IMPROVED BASE DESIGN FOR PORTLAND CEMENT CONCRETE PAVEMENTS

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BACKGROUND

In the past twenty years or so thousands of lane miles of concrete pavements have been constructed and for the most part, have carried considerably heavier traffic loads than were anticipated in the design stage. In general, these pavements have performed as expected, although there have been a variety of problems and some surprises associated with each of the approaches that have been used in concrete pavement construction. As examples, steel corrosion has been a great concern in continuously reinforced pavements; extending cement treated bases a foot beyond the edge of pavement has not totally prevented pumping; and jointed pavements develop step-off at the joints.

Concrete pavements can be classified in one of the following categories:

1. Continuously reinforced
2. Jointed reinforced
3. Non-reinforced with closely spaced contraction joints
4. Prestressed (still regarded as experimental in most states)

Despite vast differences in theoretical concepts, design justifications, construction practices, and costs of the above categories there are also striking similarities.

1. Nearly all pavements are between 8" and 10" thick.
2. Nearly all are constructed on a stabilized base.
3. The amount of longitudinal reinforcement, when used, is usually 0.6%.

An infinite variety of paving details, many of which deal with the joint between slabs, have been incorporated into design systems in an effort to achieve a "zero maintenance" pavement. That worthwhile goal is, however, yet to be attained.

California's experience with concrete pavements is almost totally limited to the non-reinforced type with "short" joint spacing. Slab lengths are in a repeated pattern of 12, 13, 19, and 18 feet. Weakened plane joints are skewed counter clockwise 2 feet in 12 feet and are constructed to a depth of 2 inches by sawing or using a tape insert in the plastic concrete. Concrete is designed to achieve a modulus of rupture of 550 psi at 28 days. A stabilized layer, referred to as cement-treated base (CTB), underlies the

pavement and extends outward one foot on each side of the slab. A subbase layer usually underlies the cement-treated base. Shoulder construction consists of asphalt concrete surfacing over untreated base material.

Concrete pavements in California are considered to have performed quite well in that the design life of the pavement is usually achieved and, in most cases, is exceeded by several years of service. One characteristic of pavement performance that is manifestly apparent in the design currently used, is that of faulting or step-off that occurs at transverse joints. All of our pavements eventually develop some degree of faulting, the magnitude and rate of which varies considerably. For the most part, it remains within tolerable limits and goes unnoticed by the traveling public. In some cases, faulting can be measured as early as a year or two after opening to traffic, although riding quality may not be affected for several years. Pavements 12 to 15 years old are occasionally found to have a step-off of 1/4 inch or more and the riding quality of the highway is adversely affected. In nearly all concrete pavements that have reached a terminal condition, severe faulting has developed. Varying degrees of shoulder distress are directly linked to the faulting condition.

The development of faulting appears to be fairly consistent within the limits of the original construction project. Whether in cut or fill or on the high or low side of superelevation, there is normally no significant difference in the degree of faulting. Its occurrence is primarily limited to the outer lane, however, it sometimes is present in the outer two lanes.

Extensive research has been conducted on the subject of faulting (1, 2, 3, 4). For this malady to occur the following conditions must exist:

1. The pavement slab must have a slight curl with the individual slab ends raised slightly off the underlying stabilized layer. (Thermal gradients and differential drying within the slab create this condition.)

2. Free water must be present.

3. Heavy wheel loads must traverse the transverse joint first depressing the approach side of the joint, then allowing a sudden rebound, while instantaneously impacting the leave side of the joint, causing a violent pumping action of the free water.

4. Pumpable fines must be present. (Untreated shoulder base material, the surface of the stabilized base, and foreign material entering the joints are, in the order listed, the sources of pumpable fines.)

The fines are driven in the direction opposite to that of traffic flow and are deposited under the approach side of the joint. The depth of buildup of these fines has been found to exactly coincide with the measured step-off on the pavement surface. Waterborne fines are sometimes ejected onto the pavement surface also.

Typical stages in the life of a concrete pavement are shown in Figure 1. In Stage 1, the initial step-off, say less than 1/16 inch, is accompanied by shoulder cracking located primarily on the down traffic side of the joint. As the step-off increases in Stage 2, the cracking is extended longitudinally and is accompanied by a shoulder depression in the vicinity of the joint. It is at this

point that maintenance of the shoulder becomes necessary. The depressions are filled with localized patches and the cracks are filled with a hot-poured sealer.

In Stage 3, the riding quality of the road is seriously affected. It may be necessary to grind the pavement, removing a tapered segment from the slab surface. Shoulder maintenance may call for a continuous patch one to two feet in width.

In Stage 4, the slabs can no longer carry traffic without breaking up because of the non-uniform support conditions. While cracks in the concrete may follow a somewhat irregular pattern, they quite often start on the outside edge of pavement, 5 or 6 feet down traffic from the joint and are skewed to the left. Step-off is in the range of 1/8 to 1/4 inch with occasional joints in excess of 3/8 inch. An overlay is necessary at this point.

In view of the foregoing observations, it seems obvious that the ultimate failure of the pavement has little relationship to considerations of design thickness, magnitude of loading, or concrete strength. The underlying problem affecting pavement performance and service life is, instead, related to physical changes that are occurring beneath the concrete slab which are caused by repetitions of axle loadings that are heavy enough to cause slab deflections. While this conclusion is arrived at from experience with non-reinforced slabs and short joint spacing, similar conditions could well exist in reinforced slab and continuously reinforced pavements with a comparable adverse effect on performance.

The drawing of a cross-section of concrete pavement fails to illustrate one important element that is present during a significant part of each day. That element is the void space associated with concrete curl due to thermal and moisture gradients and it exists beneath the slab, primarily at slab ends and edges. It is present in reinforced and non-reinforced pavements. Compacted bases under the slab and in shoulders often have low permeability and create what is referred to as a "bathtub" section. When free water is available to fill the void it has little opportunity to escape and an adverse effect on the pavement is bound to result.

Highway engineers have not yet adequately recognized the need for giving full consideration to the effects of surface water entering the structural section. Cedergren's book, "Drainage of Highway and Airfield Pavements" (5), thoroughly documents this concern by a few engineers over an extensive period of time and yet little progress has been made. Decision-makers are concerned with increased initial costs, often ignoring the possibility of reduced maintenance, improved service to the public, and extended pavement life.

To negate the ravages of surface water entrapped within the structural section certain design features must be incorporated into the typical cross-section of a concrete pavement and a non-erodible base needs to be constructed. The remainder of this paper deals with recent experience in California on these subjects.

STRUCTURAL SECTION DESIGN FEATURES

The design features to be discussed consist of either replacement materials for all or a portion of the standard untreated shoulder base material or inclusion of new design elements designed to allow the base material to function as the designer presumed. Six such features are shown in Figure 2. All of the items have been constructed at one or more locations as experimental sections and their effect on the development of faulting is being monitored. Items 1 and 2 do not improve the drainage condition but provide a barrier between the free water and the erodible shoulder base material, blocking movement of fines to the underside of the slab.

Items 3 and 4. An asphalt treated permeable material is non-erodible and effectively drains free water which enters the shoulder from beneath the pavement slab. Outlets for removal of water contained in the permeable material are necessary to prevent its acting merely as a reservoir. Where outlets are not provided, some advantage is still realized as water is readily removed from the vicinity of the joint and is distributed longitudinally in the shoulder area.

Item 5. The concrete shoulder certainly solves the problem of an erodible shoulder base and may assist in drainage of water from beneath the traffic lanes. Slab curl in the shoulder would be expected to be similar to that of the main slab allowing free water to flow to the edge of the concrete shoulder. Additional load carrying capacity in the outer traffic lane is also expected with the use of concrete shoulders.

Item 6. A low cost drainage system can be easily incorporated into new construction. The slotted polyvinylchloride (PVC) longitudinal drain is the same product as is commonly used in horizontal drains. The pipe is laid on top of the CTB adjacent to the outer edge of the pavement slab where it is readily accessible to free water. Solid PVC outfalls have been installed at 100 ft. and 200 ft. intervals on the two projects where this type of drainage system has been used. Collected water has been discharged onto the slopes of the shallow fills in the test sections. "Conventional" shoulder construction is used atop the drains.

Observations of drainage effectiveness have been quite impressive in the two years since the initial installation. Discharge during rainfall has been as high as 100 gallons per hour on individual outfalls and more significantly, flow was found to stop shortly after the cessation of rainfall, greatly minimizing the saturation period for the structural section as well as the embankment and shoulders.

A fairly extensive installation of the longitudinal drainage system is planned for the near future. In addition to the details shown in the simplified sketch in Figure 2, various collector lines become necessary as the highway is located in cut and fill sections. On high fills free discharge cannot be tolerated if the fill slopes are subject to erosion. Treatment on the high side of superelevation is open to question. It is currently believed desirable to place the drain in the same position at such locations to afford maximum protection to the outer, truck carrying lanes.

Recent costs of the 1-1/2" dia. slotted pipe have been between $0.75 and $0.85 per ft. and the solid pipe between $0.45 and $0.65 per ft. It is normally purchased in 10 or 20 ft. lengths with ends milled to provide a slip-fit connection. The only fittings required are tees to connect the outfall lines. Placement costs are nominal as very little labor is involved. A total cost, in place, of under $1.50 per foot is expected, except where a collector system is necessary.

While much is still to be learned about the performance and benefits of the longitudinal drain system, it appears to offer a significant contribution to pavement performance at minimal cost.

NON-ERODIBLE STABILIZED BASE

With the realization that the surface of cement-treated bases were erodible and provided fines that contributed to pavement faulting, the use of a lean concrete base (LCB) was investigated (6). This concept was not new, having been used in Great Britain (where it is referred to as a wet lean mix) and other foreign countries at least as early as 1957. In recent years other states, with the support of the American Concrete Paving Association, have used what is referred to as "Econocrete". Whatever term is used, the product is essentially the same, being constructed with base quality aggregate, cement contents in the range of 7 to 10%, and sufficient water to provide a plastic concrete. Mixing is done in a concrete mixer and placing is accomplished with concrete paving equipment. The material has a slump of 2 to 4 inches and forms a tightly knit uniform surface without requiring additional finishing behind the slipform paver.

In 1973, it was decided to take a serious look at this "new" structural element. A preliminary laboratory investigation was conducted to determine target strength levels and appropriate mix proportions for LCB. Following evaluation of data two paving projects were selected for large scale field trials of LCB. To provide a basis for comparison, a significant portion of each was constructed using LCB, the remainder being CTB.

Monterey Project

The first trial was conducted on a section of State Highway 1 on the Coast near Monterey. LCB was constructed on two miles of the 10 mile project. Conventional CTB was used on the remaining eight miles. LCB was placed to the same thickness (0.35 feet) and width (38 feet) as the CTB.

LCB was mixed in a central-mix concrete plant. A Guntert-Zimmerman slipform paver placed the entire 38 feet monolithically. Two longitudinal weakened plane joints, off-set one foot from the planned interior pavement lane lines, were constructed by the plastic insert method to prevent coincidental cracks in base and pavement. No transverse weakened plane joints were constructed. Pigmented liquid curing compound was applied through conventional spray equipment.

When LCB placement began, the moisture content was set at 13 percent by dry weight of aggregate and the cement content was 8.5 percent. Corresponding values for CTB were 8 percent and 5.0 percent, respectively. Aggregate gradation is shown in Table 1.

To correct surface finishing difficulties encountered in the first few hundred feet of LCB, additional water and air-entrainment were incorporated into the mix. These adjustments resulted in a smooth, sealed surface with sharp vertical edges and no further placement problems were experienced. The final moisture content was about 17 percent, producing a slump of 3 to 4 inches.

Traffic was prohibited on the LCB for 72 hours after placement. At the end of this period the contractor started concrete paving operations. Very few transverse cracks could be found in the base at that time.

The base was not used as a haul road, however, maneuvering of loaded concrete trucks was permitted ahead of the slipform paver. There had been apprehension concerning the affect of heavy wheel loads on the LCB at early ages. To determine relative stiffness, Dynaflect measurements were made at ages up to 5 days and compared to measurements obtained on CTB at the same ages. Although there was some variability in the results, it appeared there was no significant difference in the deflections.

On the whole, the trial was considered successful. The contractor was satisfied with production rates and considered the early placement problems to be minor. He also concluded that his overrun of paving concrete was less on the lean concrete base than on the cement treated base.

In 1975, cores were obtained and tested to compare uniformity of lean concrete base and cement treated base. Six cores of each material were broken in compression. Average strength of the LCB was 1575 psi, ranging from 1525 to 1630, while that of the CTB was 1510 psi, ranging from 1310 to 1830. A more uniform product is thus indicated for LCB.

Compton Project

The second trial was conducted on a section of State Highway 91 just south of Los Angeles. This amounted to constructing about 10,000 cubic yards of LCB on 3 miles of an 8-lane highway, approximately half of the total project. As with the Monterey trial, longitudinal weakened plane joints, offset 1 foot from the planned interior pavement lane lines, were constructed by the plastic insert method. No weakened plane joints were constructed and curing was accomplished with pigmented liquid curing compound.

Aggregate for both the LCB and the CTB was made from reclaimed roadway material consisting of broken concrete pavement, cement treated base, asphalt concrete pavement, curbs, drop inlets and other miscellaneous waste. The aggregate was produced at the jobsite with 3/4-inch maximum size for CTB and 1-1/2-inch maximum size for LCB. Grading for the LCB is shown in Table 1.

A top size of 3/4-inch is conventionally specified for CTB to minimize tearing and loosening the surface during fine grading operations. Since the LCB is vibrated into place by the slipform paver, 1-1/2-inch top size could be used without adverse effect upon the surface and some savings in crushing costs could be realized.

For this project the moisture content was about 16 percent, cement content was 8 percent and entrained air varied from 3 to 4 percent.

It is interesting to note that 6 to 9 percent air was naturally entrained, possibly because of road oils or the presence of asphalt in the reclaimed aggregate. In order to avoid the higher strength loss with so much entrained air, Tributyl Phosphalt air detraining agent was used to reduce the air content to between 3 and 4 percent.

A modified Blaw-Knox slipform paver was used to place the LCB monolithically 50 feet wide and 0.4 foot thick. No further finishing was performed and curing compound was applied almost directly behind the paver.

As contrasted with the Monterey project, no placement problems at all were encountered. The finished LCB had the appearance of a conventional PCC pavement slab except that it lacked the pavement surface texture.

On this project loaded concrete trucks had to use the stabilized base as a haul road. At a number of locations in the CTB section extensive damage resulted which required subsequent removal and reconstruction. In vivid contrast, no cracking or evidence of other damage due to the hauling occurred in the LCB.

Just before pavement was placed, Benkelman beam deflection measurements (18,000 lb. single axle load) were made on about 1000 feet of each type of base. Both sections were 19 days old. Deflections of the CTB ranged from .012 to .040-inch with an average of .024-inch. For the LCB, the range was .008 to .021-inch with an average of .012-inch. The greater stiffness of the LCB may provide a bridging action and account for the lack of damage from the loaded haul trucks.

Four sets of samples were taken from each of the two types of base for compressive strength tests. Cores were taken after about three weeks for 28-day breaks. Additional cores were taken at about 12 weeks for 91-day tests. Results are shown in Table 2.

In analyzing the strength data one must be aware that there are vast differences in the techniques of fabricating the field specimens. Since LCB is a plastic concrete it is treated as such and the 6 x 12 cylindrical specimens are fabricated in the same manner as concrete. The 6 x 6 cylindrical specimens are fabricated in a similar manner, by placing two layers of material in the container and rodding each 25 times. By contrast, CTB specimens are fabricated in accordance with Test Method No. Calif. 312, which prescribes a considerable compactive effort with a tamping rod, followed by applying a 15,000 pound sustained load for a period of one minute. Specimen strengths for CTB indicate a much higher strength than is actually obtained in the roadbed. A realistic comparison of in place strengths of LCB and CTB is shown by the 5-inch cores, where the LCB is seen to be significantly greater.

As at Monterey, the concensus of opinion of those who witnessed the LCB operation thought it was an excellent method of constructing base for portland cement concrete pavement. The finished product is believed to be superior structurally to CTB and will definitely be more erosion resistant.

Based upon performance observations and the test data generated on the Compton project, it appears safe to design LCB with 0.05-foot less thickness than CTB. The savings associated with the reduced thickness, plus savings in paving concrete afforded by construction on a smoother subgrade, result in a comparable total cost even though the LCB has a higher cement content by about 3 percent. Other advantages in the use of LCB are: (1) A reduction in equipment needs and set-up, as the same mixing, placing, and curing equipment used for concrete pavements is used for LCB; (2) The processes of soil compaction and fine trimming are eliminated; and (3) Inspection is simplified and less costly.

SUMMARY

Improvements in base designs in shoulder areas and beneath pavement slabs are essential to attain better performance from concrete pavements. Such improvements need to take into account the presence of free water and the sources of transportable fines which are: (1) Untreated shoulder bases; (2) Erodible base beneath the pavement slab; and (3) Extraneous fines entering through pavement joints. Fine material becomes redeposited beneath the pavement slab resulting in an alteration of support conditions which leads to adverse performance and ultimate failure.

The design features presented depict some recent developments directed at a solution to these problems. Field experience is limited at this time but initial observations provide a basis, for optimism, especially with respect to the effectiveness and economy of a shoulder drainage system and the use of lean concrete base. In addition, sealing of joints in all concrete pavements may be advisable to minimize the entry of surface water and, possibly of more importance, to preclude the entry of fines.

Further research and large scale trial installations are needed and cost-effectiveness needs to be examined. In an effort to accelerate findings, California also plans to proceed with near full scale laboratory model studies. Simulated loading and environmental conditions will be constructed in the laboratory and it is hoped that a faulting condition can be created in as little as a month or two of repetitive loading. Should this phase of the project be successful, it will then become possible to quantitatively determine the benefits of various design features in a similar time span. Findings will be implemented in the construction of new highways as well as reconstruction and rehabilitation on older ones.

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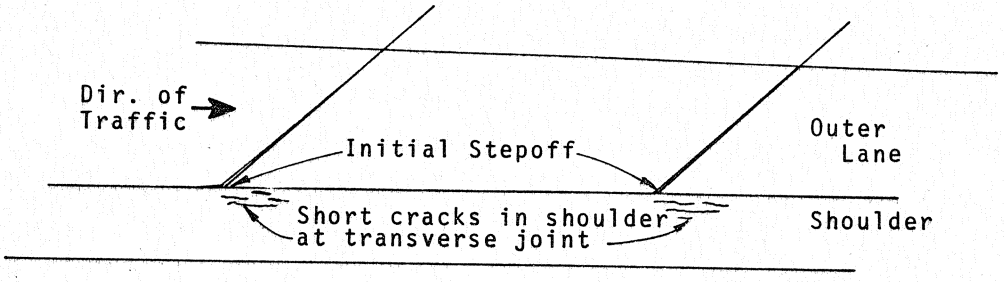
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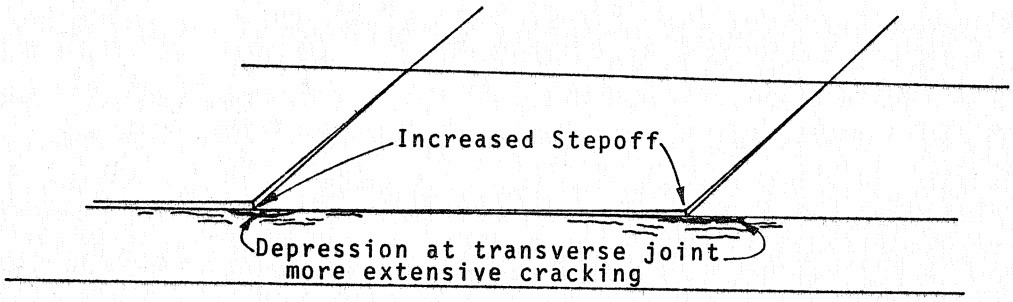
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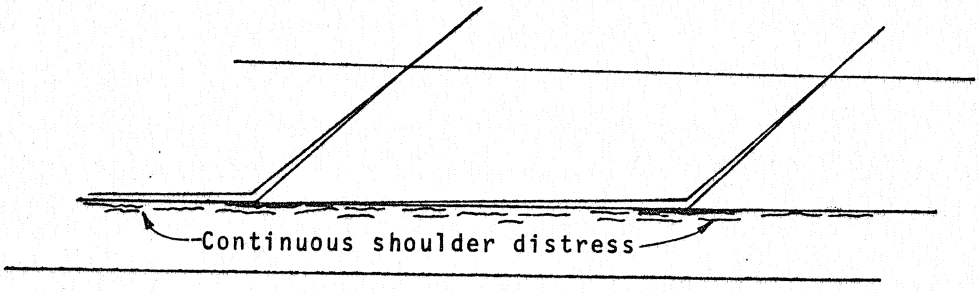
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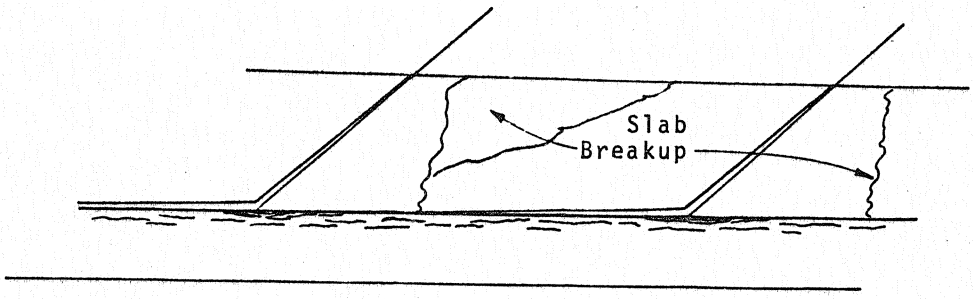
STAGE 1



STAGE 2



STAGE 3



STAGE 4

Figure 1

TYPICAL STAGES IN THE LIFE OF A CONCRETE PAVEMENT

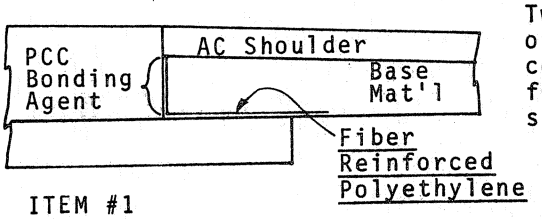
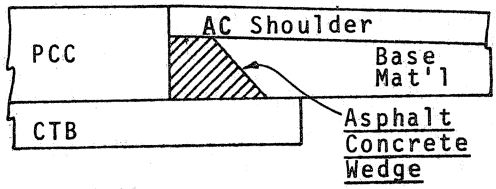
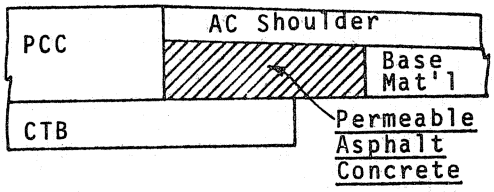
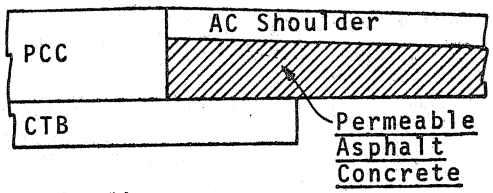
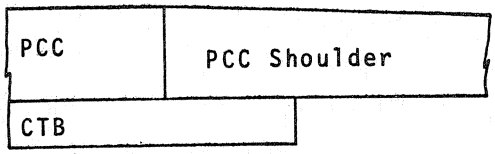
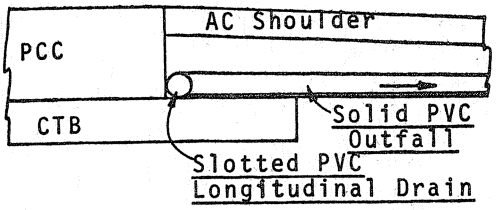
DESIGN FEATURE	COMMENT
 ITEM #1	Two foot wide strip is bonded to edge of pavement prior to shoulder construction. Membrane prevents base fines from migrating under pavement slab.
 ITEM #2	Asphalt concrete wedge provides non-erodible material adjacent to pavement slab. Also provides support to shoulder edge.
 ITEM #3	Performs as Item 2, above, used on existing highway in effort to arrest progression of faulting. Permeable material distributes water along shoulder allowing percolation throughout.
 ITEM #4	Drains free water from beneath slab and is non-erodible. Water must be allowed to escape at outer shoulder edge.
 ITEM #5	Provides non-erodible shoulder and supplies structural support to outer pavement slab.
 ITEM #6	Slotted longitudinal drain collects free water from beneath pavement slab. Water is discharged through outfall lines at appropriate intervals

Figure 2

STRUCTURAL SECTION DESIGN FEATURES

TABLE 1

GRADATIONS USED ON LEAN CONCRETE BASE FIELD TRIALS

Standard Sieve	Monterey Percent Passing	Compton Percent Passing
1-1/2	100	100
3/4	100	82
3/8	79	60
No. 4	59	42
No. 30	27	19
No. 200	12	8

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TABLE 2

COMPARISON OF COMPRESSIVE STRENGTHS AND ABRASION LOSSES (AVERAGE OF 12 SPECIMENS)

Lean Concrete Base

Compressive Strength (psi)						Abrasion Loss (Gm)	
Field Fabricated Specimens				Cores 5" dia.		Cores 4" dia.	
6 x 6 7 day	6 x 6 28 day	6 x 6 91 day	6 x 12 28 day	28 day	91 day	28 day	91 day
355	525	745	445	735	800	1.8	0.8

Cement-Treated Base

Field Fabricated Specimens			Cores 5" Dia.			
4 x 4 7 day	4 x 4 28 day	4 x 4 91 day	28 day	91 day		
940	1090	1910	610	650	2.2	3.2