FAULTING OF PORTLAND CEMENT CONCRETE PAVEMENTS

D. L. Spellman, J. H. Woodstrom, and B. F. Neal, California Division of Highways

The findings from a previous field investigation of the causes of faulting of portland cement concrete pavements are summarized, and possible corrections are discussed. Details are given of a number of experimental shoulder features that have been incorporated into construction projects. Also reported is a laboratory study of lean concrete base (wet-lean cement-treated base). This material could be placed with a slip-form paver using internal vibration. Advantages would be the elimination of trimming of cement-treated bases and a superior abrasion resistance. Other experimental construction and design features that could have an effect on faulting are briefly covered.

•THE term faulting refers to the vertical displacement of concrete paving slabs at joints. As faulting progresses, riding quality is adversely affected, and cracking of the slabs may follow. Because "ride" is influenced by several factors, including vehicle wheelbase, suspension, and weight, there is some disagreement on the degree of faulting that seriously affects ridability. On a moderately faulted pavement (e.g., 0.12 to 0.25 in.), some vehicles may not be affected, but drivers of trucks and a number of the lighter-weight cars may feel considerable discomfort.

"Pumping" or "blowing" has long been considered to be associated with faulting. In 1946 California adopted the cement-treated base (CTB) for use under portland cement concrete (PCC) pavements. This greatly reduced pumping at joints, but it was not until about 1960, when the CTB was widened 1 ft on each side of the pavement, that edge pumping was virtually eliminated. Very little evidence of pumping is now seen, but some faulting is still occurring. In past years, faulting did not appear to be serious until pavements were about 12 to 15 years of age. More recently, a few projects were found to develop moderate faulting within 5 years after construction.

A limited statewide faulting survey of PCC pavements constructed since 1960 was made in early 1968. The survey consisted of selecting random locations on each project and measuring the vertical displacement, if any, at approximately ten consecutive joints. These are undoweled joints either at standard 15-ft spacing or at our current spacing of 13, 19, 18, and 12 ft. Because of traffic conditions in urban areas, measurements were made only on rural highways, although many of the urban freeways were driven and many conditions were observed.

Pavements in all areas of the state were found to be about equally subject to faulting. Generally, only the outside or truck-lane joints are faulted, with the greater magnitude at the outer edge and a lesser amount at the inner edge. There were a few exceptions noted, especially near urban areas where there are three or more lanes in each direction and a heavy concentration of truck traffic in all lanes. It was also noted that there was usually less faulting in urban areas. This may be attributable to the fact that better drainage is provided by curbs and gutters and more paved areas, thus decreasing the chance of water getting under the pavement.

Of the projects surveyed, 85 were in the age range of 3 to 8 years. Of these, 12 had experienced some faulting greater than 0.10 in., and four of the projects had some joints that were faulted 0.15 in. or more. It is reasonable to assume that faulting will continue to increase on these projects. To check on the progression of faulting and the

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effect of seasonal changes, we established test sections throughout the state. Both new and old pavements were selected in areas that include the coastal, valley, mountain, and desert regions of California, and measurements are being made at 3- to 4-month intervals.

In 1968 and 1969, field investigations were carried out to determine the cause (or causes) of the faulting observed. The research was done with the cooperation of the Federal Highway Administration and the assistance of the Portland Cement Association in the form of manpower and specialized equipment. More detailed information on the 1968-69 investigation is given elsewhere (1).

A total of 14 openings were made at pavement joints in three different geographical regions: valley, coastal, and mountain. Ten of the joints were faulted in amounts varying from 0.10 to 0.30 in. At each site, a section of concrete 3 ft wide and approximately 3 ft on either side of the joint was removed. At each faulted joint, a buildup of granular material was found under the approach slab and, in some cases, under the leave slab as well, though to a lesser degree. ("Approach" and "leave" refer to the slabs on either side of transverse joints. If traffic is considered as moving from left to right, the approach slab is on the left and the leave slab is on the right). The buildup differential was approximately equal to the amount of the fault. There was no evident settlement or faulting of the cement-treated base.

At several locations, tracer sands were placed under slabs near the joints and under the shoulder pavement prior to removal of the 3- by 6-ft sections. Upon exposure, definite evidence of strong water action was found under the leave slab but less action under the approach slab. Small channels caused by rapid water movement were evident under the leave slab at some sites. At one location, there were indications that the water may have moved in a circular path or at least involved strong movement in a direction transverse to the centerline of the pavement in addition to longitudinal movement.

Various tests were made on the pavements and construction materials at the sites being investigated. These included strains, deflections, load transfer effectiveness across joints, joint openings and movements due to temperature changes, slab curl, compressive strength, and petrographic and chemical tests. Many of the test results have not been of particular value in determining the cause of faulting. By performing petrographic and chemical tests, however, the source of the buildup at two sites was identified. At one site, the source was the cement-treated base; at the other, it was the shoulder material. The shoulder is also suspected of being the source of the buildup at a third location. Unfortunately, on most of the projects investigated, the construction material used in the base and the shoulders was from the same source or was of similar appearance and composition; therefore, the source of the buildup could not easily be identified. The relatively high cement content (based on calcium oxide determinations) of the buildup material at most sites strongly suggests that the CTB is a major contributing source. A small amount of the material may also come through the joint from the pavement surface and possibly some from the joint interface due to the grinding action caused by slab movements.

Abrasion of the lower surface of the concrete slab is not considered a source of the buildup because in most instances the asphaltic curing seal was still intact on the slab bottom.

The effectiveness of load transfer across the undoweled transverse joints was found to be highly variable with changes in pavement temperature because of joint interlock. This indicates that, when the pavement is cooler such as in the winter months, the slabs are subject to more deflection from heavy wheel loads. Conditions that contribute to slab curl also result in higher deflections under loads.

When free water is available beneath the slabs in the vicinity of the joints, the water may be repeatedly moved in all directions under the downward deflection of the slabs caused by moving loads. As a load approaches a joint, water is moved in the leave direction relatively slowly, accumulating under the leave slab. Some water may also be forced into the shoulder area. As the load crosses the joint, there is a sudden rebound of the approach side of the joint creating suction and a sudden depression of the leave side of the joint creating pressure, which impart to the accumulated water great force and, therefore, velocity in the direction of the approach side. As the wheel load continues past the joint, the water slowly returns to the leave side. The net effect is a series of low-velocity movements of water in the leave direction and a series of high-velocity water movements back toward the approach slab. Water in the shoulder may also reenter the space beneath the slabs. The high-velocity water movements would readily carry any available loose material backward, tending to deposit particles under the approach slab. This action, repeated over a period of time, eventually causes a buildup under the approach slab and thus creates a "faulted" joint.

The following conclusions were made:

1. Faulting of PCC pavement joints is caused by an accumulation or buildup of loose material under the slabs near the joints. This accumulation may occur only under the approach slab, or it may be a differential buildup under both slabs with the thicker layer under the approach side.
2. The buildup is caused by violent water action on available loose or erodible materials that are beneath or adjacent to the slabs. The water is moved backward (and probably transversely) by the fast depression of the curled or warped slabs under heavy wheel loads and by the suction caused by the release of load on the approach slab, which erodes and transports any loose material.
3. The major sources of the buildup are the untreated shoulder material and the surface layer of the cement-treated base. Minor amounts may come from abrasion of the concrete joint interface and from material on the pavement surface moving downward through the joints.

POSSIBLE SOLUTIONS

As a result of the findings from this investigation, numerous ideas were considered as possible solutions to the faulting problem. Among these were the following:

1. Use of continuous reinforcement.
2. Use of doweled joints to eliminate curl and to promote load transfer.
3. Use of shorter joint spacing—possibly 6 to 8 ft. Although this would not eliminate curl, it would reduce the distance through which curl acts and provide tighter joints with better interlock.
4. Construction of base and pavement monolithically. Possibly, the increased thickness, rigidity, and weight would reduce curling tendencies and result in less deflection.
5. Prevention or minimization of the entrance of water. This would involve maintaining seals of all joints and cracks.
6. Construction of free drainage to the outside for any water that gets under the slab. This would reduce the time that water is available to erode base or shoulder materials.
7. Use of more erosion-resistant base and shoulder materials. Lean concrete or asphalt concrete should serve satisfactorily for base and asphalt concrete for the outside shoulder adjacent to the slab. (The shoulder next to the median is not considered to be a contributing factor to the faulting problem.) An alternative to the use of erosion-resistant material in the shoulder is the placing of a membrane seal along the edge of the slab to prevent erodible materials from getting under the slab. Erosion of the CTB is believed to be due largely to poor recementing and recompaction of the surface after trimming to grade. Possibly, the elimination of the trimming operation would enhance the erosion resistance of the CTB.

In deciding on a course of action to solve the faulting problem, we had to consider several factors. One of the most important was the effect of any change on the contractor's operation and his production. In recent years, concrete pavement production rates have increased tremendously. With two large mixers and fast-charging equipment, a central batch plant can produce approximately 800 cu yd of concrete per hour, and a slip-form paver can place that concrete at a rate of up to 30 ft/min for conventional 24-ft wide and 0.70-ft thick pavement. The use of bottom dump trucks has increased the speed of concrete delivery such that production rates of up to 2 miles of pavement in an 8- to 10-hour day are possible. These rates of production plus some changes in design and construction details are largely responsible for bid prices remaining about the same since 1956. Any construction or design change that would slow the high-speed operation would have a significantly adverse effect on bid prices. For example, on a recent project in California, it was found that, with the use of continuous reinforcement and concrete delivered from the side by belt, production rates in some cases were 50 percent lower than those of conventional pavement placing. Although production rates vary with the type and amount of placing equipment being used (and there are records of placing 2 miles of continuously reinforced concrete pavement per day), there is little doubt that, with the equipment and methods being used in California, placing costs are higher when side delivery is required. Preplaced dowels would result in similarly increased costs.

Maintaining sealed joints for the life of a pavement is considered impractical with currently available methods and materials. It was decided, therefore, that the most practical and economical solution to the faulting problem was to develop an erosion-resistant base and to prevent the movement of untreated material from the outer shoulder. Several experimental shoulder sections have been constructed and are now being monitored for performance.

EXPERIMENTAL SHOULDER SECTIONS

The following is a description of the experimental shoulder sections (outside shoulder only):

1. Four 1,000-ft sections were placed on I-880 near Sacramento. Section 1 used class 2 permeable base in lieu of the standard section of class 2 aggregate base. The shoulder was surfaced with 0.25-ft asphalt concrete (in all sections). The intent here is to reduce erodibility and to increase drainage of water from under the pavement. Section 2 is essentially the same as section 1, except that a seal of a fairly thick coating of 60- to 70-penetration asphalt was sprayed along the slab face and on the extra width of CTB before the base was placed. Section 3 is the same as section 2 except that a class 2 aggregate base was used. In section 4, asphalt concrete (AC) was placed at the full depth of the slab and the full width of the shoulder (10 ft).
2. One section was placed on I-5 near Willows in northern California. The aggregate base of the shoulder was replaced with permeable AC (very open graded) in a 1,000-ft section (Fig. 1).
3. Two 2,000-ft sections were placed on US-99 south of Sacramento. In section 1 a seal consisting of a fiberglass-reinforced plastic strip (2 ft wide) was placed along the edge of the slab and over the widened CTB in the shoulder. Aggregate base and AC were then placed as usual (Fig. 2). In section 2, the aggregate base was replaced by permeable AC (Fig. 3).
4. One 2,000-ft section was placed on I-205 south of Sacramento. A layered membrane of coal tar and fiberglass (2 ft wide) was placed along the slab and over the CTB extension as in the US-99 section.
5. Two 2,000-ft sections were placed on I-80 west of Sacramento. This was a partial shoulder replacement of a pavement that had been in service about 8 years and had moderate faulting. A 2-ft wide section of the outer shoulder adjacent to the slab was removed down to the bottom of the slab. Loose material was broomed away, a tack coat of asphalt emulsion was applied, and then 0.5-ft permeable AC and 0.25-ft dense-graded AC were used to complete the shoulder. A 2,000-ft section was replaced in both the eastbound and westbound lanes. The basic objective of this work was to eliminate erodible shoulder material from the areas adjacent to the slab to see if faulting could be arrested. In addition to providing erosion resistance, the permeable AC is expected to provide better drainage that may also help reduce faulting tendencies. Performance of the test sections will be compared to that of adjacent untreated areas (Fig. 4).

Because less than 10 percent of the aggregate passed the No. 4 sieve and 2 percent asphalt was used, there was some difficulty in compacting the permeable AC. After some experience, it was found that cooler mix temperatures and lighter rollers (6 to 8 tons) provided better results. On the shoulder replacement test section, wheel rolling in the confined area was felt to be sufficient. A steel-wheeled roller was used on the dense-graded surface course. The cost of the permeable AC under the experimental conditions was 20 to 40 percent more than the dense-graded mix.

Some difficulty was also encountered in placing the membranes. Although an asphalt emulsion was satisfactory as an adhesive for the membranes on flat surfaces, it would not hold them for a sufficient time on vertical surfaces. As a result, it was necessary to hold the membrane against the slab by hand while the aggregate base was being placed against it. Finished placement proved to be satisfactory, at least for the plastic; the shoulder was examined about 8 months after placement. The material was found to be solidly stuck to the concrete and CTB and had conformed to all irregularities caused by excess concrete left on the edge during pavement construction (Fig. 5). The material cost for fiberglass-reinforced plastic was about $600 per mile, whereas the cost of the layered coal tar and fiberglass was about three times as much. The underground life of the plastic is unknown; however, if the theory of its use is correct, it would probably be sufficient to at least delay faulting for many years.

The sections with a 60- to 70-penetration asphalt membrane were also examined about a year after construction. Although the asphalt is readily visible, there does not appear to be sufficient thickness to be fully effective as a seal in preventing erosion.

The experimental shoulder sections are being monitored on a seasonal basis. To date, there has been no difference in performance noted between experimental and control sections.

Other possible solutions to prevent erosion of shoulder materials have been considered but not tried. One is the use of a membrane that could be sprayed on, such as plastic or polyurethane foam. Another is to place a small wedge of AC next to the slab and "wheel roll" with a motor grader. Either of these methods could reduce faulting potential by eliminating the availability of loose material adjacent to the bottom of the slab.

BASE MATERIALS

Although base settlement has long been suspected as a cause of faulting, there was no evidence found during the field investigation of any such settlement. (All pavements opened had cement-treated bases.) There was, however, positive evidence of erosion of the base surface under the leave slab. The evidence was in the form of rivulets caused by water movement, which might result in some lack of uniform support but would not allow the slab to be depressed (Fig. 6). The top portion of the CTB at many locations has been found to be loosely cemented and readily erodible. Although drying of the surface before curing may be responsible for part of the problem, much is felt to be due to the trimming operation used to conform to grading tolerances. Because a high base will result in thin pavement, for which a contractor is penalized, and a low base results in the use of excessive concrete, considerable effort is exerted in obtaining the proper grade. Trimming is usually done about an hour or more after original placement. The surface material, once loosened, is never fully rebonded and so does not form a monolithic erosion-resistant base.

To eliminate the need for trimming, a local paving machine manufacturer proposed the idea of placing CTB with a slip-form paver. By adding extra cement and water to form a "wet-lean" CTB or "lean conçrete base" (LCB), the material could be vibrated internally and placed like concrete to final grade with no rolling or trimming needed. Although the manufacturer had done this in other countries, little was known of the properties of such material. A laboratory testing program was carried out to determine the advantages and disadvantages of LCB and to compare its properties with those of CTB.

Tests were performed using typical CTB aggregates from six sources. The aggregates from these sources had a representative range of characteristics such as durability, particle shape, and geological origin. The CTB specimens were fabricated by following routine procedures and by using the cement content necessary to obtain a

Figure 1. Permeable AC shoulder being placed on I-5.

Figure 2. Fiberglass-reinforced plastic placement, US-99.

Figure 3. Rolling of permeable AC, US-99.

Figure 4. Partial shoulder replacement, I-80.

Figure 5. Shoulder opening showing plastic conforming to irregularities.

Figure 6. Channels indicating water movement on CTB surface.

compressive strength of 750 psi at 7 days. Similar mixing procedures were used for LCB samples, but enough water was added such that the mixture resembled concrete with an approximate 2-in. slump. Cement contents of 6, 9, and 12 percent were used. The moisture content needed to produce the 2-in. slump was considered optimum, and other mixes were made using 1.5 percent less water and 1.5 percent more water. Aggregate gradings were also varied from the middle of the specification limits to both the fine and coarse sides of the limits. Internal vibration was used in compacting the LCB specimens.

Specimens of both materials were fabricated for comparison of the following properties: compressive strength, flexural strength, shrinkage, and abrasion loss. Tables 1 through 6 show how CTB compares to LCB made with 9 percent cement, medium grading, and optimum moisture content.

From these laboratory tests, it appears that a lean concrete mixture could be made having properties satisfactory for base. Superior abrasion resistance is a highly desirable property. Equivalent compressive strength can be achieved; LCB, however, requires approximately twice as much cement as does CTB. This increase in cost could be partially offset by the elimination of rolling and trimming equipment normally required. For some contractors, the immediate need for a central mixing plant and slip-form paver for concrete paving would be an added expense.

A few contractors have been contacted regarding a trial of LCB. Probably because of their prior planning and uncertainty, none has expressed interest in changing his method of operation.

Recently it has been noted that a few contractors are changing their CTB placing methods. They have changed to central mixing, whether required or not, and to placing with a slip-form paver. Instead of a wet mix and internal vibration, they use the regular dry mix and a vibrating screed behind the paver, followed by rollers. This results in a much harder appearing surface and trimming is seldom if ever, necessary. Unfortunately, there is no test method available for measuring the abrasion resistance of CTB in place. If the trend to the type of construction continues, our objection to CTB due to trimming may be overcome (Fig. 7).

OTHER BASE ALTERNATIVES

Asphalt Concrete

At several locations, PCC pavements have been constructed directly over old AC roadways or over AC on CTB used for detour purposes. Some of these pavements have exhibited very good performance with no apparent abrasion of the base taking place. A further trial of AC base has been planned for the near future. Cost data will be obtained, and performance will be compared to that of CTB sections and the use of CTB on the same project.

Monolithic Base and Pavement

A proposal now being considered is the construction of base and pavement in one layer, i.e., a nontreated base. As mentioned in the first faulting report, the increased thickness and weight of a monolithic slab should reduce curling and deflection. The thickness necessary to provide the desired features is now being studied. Also to be considered, however, is the effect that elimination of the widened CTB would have on pumping of the subgrade.

OTHER EXPERIMENTAL CONSTRUCTION

Continuously reinforced concrete pavement is considered as one solution to the faulting problem. Under another research project, approximately 10 miles of this type of pavement construction has been monitored. A report on construction details and comparative costs will be made at a later date. Other experimental features were incorporated into the same project, which might also be useful in preventing faulting.

Table 1. Cement and optimum moisture contents of CTB and LCB.

Sample Number	Cement Content (percent) CTB	Cement Content (percent) LCB	Moisture Content (percent) CTB	Moisture Content (percent) LCB
70-1089	3.5	9.0	8.1	10.8
70-1097	4.5	9.0	8.0	13.7
70-1122	4.0	9.0	7.8	12.5
70-1127	5.5	9.0	8.1	13.5
70-1142	5.5	9.0	6.6	12.9
70-1308	3.2	9.0	6.6	11.6

Table 2. Compressive strengths of CTB and LCB.

Sample Number	After 7 Days (psi) CTB	After 7 Days (psi) LCB	After 28 Days (psi) CTB	After 28 Days (psi) LCB	After 90 Days (psi) CTB	After 90 Days (psi) LCB
70-1089	842	765	1,055	1,119	–	–
70-1097	757	544	1,152	721	1,272	–
70-1122	738	350	541[a]	689	1,304	–
70-1127	812	450	871	692	1,131	938
70-1142	772	402	910	597	1,412	1,081
70-1308	825	640	773	1,230	884	1,437
Average	791	525	952	841	1,201	1,152

[a]Not included in average.

Table 3. Flexural strengths of CTB and LCB.

Sample Number	After 7 Days (psi) CTB	After 7 Days (psi) LCB	After 28 Days (psi) CTB	After 28 Days (psi) LCB
70-1089	50	168	89	251
70-1097	184	203	195	380
70-1122	106	56	171	231
70-1127	155	147	207	261
70-1142	154	133	207	246
70-1308	110	175	155	374
Average	126	147	171	290

Table 4. Seven-day surface abrasion losses.

Sample Number	CTB (grams)	LCB (grams)
70-1089	44.5	3.4
70-1097	16.7	0.5
70-1122	37.8	10.7
70-1127	15.4	5.0
70-1142	11.4	12.3
70-1308	4.0	1.5
Average	21.6	5.6

Table 5. Fifty-day shrinkage values.

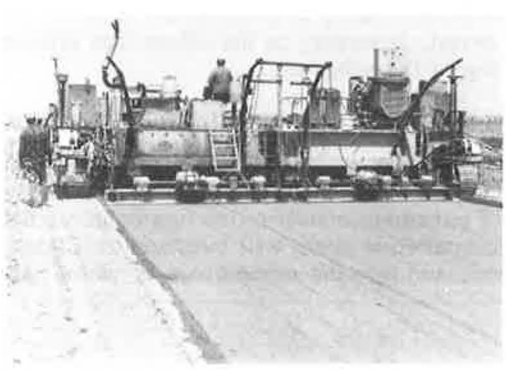
Sample Number	CTB (percent)	LCB (percent)
70-1089	–	0.032
70-1097	0.111	0.138
70-1122	0.065	0.118
70-1127	0.042	0.053
70-1142	0.029	0.032
70-1308	0.026	0.023
Average	0.055	0.066

Table 6. Properties of LCB.

Characteristic	Cement Content (percent) 6	9	12	Moisture Content (percent) Optimum - 1.5	Optimum	Optimum + 1.5	Grading Fine	Medium	Coarse	Curing Period (days) 7	28	90
Compressive strength	I	I	I	D	D	D	I	I	I	I	I	I
Flexural strength	I	I	I	D	D	D	I	I	I	I	I	I
Abrasion losses	D	D	D	I	I	I	D	D	D	D	D	D
Shrinkage	SD	SD	SD	I	I	I	D	D	D	–	–	–
Workability	SI	SI	SI	I	I	I	D	D	D	–	–	–

Note: I = increase, D = decrease, SD = slight decrease, and SI = slight increase.

Figure 7. Placing CTB with slip-form paver.



Short-Joint Spacing

Two sections of pavement with short-joint spacing were constructed. Joints were skewed (4 ft in 24 ft counter clockwise) and sawed at repeat intervals of 8, 11, 7, and 5 ft. The length of the four slabs is about one-half that of our normal spacing. A check before shoulder construction indicated that more than 80 percent of the joints had cracked on at least one side of the centerline joint soon after construction. Performance will be monitored to determine if faulting tendencies are reduced as compared to normal joint construction.

Lean Concrete Base

This base should not be confused with the type previously referred to in this report. On this project, two experimental base sections were constructed with 4-sack concrete made with concrete aggregates. The base turned out to be stronger than anticipated, with a compressive strength of more than 3,000 psi in less than 28 days. No problems with surface abrasion are anticipated in these sections, and the test section should provide more positive evidence about intrusion of shoulder material if it occurs.

7.5-Sack Concrete

Although the job control concrete contained 5.5 sacks of cement, two experimental sections were constructed with concrete containing 7.5 sacks per cubic yard. The effect of extra strength concrete on performance characteristics such as curl and deflection will be studied.

Extra-Thick Pavement

These sections were constructed 0.95 ft in thickness over 0.45-ft CTB. Although constructed as "no-fatigue" sections, it was found that the extra thickness did not present any particular construction difficulties, and it, too, should provide some interesting data relative to deflection under load.

SUMMARY

To find solutions to the faulting problem, California has so far concentrated efforts toward preventing erosion and movement of materials of the base and the adjacent portion of the outside shoulder. Several experimental sections have been constructed, and others are being planned. Test sections are being monitored on a regular basis so that conclusions can be drawn as soon as possible. In the meantime, still other possible solutions are being actively considered. It is likely that any implementation will result in an initial increased pavement cost (which can be offset later in decreased maintenance); however, if such implementation can be made without adversely affecting paving production, then the increased cost will be much less.

ACKNOWLEDGMENTS

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