Why All Important Pavements Should Be Well Drained

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During the hours, days, and months that pavements are filled with water, heavy vehicle loads cause severe damaging actions such as erosion and pumping, disintegration of cement-treated bases, stripping of asphalt coatings from bituminous-treated bases and subbases, and overstressing of weakened subgrades. The presence of liberal amounts of water causes or increases non-load-bearing damage such as D-cracking, blow-up, frost action, expansion, shrinkage cracking, accelerated oxidation and loss of flexibility, and general deterioration of pavements and bases. Pavements designed without fast internal drainage can stay filled with water during much of the year while they are also subjected to damaging environmental conditions. If pavements are provided with fast internal drainage, water-related damage is almost entirely eliminated, which increases pavement life substantially and saves billions of dollars a year in the United States alone. Even though the need for good drainage and the benefits it can provide have been known for centuries, few modern pavement designers use it. In this author's view, the best methods available should be used in designing pavements, and in addition every important pavement should be provided with an internal drainage system capable of rapidly removing all water that enters.

When a pavement is filled with water, heavy vehicle loads cause severe damaging actions such as erosion and pumping, disintegration of cement-treated bases, stripping of asphalt coatings from bituminous-treated bases and subbases, and overstressing of weakened subgrades. Also, the mere presence of abundant water causes or accelerates numerous non-load-bearing actions such as D-cracking, blow-up, frost action, expansion, shrinkage cracking, increased oxidation and loss of flexibility, and general deterioration of wearing courses and stabilized bases.

Pavements designed without rapid internal drainage can remain filled with water a number of days or weeks after each saturating rainfall, adding up to several months of damaging environmental conditions each year. When good internal drainage is provided, however, water-related damage can be virtually eliminated or at least greatly reduced. Rapid drainage could probably provide at least 10 times more benefit to pavements than do any of the "modern" design and structural strengthening techniques developed in the past 20 to 30 years.

Even though the detrimental effects of poor drainage have been of concern for centuries and thoroughly documented in several major road tests in the past several decades (*1–3*) and the benefits of good internal drainage have been well documented, few designers even consider good drainage as a viable design concept that can extend pavement life three or four times and save billions of dollars a year. Continued presentation of the facts will, it is hoped, convince more and more designers of the need to return to the good drainage ideas advocated by John L. McAdam nearly 200 years ago.

Designers should use the best methods available to design good, economical pavement systems. In addition, every important pavement should be provided with a drainage system capable of removing free water rapidly instead of over the days and even weeks needed when good internal drainage is not used.

INTRODUCTION

This paper is a brief review of the historical development of basic philosophies of road design and an explanation of how the modern "undrainage" concept became so popular and is so hard to overcome. The damaging actions that take place in undrained pavements filled with water are reviewed, and estimates are given of the costs of not designing all important pavements as well-drained systems that can rapidly eliminate free water and preserve pavements in a relatively "dry" condition essentially 100 percent of the time.

From historical times road builders have known of the damaging actions of water in structural sections and have tried to design roads that will not fail prematurely because of water. Starting with the Appian Way in 312 B.C., the ancient Romans built their military roads very strong, but they also drained swamps to be crossed by their roads and usually provided a layer of broken slag or tile within the foundation layers, which probably improved internal drainage.

Centuries later, wise road builders such as John L. McAdam (*4*) and Pierre M. Tresaguet of France (*5*, p. 3) warned of the consequences of excess water in structural sections and used open-graded stone or gravel in their construction. Sometimes, when an intervening layer of screenings or fine gravel was not placed on clay subgrades to act as a filter, the soil worked into the stone or gravel with undesirable results.

Because of experiences like this, and with the development of modern "rational" and experimental methods for designing pavements, the pendulum swung to the

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extreme of relying on density and strength as complete solutions to all problems and believing that good internal drainage is no longer necessary to achieve long-lasting, trouble-free pavements (*6*). This is the one factor above all others, in my view, that is responsible for the untimely deterioration of modern pavements under both traffic-related and non-load-bearing environmental damaging actions and that results in enormous losses in money, energy, and natural resources.

CHRONOLOGY OF ROAD DESIGN

After enactment of the U.S. Federal Aid Act of 1916, pavements were designed (in the United States) on the basis of soil classification (A-1, A-2, etc.) and the designer's experience and judgment. Since the development of modern soil mechanics methods, pavement designs have been based almost entirely on strength factors obtained by conducting static tests on specimens of base, subgrade, and other layers that have been presaturated for testing.

On and off for centuries road builders have believed in good drainage. Nearly 200 years ago, John L. McAdam (*4*) said, "If water pass through a road and fill up the native soil, the road whatever may be its thickness, loses support and goes to pieces." He also commented, "The erroneous opinion . . . 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 . . . [so] that a road may be made sufficiently strong artificially to carry heavy carriages . . . has produced most of the defects of the roads of Great Britain." After McAdam's time, good drainage was commonly preached as necessary for good roads. One text on road design said, "There are just three things necessary for a good road: drainage, drainage, and more drainage."

However, as modern rational methods came into widespread use for pavement design, many designers developed a high level of confidence in their newfound methods of using static tests to evaluate their materials. However, wheel loads apply dynamic forces to pavements, bases, and subgrades, and these design theories assume intergranular pressure distributions that cannot exist in real-world saturated pavements. The presence of abundant free water also causes or accelerates the previously mentioned non-load-bearing detrimental actions.

Many designers are so sure of the modern methods and so sure that drainage is unimportant that they look with disfavor on anyone who believes in good drainage as a viable design concept. In the course of interviews conducted during development of the FHWA's *Guidelines for the Design of Subsurface Drainage Systems for Highway Structural Sections*(*7*) one state highway engineer in the Great Lakes area said, "I have nothing but contempt for anyone who thinks pavements can be drained." A top pavement designer in a major western state said during those interviews, "But, of course, it is neither necessary, practical, nor economical to drain a pavement."

Since the issuance of the FHWA's pavement drainage guidelines in 1972, some change in the attitude of designers has been taking place, but very slowly. Under the nudging of the FHWA about 40 percent of the states are experimenting with "new" or "improved" drainage systems, and about 10 percent are actually using the high-permeability open-graded drainage layers proposed in the Guidelines. (The drainage systems in the Guidelines use a full-width base drainage layer composed of open-graded aggregate in the range of ¼-in. minimum size to ½- to 1½- in. maximum size protected with suitable bases or "filters" and provided with collector pipes and outlet pipes to ensure positive removal of all water that enters.)

At the present time (1987) most pavement designers are using the rational methods without providing internal drainage, but a few are awakening to the marvelous benefits of good drainage and putting it to work in their designs (*6*, pp. 20–21). Raymond Forsyth of Caltrans has been a prominent advocate of good drainage (*8*). California has, since 1982, required the use of positive rapid drainage on most new pavements on its state system. Drake (*9*), Haughton (*10*), and Craven (*11*) are other North American designers who are making use of good drainage ideas. Particularly noteworthy in my view is the landmark work of Roger Lorin in France who has been designing important airport pavements since 1980 with good built-in drainage (*6*, pp. viii, 20). His approach is in sharp contrast with that of most American airport pavement designers who consider strength and density of paramount importance and drainage unnecessary. In a letter to me dated August 1986, Lorin very aptly expressed the need for drainage of airport pavements: "[W]ith a drainage layer of porous concrete, water will no longer become under pressure when an aircraft is passing over, which avoids high-speed water movements, back and forth, under the slab creating voids by attrition of the cement-treated base. By eliminating pore pressures and water movements, the porous drainage layer eliminates pumping effects." Why all airport designers do not understand the need for rapid elimination of free water is difficult to comprehend when it should be so obvious.

With the help of the FHWA and a few progressive-thinking engineers like the ones just mentioned, the "undrainage" attitude is being slowly overcome. This author hopes that it will be a thing of the past before long.

Figure 1 shows the use of a highly permeable drainage layer in pavement structural sections (k = 10,000 to 100,000 ft/day) to rapidly eliminate free water and prevent or greatly reduce water-related damage to pavements. The figure shows the differences in water conditions in pavements of several designs, both without and with good drainage. In the undrained pavements, all wearing courses, bases, and subbases will be subject to flooding for a minimum of a few weeks a year in arid desert areas and many months a year in rainy climates. In the well-drained designs all layers above the drainage layer will be in a moist or damp condition, not in a fully saturated condition, nearly 100 percent of the time, so the detrimental traffic-related and non-load-bearing damaging actions will be virtually nonexistent. In my view all important pavements should be given the protection shown in the left half of Figure 1.

DAMAGING ACTIONS OF WATER

Traffic-Related Damage

When a pavement is filled with water, every heavy vehicle load passing over it produces a pore pressure wave that moves along at the speed of the vehicle. Spellman (*12*) found that heavy vehicle impacts caused "violent water actions" at the interface between portland cement concrete (PCC) pavement and a cement-treated base (CTB), which caused erosion of cavities under the PCC pavement and ejection of material from the leading edges and its buildup under trailing edges. This action caused loss of support and produced the uncomfortable "faulting" or "step-off" so common in PCC pavements that are being damaged by traffic impacts and undrained water.

As part of the comprehensive field studies undertaken for the FHWA during development of its pavement drainage guidelines (*7*), holes were drilled in a 12-year-old California Interstate highway constructed with PCC on CTB. Although it was on a fill 40 ft high, this section of pavement was already showing excessive faulting and cracking. A hole drilled into the interior of an uncracked slab directly under the wheelpath in the truck lane revealed that the CTB had completely disintegrated into a cohesionless mass that could easily be removed with a small scoop, or even with fingers. A maintenance supervisor told the investigating engineer that this was a common occurrence along this highway; at every location where he had dug out failed pavements to be replaced with high-early strength PCC patches, the CTB was soft and disintegrated. To verify the condition of the CTB in the central passing lane where

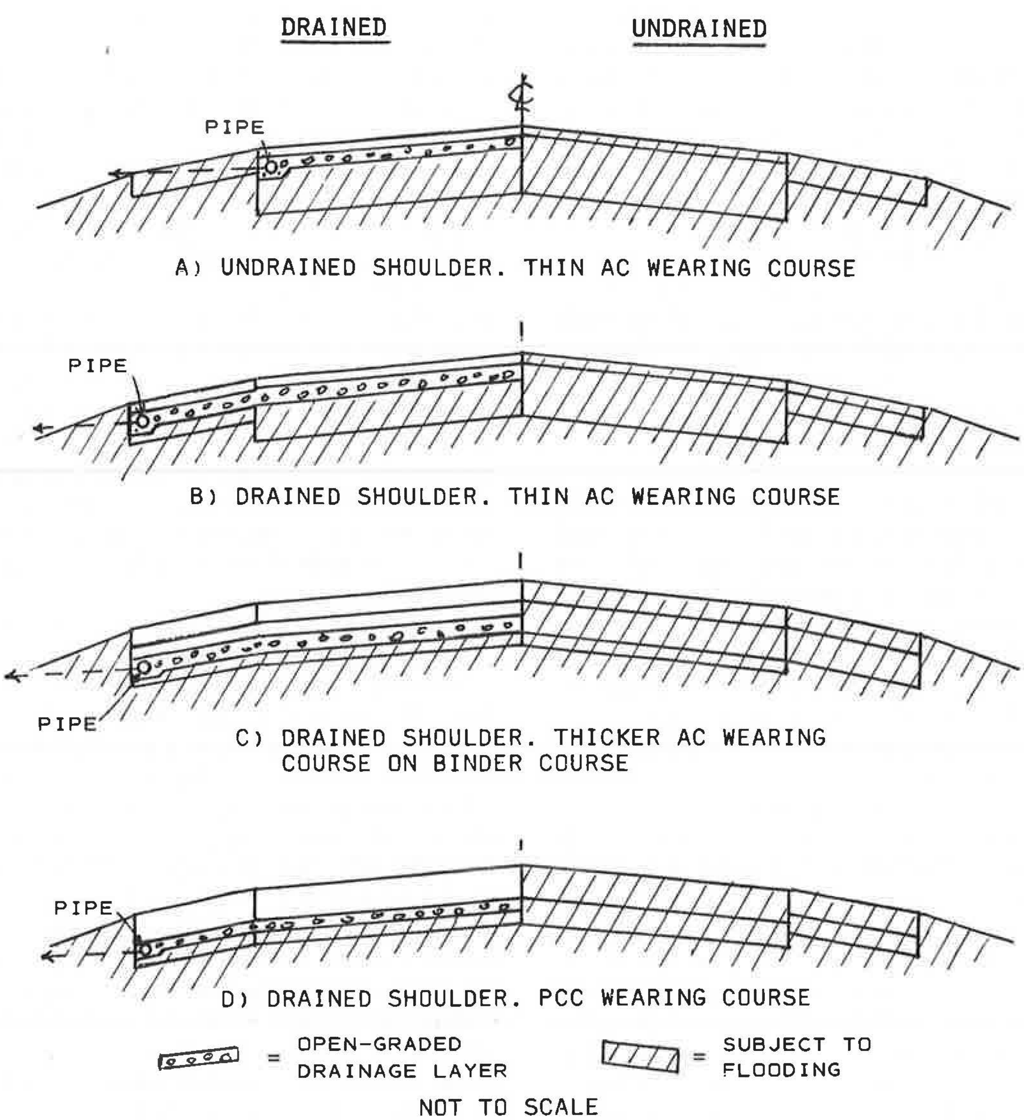

FIGURE 1 Differences in water conditions in drained and undrained pavements.

trucks seldom operated, a hole was drilled into the concrete and a very solid core of CTB was recovered under the PCC core, giving evidence that the CTB had been properly placed.

My explanation of the disintegrated CTB is that pore pressure waves moving under the pavement produce pulsating actions that may leach the cement out of the CTB. At any rate, any benefit from the cement treatment was lost under the truck lanes; the CTB was behaving as a cohesionless sandy base containing fine gravel.

In addition to the kinds of damage just discussed, heavy wheel impacts on water-filled pavements cause stripping of asphalt coatings from bituminous-treated bases and subbases, overstressing of weakened subgrades, increased rates of general deterioration, potholes, break-out of chunks of pavement from wearing courses, losses in safety and comfort to users, and reduced overall serviceability, as well as high repair and replacement costs.

Non-Load-Bearing Environmental Damage

The mere presence of abundant free water in structural sections causes or greatly accelerates non-load-bearing environmental actions that cause premature failure of pavements. Some of these actions do not occur at all in pavements that contain little or no free water.

D-cracking, for example, progresses only in the presence of abundant water. Rapid elimination of free water by the use of the good drainage systems recommended in the FHWA guidelines (*7*) could be very beneficial in reducing D-cracking, but good drainage systems are hardly ever thought of as a primary remedy for this troublesome form of disintegration of concrete pavements. Studies by Verbeck et al. (*13*) for the Portland Cement Association (PCA) on some 4,400 lane miles of pavements in Ohio led to the following statements in their report: "The field and laboratory observations . . . are taken as evidence that D-cracking is caused by stresses generated during the freezing of critically saturated coarse particles. . . . D-cracking is initiated when atmospheric moisture penetrates open joints and cracks, and together with moisture already present beneath the pavement, raises the degree of saturation of the coarse aggregate to a critical level. . . . If allowed to progress, the entire pavement will be converted to an incoherent mass of rubble."

Under Conclusions and Recommendations, the PCA report says, "It is thus recommended that precautions be taken to upgrade the coarse aggregate and reduce the flow of moisture through the joints." Nothing is said about improving internal drainage, although the rapid elimination of free water by good internal drainage systems offers a practical and economical means of reducing damage due to D-cracking. Trying to keep cracks and joints watertight is, of course, virtually impossible.

In a study of drainage needs of airfield pavements for the U.S. Army Corps of Engineers Construction Engineering Research Laboratory (CERL) (*14*), I found that D-cracking was much more severe in the 150-ft-wide runway of a major airfield in the Great Lakes area than in the 75-ft-wide taxiways. Water can drain out of a 75-ft-wide pavement in about ¼ the time needed to drain 150-ft-wide pavements (drainage time increases approximately in proportion to the squares of the widths). The much greater deterioration of the runway than the taxiways is evidence that increased retention time of water leads to greater D-cracking. It also corroborates the concept that good drainage can reduce D-cracking. If water can remain in the runway about four times longer than in the narrower taxiways after each saturating event, it is to be expected that the runway will suffer much greater non-load-bearing environmental damage than the taxiways.

Other kinds of non-load-bearing environmental damage, such as blow-up, frost action, expansion, shrinkage cracking, increased oxidation and loss of flexibility of asphalt concrete pavements and bases, and general deterioration, are related directly to the amount of time per year that structural sections remain in an essentially flooded condition. Hence, all of these kinds of damage can be greatly reduced by good internal drainage systems.

WARNINGS OF MOUNTING PROBLEMS WITH UNDRAINED PAVEMENTS

Collectively, the pavements of the U.S. Interstate system represent the biggest "experimental road test" of all time. Before much of the Interstate system was built, designers reviewed the results of the WASHO Road Test in Idaho (*1*) and the AASHO Road Test in Illinois (*2*), in which not a single one of the hundreds of test pavements contained a good internal drainage system. Although those tests proved that excess water was always the prime factor in failure of the road test pavements, drainage was completely ignored as a viable design option for Interstates or other important roads. As a consequence, the Interstate system was designed on the concept that if the specified kinds of pavement and base materials were used, and appropriate rational design methods were employed, fast removal of water from within structural sections of pavements would not be necessary.

The entire Interstate system (with few exceptions) therefore represents a technology that depends on strength, not on drainage, for performance. It represents the philosophy of most pavement designers. To illustrate, in August 1962 a prominent advocate of the "strength" philosophy and a staunch antidrainage champion told an international gathering of pavement designers (*15*), "The pertinent question should be, What is underneath the pavement?—not what falls on top of it." This attitude, which has been shared by most designers of Interstates and other pavements—even to the present day—is in my view the major reason for the untimely failure of most modern pavements. What has been put under pavements has not been able to handle what has been falling on them.

Those supervising and reviewing the major road experiments, such as the AASHO Road Test, were interested only in developing combinations of pavement and base that would withstand traffic and environmental conditions without the benefit of good internal drainage. Because of this view, not one of the hundreds of individual designs incorporated internal drainage systems. Likewise, although some pavements of the Interstate system were provided with drains to control groundwater, spring inflow, and the like, not a single mile had a drainage system for rapid removal of infiltrated surface water. The system is therefore an "experimental road test" of undrained pavements. Its performance is a measure of the effectiveness of the design methods used. Many miles of Interstate started to deteriorate in as little as 6 to 10 years, far short of the life that should have been reasonably expected.

One of the early indications of coming problems with the Interstates was a report issued by the General Accounting Office (GAO) to Congress in 1970. As summarized in an article in *Civil Engineering* (*16*), that report says that surveys made of pavements put down before October 1963 indicated that some 2,800 mi of Interstate pavements already needed overlays at an estimated cost of $200 million. A little later an FHWA report (*17*) said that $329 billion out of a total road construction and repair budget of $450 billion would still be needed from 1976 to 1990 "to keep 1975 levels of condition and performance on the nation's highways." As shown later, I have estimated that at least ⅔ of the $329 billion, or $217 billion, could have been saved by good drainage of all important pavements. This is $15 billion a year in the United States alone.

More recent indications of the growing problems with undrained pavements in the United States are given in the Secretary of Transportation's *1985 Needs Report to Congress* on the condition and performance of the nation's highways (*18*). That report says, "Based on data supplied by the State highway agencies, the percentage of the Interstate pavements needing repair increased from 9 percent in 1981 to 14 percent in 1982." The report also says that failing pavements "will result in over 1 million miles of major roadways requiring work to the end of the century."

In my view, if all major pavements constructed in the past 20 to 30 years had been built as well-drained systems, hardly any would be needing more than normal maintenance and a periodic overlay to compensate for normal wear and tear.

The accelerating problems with the national pavement system have alarmed taxpayers, public officials, and the media. Our "magnificent pavement system," which was supposed to represent the best thinking and modern technology and consumed vast amounts of materials, energy, and money, has been falling apart and little can be done but to pour large amounts of money into repair and replacement projects. A *U.S.News & World Report* article (*19*) says that American roads—the most expensive public works undertaking of all time—are being battered to pieces. Numerous other national publications and local media have expressed concern over deteriorating pavements.

ESTIMATED DOLLAR LOSSES CAUSED BY LACK OF DRAINAGE

Estimating the amount of money being wasted by the "undrainage" practice requires reasonable estimates of two factors: (a) the relative rates of damage per load impact to typical undrained, "flooded" pavements and to well-drained or "nonflooded" pavements and (b) the length of time each year the undrained pavements remain full or essentially full of water and thus are in a flooded condition.

Documented information from major experimental road tests (*1*, *2*) provides valuable insight into the potential rates of damage to flooded pavements versus nonflooded or well-drained pavements. I use the term "severity factor" to compare damage rates for undrained and drained pavements. Thus, if the rate of damage per heavy wheel impact is 10 times greater under flooded conditions than under nonflooded conditions, the factor is 10, and so on. That is, each flooded impact shortens pavement life 10 times faster than each nonflooded impact for a factor of 10. Table 1 gives a summary of calculated severity factors for the WASHO Road Test, the AASHO Road Test, and experiments conducted by the University of Illinois in its circular test track (*3*). For the AASHO Road Test, severity factors ranged from around 10 to around 40. For the WASHO Road Test, the factor ranged as high as 70,000 (spring thaw conditions). For the tests run at the University of Illinois, the factor was around 200.

In my estimate of the losses caused in the United States by poor drainage, I used a severity factor of 15, which I believe is rather conservative for a nationwide estimate.

Next, to estimate the average length of time pavements in the United States stay filled with water each year, I used the information in Table 2, which was included in the study for the FHWA's *Guidelines for the Design of Subsurface Drainage Systems for Highway Structural Sections* (*7*). At eight state highway sites and one county road site (selected

TABLE 1 SEVERITY FACTORS FOR FLOODED VERSUS DRAINED STRUCTURAL SECTIONS AS ESTIMATED FROM PUBLISHED REPORTS (*14*)

Test	Behavior Reported	Severity Factor
WASHO Road Test (*1*)	Worst damage occurred during frost melt period	70,000:1
AASHO Road Test (*2*, p. 40)	Damaging effects of traffic were more severe in spring frost melt period than in summer and fall	10:1 to 40:1
University of Illinois circular test track (*3*)	Before saturation, 700,000 load applications produced 0.2 in. to 0.5 in. rutting; after saturation, 12,000 additional load applications destroyed the pavements while causing 0.5 in. or more additional rutting	200:1

TABLE 2 ESTIMATED LENGTH OF TIME STRUCTURAL SECTION REMAINS ESSENTIALLY SATURATED AFTER IT STOPS RAINING

Case Study	Estimated Time (days)	Relative Time (Eureka = 1)	Special Notes
California	20	2000	Section is on 50- to 60-ft high clayey fill with some sandy material
Connecticut	15	1500	Section is on shallow fill on low side of superelevated curve; clayey subgrade layers over sandy fill
Eureka (Humboldt Co., Calif.)	0.01	1	Has highly permeable base drainage layer under full width of traveled way, with an outlet pipe
Georgia	12	1200	Section is on clayey sand—silty sand fill
Michigan	0.2 (unfrozen)		
	Infinite (frozen)	20	Section is on sand fill; freezes in winter
Oklahoma	15	1500	Has black base that is not directly drained
Pennsylvania	12	1200	Section is on silty sandy fill; 6-in. underdrain pipe under subbase, which is also daylighted
Utah	8	800	Section is on clayey sand fill; base is daylighted
Washington	5	500	Section has 2-in. porous base with no outlet and is not daylighted

SOURCE: K. O'Brien, J. Arman, and H. R. Cedergren, *Development of Guidelines for the Design of Subsurface Drainage Systems for Highway Pavement Structural Sections,* Final Report, FHWA, U.S Department of Transportation, Feb. 1973. Table 5, p. 68.

by the FHWA and local engineers), holes were drilled and tests run on typical samples of pavement, base, subbase, and subgrade to evaluate conditions at each site. Taking into account all known factors such as permeabilities of structural layers, bases, and subgrade; lengths of drainage distances; slopes; and the like, an estimate was made of the length of time the pavements at each site could remain filled with water after a saturating event. Omitting the Michigan site and the Humboldt County site, which are not typical of normal state highway pavements, the times range from 5 days to 20 days, with an average of 12 days per saturating rainfall. If each location in the United States has as few as 10 saturating rainfalls a year (most areas will have more), its pavements would be essentially flooded at least 4 months a year or 33 percent of the time. Trying to be conservative in my estimate, I assumed that pavements in the United States are filled with water an average of only 20 percent of each year.

If traffic loads with a severity factor of 15 act 20 percent of the time each year and the balance of the year they act with a factor of 1.0, the life cycle of the average pavement will be reduced to less than ⅓ of that experienced with wheel loads that have a severity factor of 1.0 during 12 months each year. On this basis, the losses in serviceability that are being caused by undrained water in the United States are more than ⅔ of the $329 billion the FHWA estimated as necessary to keep the nation's roads in serviceable condition to 1990 (*6*, pp. 60–61; *17*).These losses could have been saved by widespread usage of good drainage—$217 billion for the 14-year period or $15 billion a year (*20*). On a worldwide basis I estimate that the losses caused by the "undrainage" practice could exceed a trillion dollars over a 30- or 40-year period (*21–23*).

SUMMARY AND CONCLUSIONS

During the time pavements are filled with water, heavy wheel impacts cause pore pressures and water-hammer-like actions that erode bases and cause faulting and other detrimental actions that greatly shorten pavement life. Also, abundant free water causes or accelerates numerous non-load-bearing environmental actions that deteriorate pavements.

For centuries road builders have advocated good drainage as a means of counteracting the detrimental effects of water. Unfortunately, very few pavements built in the past 30 or 40 years have been provided with good internal drainage systems, with the result that many start to fail within less than half of a reasonably expected life span.

In the light of documented proof from several major road tests and the high costs of maintaining modern pavements, I urge all designers to "return to McAdam" and put good drainage systems in every important pavement they design.

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REFERENCES

1. *The WASHO Road Test, Part 2: Test Data, Analyses, Findings*. Special Report 22. HRB, National Research Council, Washington, D.C., 1955, 212 pp.
2. *The AASHO Road Test, Report 7: Summary Report*. Special Report 61G. TRB, National Research Council, Washington, D.C., 1962, 60 pp.
3. E. J. Barenberg and O. O. Thompson. *Behavior and Performance of Flexible Pavements Evaluated in the University of Illinois Pavement Test Track*. Highway Engineering Series No. 36; Illinois Cooperative Highway Research Program Series No. 108. Urbana, Ill., Jan. 1970.
4. J. L. McAdam. *Report to the London Board of Agriculture*. 1820.
5. A. G. Bruce. *Highway Design and Construction*. International Text Book Co., Scranton, Pa., 1934.
6. H. R. Cedergren. *Drainage of Highway & Airfield Pavements*. John Wiley & Sons, Inc., N.Y., 1974; Robert E. Krieger Publishing Company, Malabar, Fla., 1987.
7. H. R. Cedergren, K. O'Brien, and J. Arman. *Guidelines for the Design of Subsurface Drainage Systems for Highway Structural Sections*. FHWA, U.S. Department of Transportation, 1972.
8. R. A. Forsyth, G. K. Wells, and J. H. Woodstrom. The Economic Impact of Pavement Subsurface Drainage. In *Transportation Research Record 1121*, TRB, National Research Council, Washington, D.C., 1987, pp. 77–86.
9. E. Drake. New Subbase Design Uses Commercially Available Aggregates. *Highway and Heavy Construction*, Vol. 122, No. 10, Oct. 1979, pp. 106–108.
10. D. R. Haughton. *Open-Graded Aggregate Highway Construction, Pine Pass Project, Canada*. Geotechnical and Materials Branch, Ministry of Transportation and Highways, Victoria, British Columbia, Canada, 1986.
11. Open-Graded Base Course at Portland Airport. *Engineering News-Record*, July 5, 1979.
12. D. L. Spellman, J. H. Woodstrom, and B. F. Neal. Faulting of Concrete Pavements. In *Highway Research Record 407*, HRB, National Research Council, Washington, D.C., 1972, pp. 1–9.
13. G. Verbeck, P. Klieger, D. Stark, and W. Teske. *Interim Report on D-Cracking of Concrete Pavements in Ohio*. Ohio Department of Highways with Portland Cement Association, Research and Development Laboratories, Skokie, Ill., March 1972.
14. H. R. Cedergren. *Methodology and Effectiveness of Drainage Systems for Airfield Pavements*. Construction Engineering Research Laboratory, U.S. Army Corps of Engineers, Champaign, Ill., 1974.
15. *Proc.*, International Conference on the Structural Design of Asphalt Pavements. Civil Engineering Department, University of Michigan, Ann Arbor, 1962, Discussion, Session 1, p. 20.
16. Interstate Pavements Failing Early. *Civil Engineering*, Aug. 1970, p. 83.
17. Nation's Roads Deteriorating Rapidly. *Engineering News-Record*, Nov. 10, 1977, p. 14.
18. Secretary of Transportation. *1985 Needs Report to Congress*.
19. America's Highways Going to Pot. *U.S. News & World Report*, July 24, 1978, pp. 36–38.
20. H. R. Cedergren. Poor Pavement Drainage Could Cost $15 Billion Yearly. *Engineering News-Record*, June 8, 1978, p. 21.
21. H. R. Cedergren. How To Save Highway Dollars. *Sacramento Union*, Dec. 16, 1978, p. D-8.
22. H. R. Cedergren. Overcoming Psychological Hang-Ups Is Biggest Drainage Challenge. *Proc.*, Second International Conference on Geotextiles, Vol. 1, pp. 1–6.
23. H. R. Cedergren. Undrained Pavements: A Costly Blunder. *Civil Engineering*, April 1987, p. 6.

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