# Economic Impact of Pavement Subsurface Drainage

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**Even though road builders have recognized the role of water in pavement deterioration since the last century, with the development of the "rational" methods of pavement design evolved a strong reliance on the ability to build pavements stout enough to resist damage without the benefits of good drainage. Even today, most designers attempt to improve the strength and "quality" of the pavement and base layers used in road construction and neglect rapid drainage. Much of the water that falls on pavements penetrates the structural section through cracks, joints, and porous surfaces. Conventional slow-draining pavements are deteriorating more rapidly than is necessary because of the impacts of heavy vehicles on flooded structural sections. The most positive pavement drainage systems use an open-graded drainage layer under the full width of a roadbed with adequate collector pipes and outlet pipes. However, the California Department of Transportation has found that retrofit edge drains are greatly reducing the rate of step faulting of existing portland cement concrete pavements. The impact of positive rapid drainage features on the performance of a number of pavements is reviewed, with particular emphasis on the establishment of a cost-benefit relationship. The results of this evaluation indicate that the increased cost of effective pavement drainage is almost incidental to the savings realized through improved performance.**

The ancient Romans, building their extensive road network, employed pavement sections that often enhanced pavement drainage. Before 1940, most pavement designers adhered to the belief that good drainage was essential for good performance. For example, Bruce *(1)* credits Tresaguet with one of the earliest improvements in pavement design circa 1764. In his pavement design, Tresaguet specified a base layer of large stone covered with a thin layer of smaller stone. Approximately 60 years later in England, Telford developed a similar design adding a thicker topping of fine stone and a crowned cross section, thereby providing better surface drainage. In 1816 McAdam began a study of stone-road construction. His design eliminated the heavy stone base used by Telford and Tresaguet and instead employed crushed stone of smaller size. Various types of macadam pavement have been used over the years. The first cement-bound pavement on record was built in Edinburgh, Scotland, in 1872, and was still in service in the 1930s.

Many macadam pavements were constructed with crushed rock placed over a thick layer of screenings, or rock chips, that served as a filter to prevent fine subgrade soils from working upward into the open-graded rock base. There is little doubt that good drainage provided by this construction technique improved pavement stability, thus enabling these pavements to provide service for many decades. In some cases, however, the open-graded rock was placed directly on fine-graded subgrade soils that gradually worked upward into the base, thereby diminishing its drainage capacity after a few years of service.

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Not all road builders of McAdam's time believed in good drainage. In 1820 he warned *(2)* that "The erroneous opinion so long acted upon, and so tenaciously adhered to, that [by] placing a large quantity of stone under the roads, a remedy will be found for the sinking into wet clay, or other soft soils, or in other words, that a road may be made sufficiently strong, artificially, to carry heavy carriages though the sub-soil be in a wet state and by any such means to avert the inconvenience of the natural soil receiving water from rain, or other causes, has produced most of the defects of the roads of Great Britain."

A belief in good drainage generally prevailed among pavement designers until the late 1930s and early 1940s. Unfortunately, with the development of "modern" testing procedures to measure the strength of soils in a saturated state, there developed a belief that resistance to free water was built into pavement design.

## UNDRAINED PAVEMENT PERFORMANCE

Free water that easily enters and collects in undrained pavements, and is acted on by traffic, is a primary cause of premature and continuing damage. In his 1820 report *(2)* McAdam stated: " . . . if water pass through a road and fill the native soil, the road whatever may be its thickness goes to pieces."

Because of the decision to live with the water that completely fills most pavements for weeks or months each year, most pavements have a built-in defect that is significantly reducing service life.

Faulting, frost damage, D-cracking, and pothole damage do not occur in the absence of free water. Several well-documented road tests made in the past 35 years or so demonstrate that, regardless of thickness or strength of pavements, rates of damage under flooded conditions (internally) can be up to hundreds, even thousands, of times greater than when little or no free water is present in the structural section.

The report of one of the earliest of the road tests, Road Test One-MD *(3)*, revealed that much greater damage occurred to 10-year-old concrete pavements in wet periods than in dry. The next major test road, the WASHO Road Test, produced rates of damage as much as 70,000 times greater during the spring thaw than in summer months when there was little or no free water in the sections *(4)*. Only a few years later, the most comprehensive of all road tests, the AASHO Road Test in Ottawa, Illinois

*(5)*, had damage rates for many of its pavements that were much greater in wet periods than in dry. W. J. Liddle, in a paper presented to the First International Conference on the Structural Design of Asphalt Pavements *(6)*, stated that the damaging actions of traffic were noticeably more severe in spring than in summer or fall. A chart of rates of loss of serviceability versus months of the year showed rates of damage up to 40 to 50 times greater in wet periods than in dry. Extensive discussions of the AASHO Road Test results were given in the Proceedings of this conference. One speaker, C. R. Foster, commented that

> the supposedly pervious shoulders did not provide adequate drainage and water was trapped in the base and subbase especially during critical periods. Pore pressures and resulting weakness developed in both of these materials. . . . we should take steps to provide better subbase drainage so as to obtain maximum benefits of our materials.

Little or no heed was paid to Foster's comments. The predominant view of those overseeing the AASHO Road Test and interpreting its results was that drainage was a low-priority item. Even though most of the severe damage to pavements of the AASHO Road Test was caused by pore pressures from impacts on undrained water, no criteria for improving roadbed drainage evolved from the AASHO Road Test and, as a consequence, the prevailing practice continued to be the design of "stout" pavements.

A few years after the AASHO Road Test, Barenberg and Thompson *(7)* employed the circular test track at the University of Illinois to evaluate some of the AC pavement designs of the AASHO Road Test. These investigators found that when free water was introduced into the test sections, after many load applications had been put on while bases were only moist or damp, the rates of damage per traffic impact were up to 200 times greater than the rate before water was added.

Despite these findings, and in addition to those of the prior road tests, no change in design practices occurred. As a result, nearly all important pavement built in the decade following the publication of these findings is of the undrained variety. Only in the past few years has there been a renewed interest in the importance of good drainage. A number of states are now specifying open-graded base drainage layers as one of their standard designs for important roads in order to achieve rapid removal of infiltrated surface water.

Cedergren *(8)* estimated that $217 billion of the $329 billion ($15 billion per year) in estimated repairs from 1976 to 1990 could be saved if all important pavements were constructed as well-drained systems. This estimate was made assuming that U.S. pavements on the average are exposed to internal flooding about 15 percent of the year, and that wet impacts cause 10 to 20 times more damage (per impact) than impacts on dry or well-drained pavements. Because many of the undrained pavements are kept in a flooded state much more than 15 percent of the time, and many have wet impact damage rates much greater than 10 or 20, the estimated $15 billion annual waste is believed conservative.

## RECENT DEVELOPMENTS IN SUBSURFACE PAVEMENT DRAINAGE

The relatively recent movement toward subsurface pavement drainage is largely due to the development of improved and economical drainage materials along with greater awareness of the nature and extent of the problem resulting from the research of a number of individuals throughout the world. In the following section, what are believed to be a few of the milestones in this evolution are described.

### Geotextiles

The problem of providing a drainage layer sufficiently permeable to remove excess water quickly and yet fine enough to preclude contamination from clogging by fines was largely solved with the development of Terzaghi's filter criterion and its subsequent modification by others. This practice has been developed to a high degree in earth dam construction in which, in some instances, up to five layers of graded materials are employed for filtration and drainage.

The use of a separate filtration layer for roadway structural section drainage, however, failed to gain wide acceptance, presumably because of the cost, complexity, and difficulties visualized in placing and compacting the open-graded drainage layer. The introduction of geotextiles to drainage applications enhanced the economical application of blanket drains in pavement drainage.

Geotextiles were first used for subsurface water drainage applications. The excellent filtration and separation characteristics associated with nonwoven geotextiles permitted the use of a single layer of a more economical drainage aggregate enveloped in a geotextile. Success with geotextiles in subdrainage in the late 1970s led to their application in pavement drainage for both groundwater and surface water infiltration. The thin geotextile filter/separator reduced excavation as well as the cost of a drained structural section. The tensile properties of geotextile filters permitted further cost reductions by facilitating the use of thin layers of open-graded stabilized drainage materials.

### Asphalt-Treated Permeable Material

One of the early proponents of two-layer subsurface drainage in highway construction was W. R. Lovering who, as a District Materials Engineer for the California Division of Highways, had many occasions to observe the results of inadequate or clogged drains through the wet cuts common in northwestern California. In 1960 Lovering made specific proposals for the employment of two-layer subdrainage systems in highways. Recognizing the difficulties inherent in the construction of a firm working table using the single-sized aggregates necessary for the drainage layer, Lovering and Cedergren proposed in 1962 *(9)* the use of a lean asphalt mix of coarse single-sized material for the drainage layer. They reported on the effect on permeability of treatment of open-graded aggregate with 2 percent asphalt. These data revealed that the presence of asphalt binder did not significantly lower the permeability of the drainage layer (10,000 to 30,000 ft/day).

### FHWA Study

In 1970 the FHWA authorized an in-depth study of the problems associated with water in state and Interstate highways under a contract with the joint venture of H. R. Cedergren of Sacramento and Ken O'Brien & Associates of Long Beach, California *(10)*. After a thorough examination of all known literature on roadbed drainage, the interview team visited engineers in each of the nine FHWA regions to discuss pavement problems with FHWA and state engineers in design, construction, and maintenance. The team then examined several hundred miles of pavement in one state in each of the regions and selected a case study site to be drilled and tested to determine the causes of problems at each site.

This study concluded that traffic impacts on structural sections containing large amounts of free water are the root cause of most pavement deterioration. The consultants were asked to develop a subdrainage system that could largely eliminate extensive entrapment of free water in structural sections. The drainage system that evolved had the following key features: *(a)* a highly permeable open-graded base drainage layer under the full width of the roadway, *(b)* a base under the drainage layer designed using a filter criterion with subbases as needed for obtaining the total thickness needed for support of loads, *(c)* collector pipes along lower edges of the drainage layer, *(d)* outlet pipes suitably sized and spaced to rapidly remove all of the water entering the system, and *(e)* markers on posts at pipe outlets to flag their locations and protect them from damage from mowers and the like.

The FHWA report of this study *(10)* provided procedures for estimating inflows and designing drainage systems to quickly remove infiltrated surface water.

### Evolution of Portland Cement Concrete Pavement Edge Drains

The primary distress mechanism of plain jointed concrete pavement, step faulting due to pumping of base and shoulder fines in the presence of free water, has been recognized and studied by pavement researchers since the 1940s. In 1952 the California Department of Transportation (Caltrans) adopted, as a standard, a cement-treated base for concrete pavements to provide a nonerodible support for the pavement slab and thus mitigate the problem of step faulting. The effect of this change was only a slowing of the faulting process. Beginning in the 1960s the faulting phenomena were studied in some depth by a number of agencies *(11–20)*. The faulting process was successfully modeled by Caltrans researchers in a laboratory environment in 1980 *(16)*. It was generally concluded in these studies that four conditions must be present for faulting to occur:

1. Heavy wheel loads,
2. Curled pavement slabs,
3. Source of fine materials, and
4. Free water and voids under and around the pavement slab.

It was concluded that if at least one of these elements could be eliminated, step faulting could be significantly arrested or stopped completely. Denying access to fines and the rapid removal of infiltrated surface water from the structural section were the logical candidates for successful mitigation of the problem because heavy wheel loads are considered inevitable and curling can only be partly reduced by the use of shortened slabs. Beginning in 1975, California, along with several other states, experimented with a number of edge drain designs from which evolved, in 1979, the present standard designs used for retrofit installations and new construction. The primary modifications made during this period were stabilization of the permeable material with cement or asphalt and elimination of the complete envelopment of the permeable material with filter fabric (Figure 1).

### Current Status

A growing recognition of the importance of positive subsurface pavement drainage resulted from the FHWA study of 1970 *(10)* and the work of a number of researchers, some of whom are cited in this paper. Subsurface drainage of pavement is treated extensively in the AASHTO *Guide for the Design of Pavement Structures* published in 1986 and will be an integral part of the Strategic Highway Research Program (SHRP). The specific pavement studies portion of the Long-Term Pavement Performance Study will incorporate 96 test sections involving both plain jointed concrete pavement and jointed reinforced concrete pavement. The effect of three different subdrainage designs will be evaluated. Similarly, 32 flexible pavement test sections that incorporate two different subdrainage designs will be evaluated. The authors believe that this comprehensive and carefully controlled study of the effect of pavement subdrainage will produce extremely valuable data on the economics of pavement drainage and, indeed, is one of the key elements of the program.

## CASE HISTORIES

### Rigid Pavement

Edge drains for rapid removal of infiltrated surface water at the pavement-shoulder joint have been used by a number of entities since the mid-1970s with mixed, although often favorable, results. The Georgia DOT placed a moratorium on edge drains in 1978 *(21)* as a result of problems created by the migration of fines into the permeable material surrounding the collector pipe. Attempts to mitigate the problem by encapsulating the entire drainage element with filter fabric proved ineffective because of the buildup of fines on the fabric and the resultant loss of drainage capacity. The California DOT found that, even with the modifications described previously, edge drains were not effective and were possibly detrimental in those instances in which the slope of the longitudinal collector was less than 0.2 percent or the outlet was subject to inundation. In general, however, edge drains have resulted in a significant improvement in pavement performance. Darter et al. *(22)* reported in 1979 that the use of experimental edge drains on three different continuously reinforced concrete projects in Illinois reduced the number of punchouts an average of 24 percent. In 1984 Darter et al. *(23)* reported the results of a comprehensive six-state concrete pavement performance study in which various design features and environmental conditions were related to pavement performance. It was concluded that edge drains significantly increased the service life for jointed

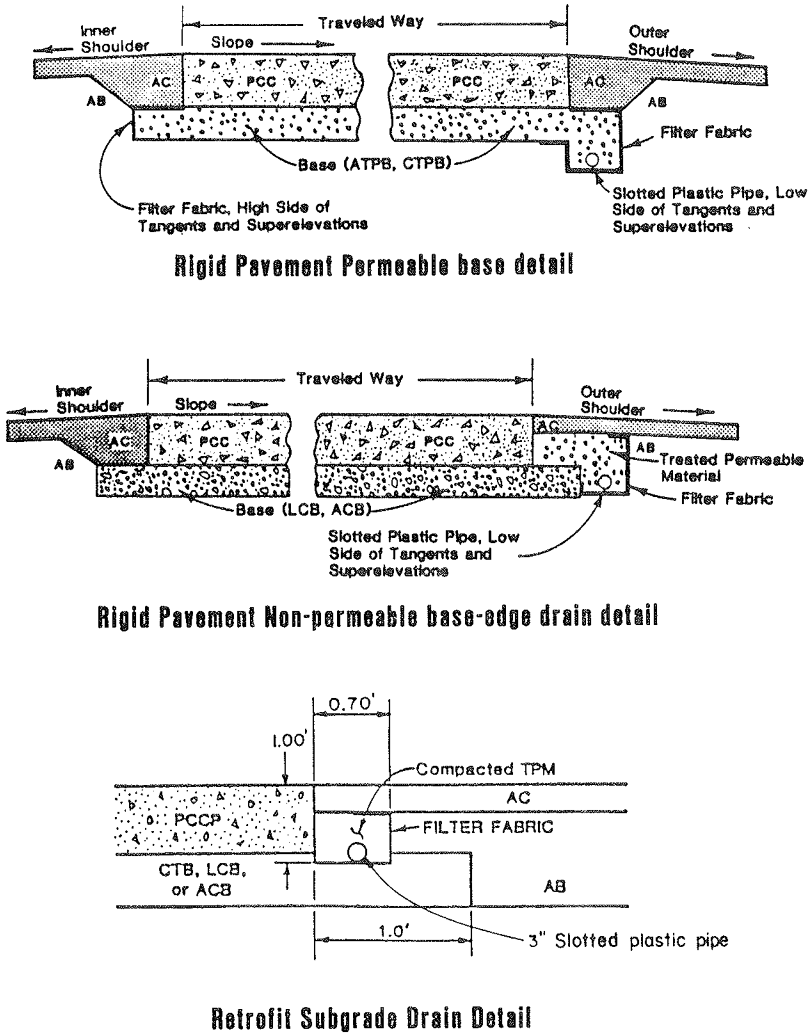


**FIGURE 1 Details of rigid pavement drainage.**

concrete pavement and jointed reinforced concrete pavement. The use of edge drains on pavements susceptible to D-cracking resulted in a large decrease in joint deterioration and pumping. The Illinois results indicated that, in terms of the rate of joint deterioration, edge drains provided a 50 percent increase in service life.

The beneficial effect of edge drains on concrete pavement performance was also convincingly demonstrated in Spain on the Valencia-Tarragona Toll Road. This facility, constructed in 1974, consisted of plain jointed concrete slabs over cement-treated base with no provision for pavement drainage. By 1978 measurements of 85 randomly selected joints on the two projects indicated that step faulting was occurring. The decision was made to install a retrofit edge drain system to slow, or stop, the progression of faulting (Figure 2). The step-off was almost completely arrested from installation until 1985.

The results of a California research study of the effect of edge drains on pavement performance *(24)* indicated that, for undrained plain jointed concrete pavements, the average faulting rate was 0.006 in./year, whereas the average faulting rate for retrofit edge drains (installed some time after initial construction) was –0.0003 in./year. This reduction in faulting, attributable to the provision of drainage, should result in significantly improved performance of portland cement concrete pavements (PCCPs).

This study also included two contracts under which some projects were initially constructed with edge drains. The average faulting rate for the undrained portions was –0.002 in./year. In contrast, on the drained portions the faulting rate averaged a relatively insignificant 0.0005 in./year. This study also indicated that the rate of slab cracking was less in the drained pavements than in the undrained pavements.

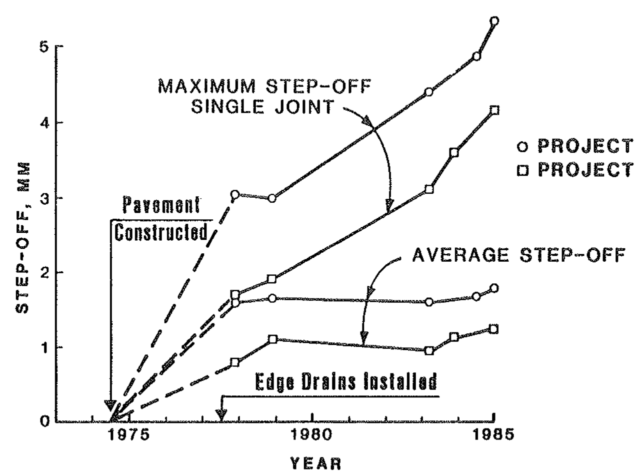


**FIGURE 2 Effect of edge drains on pavement faulting.**

Four additional projects on which drained PCCPs were used were reviewed for performance. The drained PCCPs consisted of

1. Edge drains placed during construction,
2. PCCP over an untreated permeable material (UPM),
3. PCCP over an asphalt-treated permeable base (ATPB), and
4. PCCP over a cement-treated permeable base (CTPB).

The performance of these pavements was analyzed by reviewing the Caltrans pavement management surveys that are performed every 2 years. These surveys rate all pavement for rideability and structural damage. Structural damage of PCCP is rated as a function of the type of cracking. Stages 1 and 2 (rated together) are nonintersecting cracks in the pavement slab. Third-stage cracks are intersecting cracks in the slab and are an indication of slab failure. Cracking is reported as the percentage of cracked slabs within the surveyed section.

The effect of positive drainage on the performance of these pavements (percentage of cracked slabs) is shown in Figure 3. With the exception of 7-LA-14, which has yet to show cracking in either the drained or the undrained sections, the drained sections manifest significantly lower rates of cracking. Overall, the percentage of cracked slabs in the undrained exceeds that in the drained sections by a ratio of 2.4 to 1.

### Flexible Pavement

In 1982 Markow *(25)* reported the results of a pavement performance simulation using a Federal Highway Administration EAROMAR system aimed specifically at establishing the effect of positive rapid drainage of pavements. The results indicated that, in regions that receive annual rainfall of approximately 40 in., pavement life is extended by 4 years.

Relatively few systematic field evaluations of the benefits of rapid positive drainage of flexible pavement are found in the literature. In 1981 Barenberg and Brown *(26)* reported the results of a study for the New Jersey Department of Transportation on the use of open-graded drainage layers directly under a 5-in. asphalt concrete layer on the University of Illinois test track. The performance of a standard undrained design was compared with that of drained designs in terms of rut depth and deflection level. Subgrade was an A-6 clay with an unsoaked California bearing ratio (CBR) value of 6. The open-graded permeable layers were 2.5 in. thick and placed in both a stabilized and an unstabilized state. Permeabilities ranged from 2,000 to 6,000 ft/day. The test loadings were applied by two 10:25 × 20 tires inflated to 75 psi, each bearing 3,200 lb. Before loading, an initial series of tests was made to establish the drainage characteristics of the various test sections. Water was then introduced simultaneously with the application of wheel loads. Of particular interest were Section 1, the standard undrained section, and Sections 2 and 3, which were structurally equivalent according to California pavement design criteria but which included an open-graded drainage layer. A review of the results indicated a reduction of approximately 20 percent in deflection level for the two drained sections compared with the standard design.

Given the fatigue properties of 0.4-ft-thick California flexible pavements *(27)*, the effect of a reduction in deflection level of this magnitude on fatigue life would depend on initial deflection level, pavement thickness, and equivalent single axle load (ESAL), as shown in Figure 4. For example, a 0.4-ft-thick pavement with an initial deflection level of 0.025 in. would have its fatigue life extended by 90,000 ESALs with a 20 percent reduction in deflection level. At a lower level of initial deflection, say 0.013 in., the 20 percent reduction in deflection level would increase ESALs by 7 million. This extrapolation of the results of a study of admittedly limited scope, consisting of a single subgrade condition and surfacing thickness, is intended only to illustrate the potential improvement in fatigue performance of AC pavements in a severe (wet) environment. Under these conditions, results may be conservative in that they do

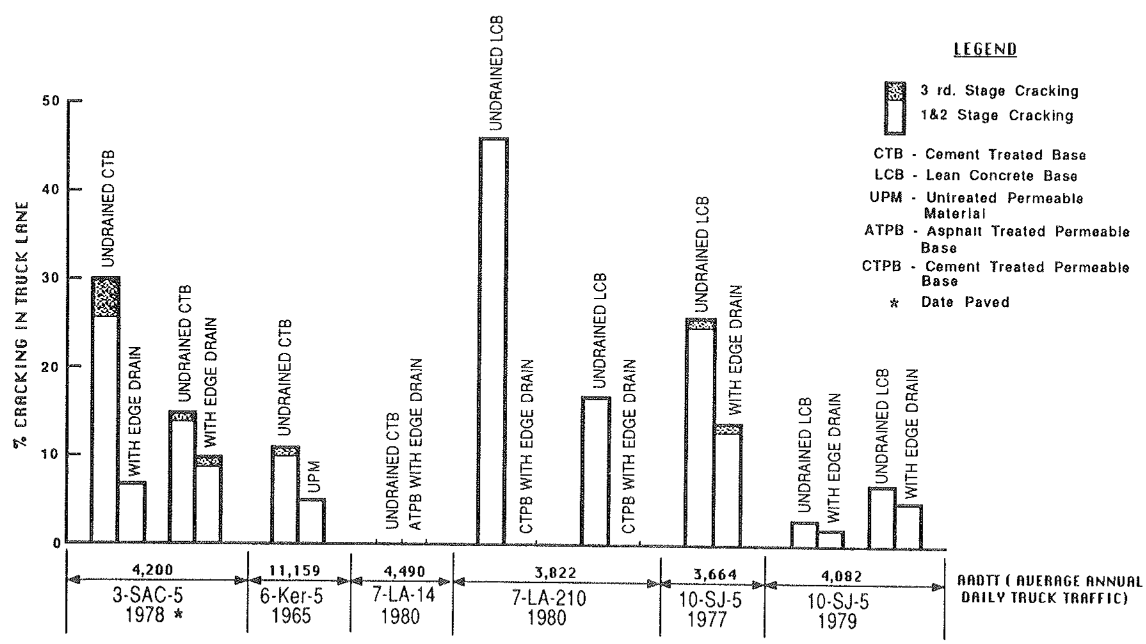


**FIGURE 3 Comparison of cracking in undrained and drained PCCP.**

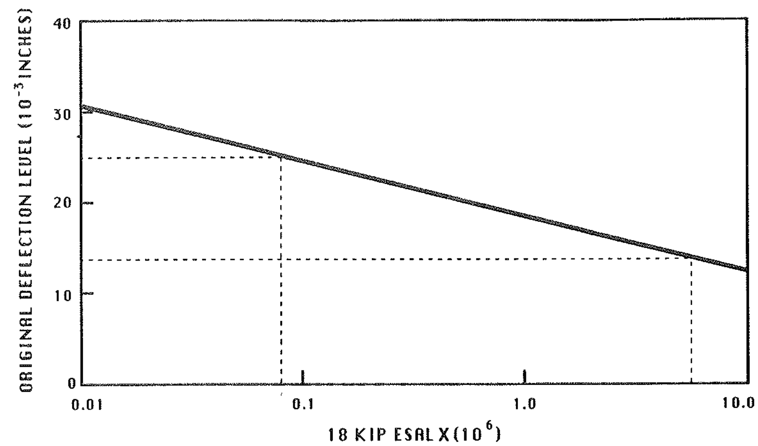


**FIGURE 4 Potential increase in 0.4-in.-thick AC pavement fatigue life resulting from 20 percent reduction in deflection level.**

not include the effects of the reduce rate of asphalt concrete oxidation, and thus embrittlement, that would result from the rapid removal of surface-infiltrated water from the drained pavement section.

In 1982 Caltrans adopted a policy of requiring the placement of asphalt-treated permeable material (ATPM) under the surfacing layer with collectors and outlets for new flexible pavement construction. The oldest pavements constructed using this drainage design have been in place only 3 years. Thus a definitive evaluation of the effect of this feature on performance is not yet possible. The earliest use of ATPM under the base layer in California was on Kneeland Road in Humboldt County, initially reported on by Cedergren *(28)*.

A 500-ft section of logging road was reconstructed by a county public works department in 1967 using a highly permeable open-graded base drainage layer after the road had failed twice in just a few years. The prior reconstructions had used the then-standard drainage materials specified by the California Division of Highways (now Caltrans), which contained several percent minus No. 200 fines that had permeabilities of perhaps 5 to 10 ft/day. Heavy logging trucks on flooded structural sections caused rapid failures in this water-abundant environment (40 to 80 in. of rain a year, plus inflows from springs etc.). The open-graded base drainage layer, graded from 3/4-in. to No. 4 sieve, was stabilized with 2.25 percent paving-grade asphalt. When tested as a case study site in the FHWA guidelines study, its permeability was found to be in the range of 10,000 to 30,000 ft/day. The two-layer drain consisted of a 0.33-ft filter layer and a 0.66-ft ATPM layer. The filter material contained more fines than would normally have been desirable, but it still met primary filter criteria. A recent (1986) field review of this 500-ft section revealed that the original pavement is still in excellent condition with no patching. As shown in Figure 5, the adjoining pavement has been extensively patched. The 19-year service life of this section (to date) is well beyond the normal 12-year life of AC pavements in California.

Gray et al. *(29)* reported on another two-layer drainage (ATPM) project on Route 299 between Arcata and Willow Creek. The experimental section consisted of 0.4 ft of ATPM underlaid by 0.3-ft Class 2 permeable material as the filter medium. The control section consisted of 0.7 ft of Class 2 permeable material.

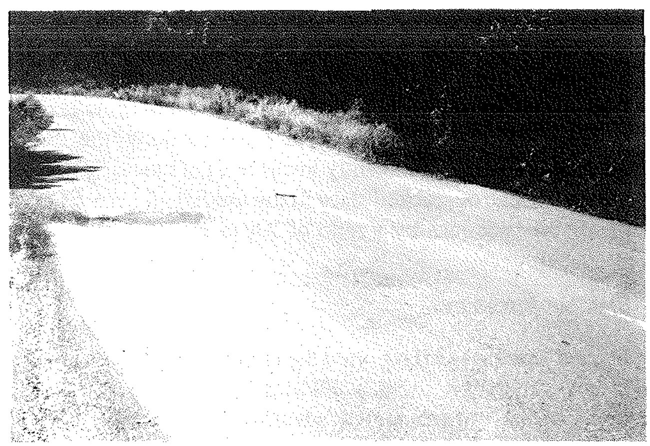

**FIGURE 5 Kneeland Road, July 1986.**

The results of in situ permeability tests revealed that the drainage capacity of the two-layer section was three to nine times that of the control section. This was not surprising because the coefficient of permeability of standard Class 2 permeable material ranges from 10 to 500 ft/day compared with 10,000 to 25,000 ft/day for ATPM. This section was not open to traffic until 1972. A recent field review indicated some fine alligator cracking of the surface in both drained sections, which have been chip sealed. However, the performance to date of this road in a severe environment (40 to 80 in. annual rainfall) under heavy logging truck traffic has exceeded the average performance of California flexible pavements.

Cedergren *(28)* cites a number of other instances of excellent performance of individual flexible pavements with positive rapid drainage.

## ECONOMICS

Attempting to quantify the economic impact of positive rapid pavement drainage is difficult, to say the least, for a number of reasons. The literature contains few controlled experimental data on the effect of drainage on pavement service life, primarily because so little research on the subject has been conducted. What is available is extremely limited in terms of variation in subgrade and environmental conditions and structural section design. Because this is the case, the authors have made what are believed to be extremely conservative assumptions about the increases in pavement service life.

With respect to flexible pavements, the work of Markow *(25)*, Barenberg and Brown *(26)*, and the case histories cited suggest a minimum increase of 4 years of service life with a drained system.

For rigid pavement, the work of Darter et al., the results of the California edge drain study, and the performance of the retrofit edge drain system on the Valencia-Tarragona Toll Road suggest a minimum 50 percent extension of service life of PCC pavements with an efficient functioning edge drain system.

To assess economic impact, a life-cycle cost analysis was not considered realistic because

1. An appropriate life cycle would be extremely difficult to establish and justify,
2. The extent and nature of required rehabilitation are uncertain, and
3. Realistic maintenance and user costs would be extremely difficult to establish.

The analysis therefore was done in terms of cost per square yard per year from construction to first rehabilitation. The assumed structural sections are equivalent in load-carrying capacity, differing only by the inclusion of rapid drainage capability in each of the two basic pavement types. Costs (in place) are from the Caltrans 1985 Construction Cost Index.

### Rigid Pavement (undrained section)

| | *Thickness (ft)* | *Cost in Place ($/yd³)* |
|---|---|---|
| Portland cement concrete | 0.85 | 65.00 |
| Lean concrete base | 0.50 | 51.00 |
| Aggregate subbase | 0.70 | 11.00 |

Converting to a square yard basis and assuming a 20-year service life, the pavement cost is

$$\frac{\$29.49/\text{yd}^2}{20\ \text{yr}} = \$1.47/\text{yd}^2/\text{yr}$$

### Rigid Pavement (drained section)

| | *Thickness (ft)* | *Cost in Place ($)* |
|---|---|---|
| Portland cement concrete | 0.85 | 65.00/yd³ |
| Asphalt-treated permeable base | 0.25 | 42.00/yd³ |
| Aggregate subbase | 1.05 | 11.00/yd³ |
| Edge drains | | 0.70/linear foot |
| Edge drain outlets | | 3.50/linear foot |

Converting to a square yard basis and assuming a 30-year service life, the pavement cost is

$$\frac{\$26.13/\text{yd}^2}{30\ \text{yr}} = \$0.87/\text{yd}^2/\text{yr}$$

This represents an annual savings of 41 percent in rigid pavement costs over the service life of the pavement due to its drainage features.

### Flexible Pavement (undrained section)

| | *Thickness (ft)* | *Cost in Place ($/yd³)* |
|---|---|---|
| Asphalt concrete | 0.70 | 60.00 |
| Aggregate base | 1.00 | 19.00 |
| Aggregate subbase | 1.40 | 11.00 |

Converting to a square yard basis and assuming a 12-year service life, the pavement cost is

$$\frac{\$25.47/\text{yd}^2}{12\ \text{yr}} = \$2.12/\text{yd}^2/\text{yr}$$

### Flexible Pavement (drained section)

| | *Thickness (ft)* | *Cost in Place ($)* |
|---|---|---|
| Asphalt concrete | 0.65 | 60.00/yd³ |
| Asphalt-treated permeable base | 0.25 | 42.00/yd³ |
| Aggregate base | 0.75 | 19.00/yd³ |
| Aggregate subbase | 1.40 | 11.00/yd³ |
| Edge drains | – | 0.70/linear foot |
| Edge drain outlets | – | 3.50/linear foot |

Converting to a square yard basis and assuming a 16-year service life, the pavement cost is

$$\frac{\$26.74/\text{yd}^2}{16\ \text{yr}} = \$1.67/\text{yd}^2/\text{yr}$$

representing an annual savings in pavement cost of 21 percent over the service life of the pavement, which does not include reduced maintenance or user costs.

### Extrapolated Savings

California historically has constructed approximately 200 lane miles of new pavement (20 percent rigid and 80 percent flexible) annually (new alignments, widenings, lane additions, etc.). Extrapolating the annual cost savings for drained pavements to a program of this magnitude, the annual savings amount to

1. Rigid pavement. A savings of $0.60/yd²/year applied to 40 lane miles per year yields a savings of $168,960 per year. For the estimated 30-year service life, a total rigid pavement savings of $5,068,800 (present dollars) could be realized.
2. Flexible pavement. A savings of $0.45/yd²/year applied to 160 lane miles per year yields a savings of $506,880 per year. For the estimated 16-year service life, a total flexible pavement savings of $8,110,080 (present dollars) could be realized. Thus, for the annual 200 lane miles of new pavement, a total savings of $13,178,880 (or 36 percent of pavement costs) can be realized throughout the service life of the pavements constructed in any given year. This does not include the

savings due to increased service life from retrofit edge drains installed on in-service pavements or maintenance and user costs.

## SUMMARY AND CONCLUSIONS

Even though the benefits of rapid positive drainage of pavements have been recognized for more than 160 years, the pavement design community has been painfully slow to incorporate it in pavement design. This is due to a number of factors, including resistance to change; a belief that resistance to free water is built into pavement design or that pavements can be effectively sealed; and, of course, the additional expense of drainage features.

In recent years the development of filter fabrics and treated permeable material, along with the evolution of slotted PVC pipe, has greatly simplified and reduced the cost of pavement drainage. Recent studies involving edge drains and the effect of permeable bases on the performance of PCC pavements, although limited in scope, provide convincing evidence that pavement service life can be significantly extended by positive drainage. On the basis of studies of Markow *(25)* and Barenberg and Brown *(26)* and individual case histories, an increase in service life of 4 years (33 percent in California) is believed to be a conservative estimate for flexible pavements. An extension of service life of this magnitude will reduce pavement costs by approximately 21 percent. Similarly, studies of the effect of retrofit edge drains on PCC pavement performance in California and Spain suggest an extension of service life of 10 years (50 percent), which equates into a cost reduction of 41 percent, not including user and maintenance costs. For the annual 200 lane miles of new construction in California, this amounts to more than $5 million for rigid pavements and $8 million for flexible pavements over the service life of pavements constructed during any given year (or 36 percent of pavement costs). Certainly one of the significant studies planned for the Long-Term Pavement Performance Study of the Strategic Highway Research Program is that portion of the study devoted to the quantification of the effect of positive rapid drainage on the performance of both flexible and rigid pavements. For this purpose 128 test sections will be dedicated throughout the United States.

## ACKNOWLEDGMENT

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