	Null Hypothesis t
All	All	138	+0.9	0.6	1.5
Joint space, ft	15	69	+3.7	0.9	4.1[a]
	20	69	-1.8	0.7	2.6[a]
Pavement thickness, in.	7	29	-1.1	1.4	0.8
	8	95	+2.1	0.7	3.0[a]
	9	7	-1.2	1.5	0.8
	10	7	-3.6	1.4	2.6[a]
Subgrade soil	A-1, A-2, A-3	42	+0.5	1.0	0.5
	A-4, A-5, A-6, A-7	96	-1.1	0.8	1.4
TST-ADT	0 to 300	105	+1.6	0.7	2.3[a]
	300 to 600	15	+0.5	1.4	0.4
	600 to 1,000	18	-1.6	1.2	1.3
Age, years	10 to 15	51	-0.6	0.8	0.7
	16 to 21	87	+2.3	0.8	2.9[a]

[a]Exceed sample error at 5 percent level of statistical significance.

The second method of statistical analysis was a simple linear regression relating observed and model serviceability indexes. The degree of correlation was influenced considerably by lack of initial data for all projects. However, the nature of the model equation is such that initial observed serviceability is that obtained by road meter measurement, which is affected by within-test variability. Initial model serviceability is additionally increased by variance related to SVF and SVO as time approaches or equals 0. Combination of all variances (those estimated at P_0 and those measured at P_t) resulted in a correlation coefficient of 0.91 and standard error of 0.22, of which 0.08 can be attributed to measurement variation.

CONCLUSIONS

The performance equations provide a new approach to evaluation and design of plain pavements. Both serviceability index and a limit to transverse joint faulting are recognized. The method is unique in that it relates component parts of roughness slope variance to pavement thickness, joint spacing, traffic, subgrade soils, and age of pavement.

Weaknesses in the analysis are mostly a result of unequal partition of projects among model variables, restriction of project samples to a northern climatic environment, lack of data from projects where subgrade soils or granular subbases or both are specially treated with a variety of additives, and limitation of pavement thickness to 10 in. Strength of the analysis rests in the range of pavement ages and the fact that a high percentage of projects are still in service in 1973, with ages ranging to 27 years in both Minnesota and Wisconsin.

Companion studies of field performance are now under way in Georgia and California. These should give direction to the influences exerted by special subbases and benign climate. Recent construction (1972-1973) of 14-in. plain pavement, with random-spaced and skewed joints but without subbase on native silty-clay subgrade soil, in the western extension of the Illinois Tollway will offer another opportunity to evaluate performance features at an early age.

Continued use of and observation of excellent performance of 6-in. pavements on the Iowa county road system show that experimentation is no longer needed in this category. It is hoped that highway departments and the Federal Highway Administration will initiate and construct additional sections of thick plain pavement that meets the requirements set forth in this paper.

ACKNOWLEDGMENTS

Collection and interpretation of pavement performance data during a 16-year period were made possible by the cooperation and assistance provided by many people. Officials and engineers of the Minnesota, Wisconsin, North Dakota, and Iowa highway and transportation departments afforded sites for survey and project data essential for the report. The author wishes to thank each of these, and especially John Swanberg, formerly chief engineer of the Minnesota Department of Highways, who immediately recognized the value and authorized the continuing surveys of plain pavement performance in 1956.

REFERENCES

1. Performance and Design of Concrete Pavements Without Dowels and Distributed Reinforcement. Portland Cement Association, Nov. 1971.
2. Pavement Performance Survey—Final Report. Minnesota Department of Highways, 1968.
3. Concrete Pavement Designed for Minnesota Traffic. Portland Cement Association, Sept. 1960.
4. Plain Concrete Pavement Designed for Minnesota Traffic. Portland Cement Association, June 1972.
5. Plain Concrete Pavement Designed for Minnesota Traffic on Secondary Roads and City Streets. Portland Cement Association, Nov. 1972.

6. The AASHO Road Test: Report 5—Pavement Research. HRB Spec. Rept. 61E, 1962.
7. Carey, W. N., Jr., Huckins, H. C., and Leathers, R. C. Slope Variance as a Measure of Roughness and the CHLOE Profilometer. HRB Spec. Rept. 73, 1962, pp. 126-137.
8. Brokaw, M. P. Development of the PCA Road Meter: A Rapid Method for Measuring Slope Variance. Highway Research Record 189, 1967, pp. 137-149.
9. Brokaw, M. P. A 5-Year Report on Evaluation of Pavement Serviceability With Several Road Meters. HRB Spec. Rept. 116, 1971, pp. 80-91.
10. Bester, W. G. Performance of Concrete Pavements on County Roads in Iowa. HRB Spec. 116, 1971, pp. 174-178.
11. California Pavement Faulting Study. California Division of Highways, Jan. 1970.
12. Pavement Faulting Study: Extent and Severity of Pavement Faulting in Georgia. Georgia Department of Transportation, May 1972.