Water-Induced Distress in Flexible Pavement in a Wet Tropical Climate

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A wet tropical climate characterized by abundance of rainfall and cool nights followed by hot days offers a favorable environment for the development of water-associated distress in flexible pavement. Surface deteriorations such as stripping and raveling have been widely reported and studied in the literature. Other forms of water-induced distress, which are caused by water trapped within the structural system of a flexible pavement, are described in this paper. The occurrence of such distress is difficult to predict, and the subsequent repair is usually quite costly and elaborate. A number of cases of water-induced distress in flexible pavement in Singapore and Malaysia are presented and discussed. The need for drainage analysis in pavement design and the importance of drainage consideration in pavement construction and maintenance are highlighted. On the basis of relevant experience in the region, some preventive measures are recommended for guarding against water-induced problems in flexible pavement.

The abundance of rainfall during the monsoon months each year in a tropical country poses special problems for highway pavement engineers. One of the most common sights immediately after a heavy rainstorm is the accumulation of dislodged aggregates at a road junction or along a bend. Also visible on the pavement surface are signs of stripping, which occurs at an accelerated rate during the rainy season. These forms of surface deterioration can be easily detected by a layman or the ordinary traveling public. Correction by surface treatment or overlay is usually used to restore the riding quality of the affected surface. These treatments are also necessary to prevent the surface deteriorations from developing into potholes and other serious structural defects. These water-related problems have been widely reported and studied in literature *(1, 2)*. Although no way has been found to completely prevent their occurrence, major repair of pavement is generally not required if the deteriorated surface is treated with timely corrective maintenance measures.

Another form of water-induced flexible pavement distress, the occurrence of which is difficult to predict and the subsequent repair of which is usually quite costly and elaborate, is described in this paper. This distress may manifest itself through one of the following phenomena: *(a)* localized wet softened areas of pavement materials that could lead to formation of potholes or depressions in the pavement surface, *(b)* localized upward heaving of the pavement surface, *(c)* separation and disintegration of various pavement layers or successive lifts of a given pavement layer, or *(d)* unevenness or undulation of the pavement surface.

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This distress should be differentiated from that which results from failure or movement of the subgrade foundation. It is directly related to accumulation of water within a pavement structure. Typically, water is trapped in a relatively porous layer sandwiched between two impervious layers after a long, heavy rainfall. This is followed by an increase of water pressure that is responsible for the manifestations of damage described in the preceding paragraph. A few typical occurrences in Singapore and Malaysia are presented in this paper to illustrate the different ways in which water could enter a pavement structure and the different circumstances under which a buildup of water pressure could take place. Recommendations about ways and means of preventing the occurrence of such distress are made.

WATER INFLOW UNDER HYDRAULIC HEAD

Potholes were found to form rapidly on the surface of a four-lane undivided roadway in the month of December 1985, approximately 1 month after the monsoon rain season began. Field investigation determined that, at about 3:00 p.m. on a sunny day, isolated spots on the pavement surface began to swell upward. The center of each swelled area rose about 20 to 40 mm above the original pavement surface. Each affected spot was roughly circular in shape and measured about 250 mm in diameter.

The total affected area covered a distance of about 4 km. On a hot afternoon the worst affected area would have more than 10 swelling spots within a distance of 200 m. These heaved-up surfaces could be easily depressed and flattened when stepped on by a human being, but they slowly returned to the swelled condition in about 20 min after the load was removed. The swelling began to subside at night when the temperature dropped and disappeared completely by the following morning.

The construction history of the roadway revealed the pavement structure shown in Figure 1. There was a 230-mm-thick base course of crushed stone. A 90-mm dense asphalt concrete layer was constructed above it, followed by an open-graded 25-mm asphalt wearing course. After about 5 years in service, a 50-mm overlay of dense asphalt concrete was laid in July 1984. Records showed that the overlay construction was carried out during a dry period. Figure 2 shows the profile of a typical core sample of the pavement structure.

Several 600- by 600-mm pits were excavated to the base course for inspection. Typically, the uppermost overlay and the bottom 90-mm asphalt concrete layers were dense and intact. The intermediate 25-mm old wearing course was damp, soft,

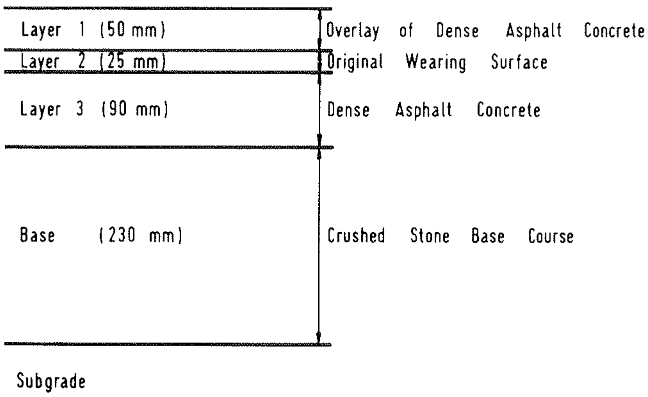

FIGURE 1 Profile of pavement structure.

and disintegrated as shown in Figure 3. Aggregates and bituminous binders of this second layer could be easily separated and extracted by bare hands. The water table was approximately 900 mm below the pavement surface. There was no sign of accumulated water within the base course, which was found to be dry and free draining. On the walls of each of these pits, as shown in Figure 4, water could be seen seeping out from the interface plane between the second and third layers. Pits were also excavated at the locations of swelling spots where only the top overlay layer was removed. There was no effective bond at the interface between this and the disintegrated layer below it. In about 15 to 20 min, approximately 40 mm of water would be collected in these pits from seepage from the underlying porous layer. A laboratory falling-head permeability test on cored samples indicated that the top and the bottom layers were practically impermeable, whereas the intermediate layer had horizontal permeabilities ranging from 2×10^{-5} to 5×10^{-2}

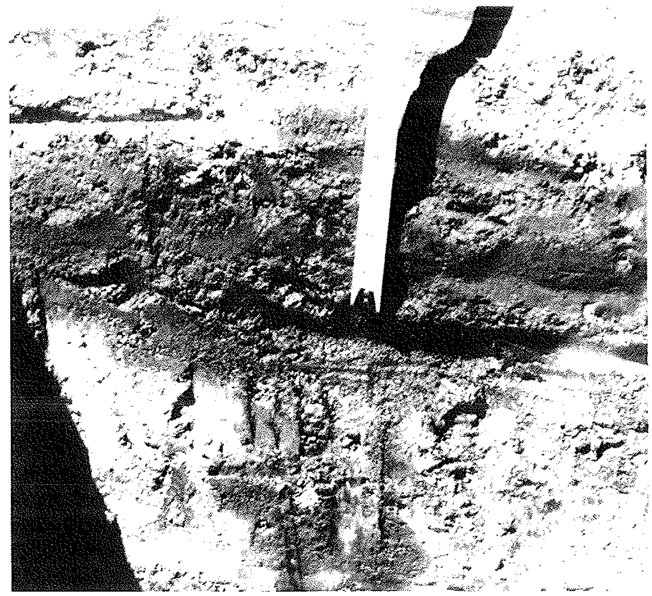

FIGURE 3 Soft damp material sandwiched between dense asphalt concrete layers.

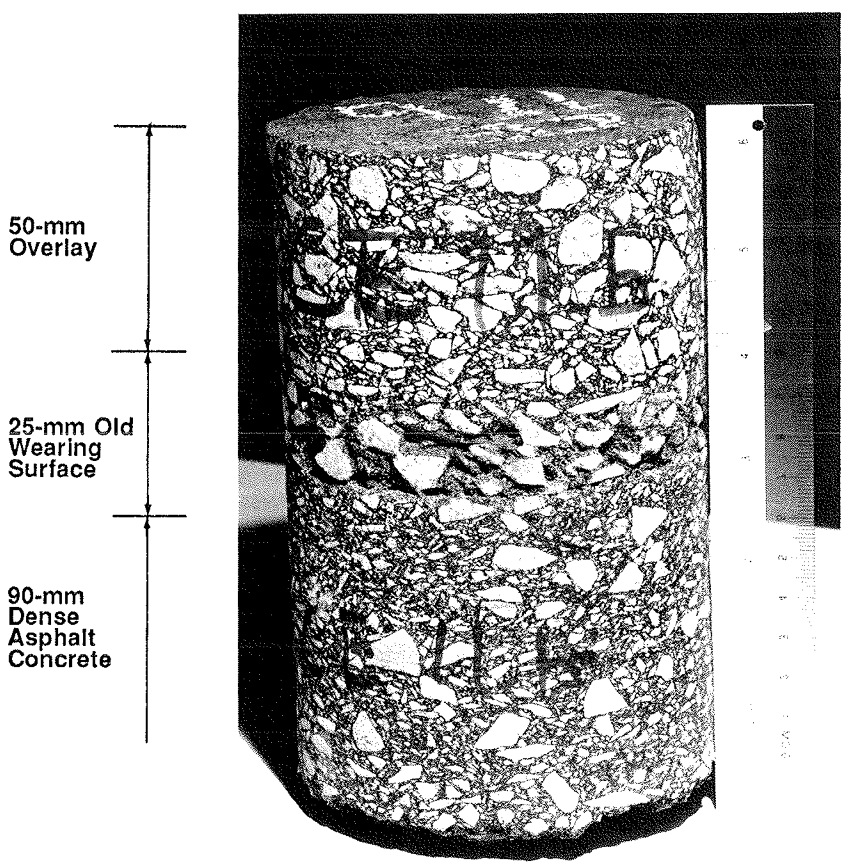

FIGURE 2 Core sample showing new overlay constructed on weathered old wearing surface.

FIGURE 4 Water seeping out from sandwiched damp layer.

cm/sec. It was believed that varying degrees of weathering and erosion by water of the old wearing surface were responsible for the large range of permeability values.

The borders of the roadway were laterite soils with poor permeability in the order of 1×10^{-5} cm/sec. During a heavy downpour, these borders were usually flooded. Field observation indicated that this floodwater took up to 8 hr to drain off. Meteorological data revealed that, in early December 1984, a 2-day and another 3-day rainstorm were recorded with 190 mm and 235 mm of rainfall, respectively.

During a site survey it was found that the flood on the borders of the roadway could achieve a sufficiently high hydraulic head (up to 125 mm) long enough for the floodwater to enter the sandwiched porous pavement layer from the edge joints of the road. For instance, under a sustained hydraulic gradient for a period of, say, 50 hr, and assuming a permeability of 5×10^{-2} cm/sec, water could travel a distance of 9.0 m in the porous pavement layer. After the subsidence of the flood, reverse flow of water was difficult because of the gentle cross-slope gradient and the unevenness of the pavement layer.

The possibility of water infiltration from the pavement surface was also examined. Field permeability tests conducted over a period of 2 days on the pavement surface indicated that infiltration through a crack-free bituminous mix was practically insignificant. Because the overlay surface was less than 5 months old and relatively free of cracks, it was unlikely that surface infiltration through cracks would cause such a widespread distribution of pressured trapped water as was found in the present case.

It is interesting to note the timing of surface swelling. The highest daytime temperature in Singapore and Malaysia, usually occurring at about 2:00 p.m., is around 32°C. The pavement surface temperature measured on a hot afternoon varies from 60°C to 70°C. The buildup of pressure that caused pavement surface swelling could possibly have resulted from *(a)* thermal changes that increased the pressure in the air and water trapped in the porous pavement layer and *(b)* lateral thermal expansion of aggregates and binders that reduced void spaces in the sandwiched pavement layer, which was confined in the vertical direction by two dense asphalt concrete layers and constrained laterally by concrete side curbs.

This water-induced problem required prompt correction because pavement deterioration in the form of potholes and surface disintegration was occurring at an accelerated pace under moving traffic. Surface treatments or additional overlay could not eliminate the problem. The only logical solution was to remove the sandwiched water-logged layer together with the top overlay surface for the entire length of the pavement. Measures were also taken to improve the drainage conditions of the area to avoid standing rain water on the borders of the roadway.

SURFACE INFILTRATION THROUGH JOINTS

A divided primary road, with two lanes in each direction, had badly deteriorated surface due to stripping and rutting. A 35-mm overlay of dense bituminous mix was applied in April 1984. Problems began to surface in September 1984 on the northbound pavement. Light brown stains in a straight-line pattern were observed on the pavement. Up to 2 weeks after a heavy rainfall, small patches of water were seen forming approximately in a straight line on the pavement surface during the warmer part of the day. Stains were left behind when these patches of water evaporated, as shown in Figure 5. Although no cracks were visible on the surface along the straight line on which stain marks were left, the line was later identified as the longitudinal joint between two neighboring overlay applications. Crack sealing was performed on locations where stain marks appeared.

Approximately 1 month after crack sealing, small patches of water and stains reappeared on stretches along the longitudinal joint. In addition, a series of longitudinal cracks with lengths varying from 200 to 450 mm was found on the wheelpaths adjacent to the longitudinal joint. Removal of the overlay layer revealed that the interface bond was ineffective at these wheelpath locations, and there were signs of accumulated water on the original deteriorated surface. It was estimated that stripping of the old surface had caused loss of binder to a depth of 20 mm. Failure to patch and seal or to mill off these stripped materials during the overlay operation had unknowingly incorporated a water-collecting layer within the pavement structure.

It was believed that after initial infiltration through the longitudinal construction joint, water worked its way along the plane of interface and collected in the stripped and rutted areas of the old surface. The disruption of interfacial bond and spreading of trapped water were aided by the pressure buildup due to rising temperature during hot afternoons as well as compression caused by traffic loadings. The initial sealing of longitudinal joints might have forced the trapped water to move sideways during a pressure buildup.

Because of budgetary constraints and possible inconvenience to the traveling public, repairs were carried out at night and only a few patches of areas that showed signs of distress were repaired at a time. At each location, as much as 60 mm of material was milled off to ensure that the deteriorated surface of the old wearing course was removed.

FIGURE 5 Patches of water emerged from pavement in hot afternoon and left stains behind when evaporated.

SURFACE INFILTRATION THROUGH CRACKS

Cracks in a pavement surface provide excellent storage space for surface water. A random survey, which was conducted on a secondary road after a 2-hr rainfall with a precipitation of 46 mm, indicated that many cracks, especially those wider than 0.5 mm, were still damp 24 hr after the rain had stopped. If these cracks are not repaired or sealed off, water that enters the cracks each time it rains tends to erode the interior of the pavement. Figure 6 shows a crack that could admit so much rain water that water was seen flowing out from the crack for several hours during the warmer part of the day after a heavy rainfall.

Given the presence of cracks and imperfect joints, it is possible that a pavement may become more permeable than the underlying base or subbase materials, thereby leading to a holding up of free water within the pavement structure during and after a heavy rainfall. Pressure buildup due to wheel load impacts or thermal changes could lead to erosion and disintegration of the pavement materials. Figure 7 shows a curb joint from which outflow of water and fines continued for more than 8 hr after a rainstorm had stopped.

CLOGGING OF SUBDRAINS

A secondary two-lane road located along the bank of an open unlined channel had the problem of water seeping out onto its

FIGURE 6 Water flowing out from crack after rain had stopped.

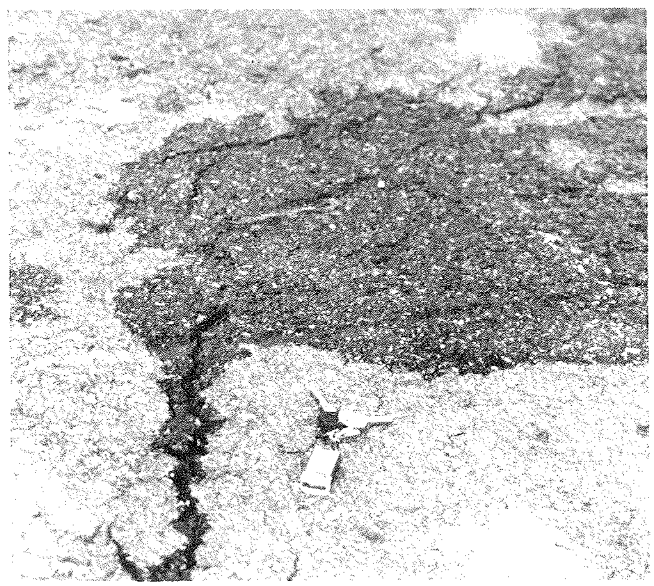

FIGURE 7 Outflow of water and fines from curb joint.

pavement surface during hot afternoons for several days after a rainfall. This problem began to appear about 2½ years after the road was constructed. At each affected spot, the upward flow of water could not be detected by the naked eye; only a damp area of irregular shape could be seen on the surface. Core samples extracted during the warmer part of the day were moist. Core samples extracted in the early morning contained fine water droplets in the bituminous mixture as a result of condensation. The total thickness of the bituminous layers was 105 mm.

Large fluctuations of groundwater table could be observed in the vicinity of the roadway. The normal water table was 760 mm below the pavement surface but rose easily to a few millimeters from the surface on a rainy day. In Singapore and Malaysia, the average number of days with rain is of the order of 155 each year *(3, 4)*. As a result of the frequent rise and fall of the water table, drainage passages tended to get clogged and water became trapped within the pavement system. Moisture could move upward by capillary action or be forced upward by thermal pressure on a hot day.

The first sign of pavement distress, as shown in Figure 8, was cracks in the surface at each wet location. A slight heaving of the surface material could sometimes be observed. This was followed by breaking up of the surface layer and disintegration of the bituminous mixture. Shallow patching, which does not correct the subdrainage condition, would not offer a solution to the problem. Because reconstruction of the relatively new pavement was costly and the request for additional funding was difficult to justify, a "repair as it occurs" policy was adopted. Deep patching that involved replacement of drainage layers had to be carried out rather frequently.

FIGURE 8 Water-induced cracks in pavement before formation of pothole.

DRAINAGE PROBLEMS DUE TO BACKFILL OF UTILITY TRENCH

On city streets and residential roads in Singapore and Malaysia, cutting of trenches in existing pavements for utility installation or repair is quite a common occurrence. In addition, the frequent problem of differential backfill settlements that contribute to unevenness and poor ride quality, poor-quality backfills that interrupt subsurface drainage, and joints that admit water may cause accumulations of water in pavement systems and lead to structural failure of pavements.

Both transverse and longitudinal utility cuts can be found, and they have become a feature with which urban road engineers have to live. Although utility cuts may occupy a small proportion of the pavement area, they are usually deep enough to cut through the entire pavement structure. Proper backfilling of these cuts is important to the overall soundness of the pavement system. The boundary joints of a utility cut are potential planes of weakness structurally as well as from a drainage point of view. Joints that are not watertight admit into the pavement structure additional water, which is not planned for in the original design. The life of a pavement can be significantly shortened if some of this additional water becomes trapped within the pavement.

FIGURE 9 Water bleeding from utility trench joint; photo taken 9 hr after rain had stopped.

FIGURE 10 Stain marks on the pavement shown in Figure 9 caused by fines transported by outflowing water.

In terms of drainage, longitudinal utility cuts are especially important because they cover a long stretch of pavement, and they cut across the lateral drainage path of the pavement. Figure 9 shows a poorly backfilled utility trench that effectively cut off the lateral subsurface drainage of the pavement. The road was originally constructed to have one-way lateral subsurface drainage across the width of the pavement. The backfill, which was not as permeable as the original pavement construction, acted as a barrier that held up water that was supposed to be discharged by the drainage layer of the pavement. Upward flow of water, as can be seen in Figures 9 and 10, continued for more than 16 hr after a heavy rainfall had stopped. Fines left on the pavement surface provided indications of the damaging effects on pavement sublayers.

Another common form of water-induced distress is pavement damage within a utility patch itself. The inability of utility cut backfill to drain off water that enters through the boundaries of utility trenches is a common cause of the problem that leads to pothole formation and disintegration of a utility trench patch.

PAVEMENTS IN CUT SECTIONS

Drainage design for pavements in cut sections is particularly important because surface runoff as well as subsurface seepage from both sides of the cut tend to converge toward the road section. Intercepting drains are usually constructed to prevent flooding of pavement by surface runoff. Cutting off of inward flow of subsurface seepage is a more difficult problem. It requires a careful study of the features of the site and ground conditions before an effective subsurface cutoff drain can be designed.

The amount of subsurface seepage can be quite substantial. Without performing a drainage calculation, there is a tendency for most designers to underestimate the amount of subsurface inflow after a heavy rainfall. Figures 11 and 12 show the surfaces of two secondary pavements in cut that were not provided with sufficient subsurface seepage cutoff. On both pavements, flows of water were found oozing slowly from the surface at several points after a rainfall. The upward flow of water would continue for 10 to 20 hr, depending on the intensity of precipitation, after the end of a storm.

Cracks would gradually develop around the point of outflow under the action of traffic. Further deterioration eventually would lead to the formation of potholes. During a spell of heavy rainy weather in December 1985, potholes occurred in such numbers in a matter of a few days that maintenance crews simply did not have the time to patch them properly. Figure 13 shows one of the repair patches where outflow of subsurface water still occurred long after a rain had stopped.

FIGURE 11 Water oozing from Point A after rainstorm.

FIGURE 12 Water oozing from Points B and C after heavy rain.

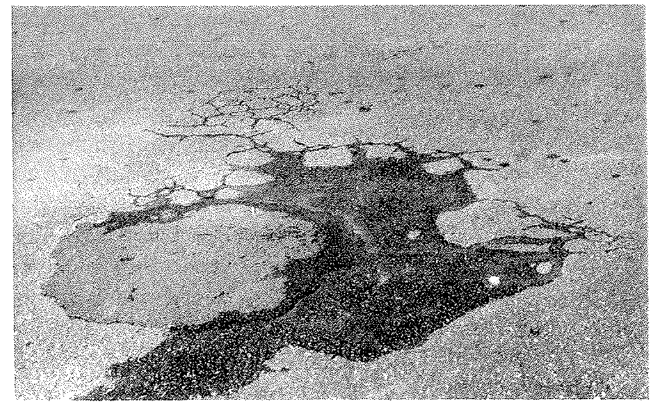

FIGURE 13 Water flowing from a poorly repaired patch.

FEATURES OF THE DISTRESS PROBLEM

Cases of pavement damage initiated or accelerated by the prolonged presence of water within pavement structures are presented and analyzed. Most of the cases presented contained telltale signs such as swelling of the wearing surface, appearance of moisture on the pavement surface, and upward bleeding of water from within the pavement system. It is clear, however, that there probably exist many other instances in which water-induced pavement damage took place without showing any telltale signs. Some important features of the distress problems follow.

- Porous layers or voids within a pavement structure serve as a storage space for water. Such storage space may be created when a porous layer is sandwiched between two relatively impervious layers, or when internal drainage paths of a pavement are interrupted by subsequent construction, or when voids are formed within pavement materials by progressive erosive action of water entering through surface cracks or joints.
- Rainfall is the source of water supply. Rainwater enters a pavement structure either by surface infiltration gravity flow through cracks or joints or by lateral or upward flow under a hydraulic head. The water may become trapped in storage spaces within the pavement structure or held up for a prolonged period because draining by gravity to pavement edges is usually slow because of the gentle gradient of pavement cross slopes.
- Pavement distress is accelerated by pressure buildup in the trapped water caused by thermal changes and vehicular loadings. The pulsating water pressure created by moving traffic appears to be a primary destructive mechanism leading to pavement damage.
- The resultant pavement damage usually takes the form of surface cracking, potholes, and disintegration of bituminous materials. It is important to note that these kinds of damage are water induced; they may not be initiated or preceded by failure in the subgrade or subbase layers.

Detection and repair of pavements affected by water-induced problems present a challenge to pavement engineers and maintenance staff. Water intrusion into a pavement structure is difficult to detect. By the time telltale signs are visible, it is too late for any preventive maintenance work because water has already entered the pavement structure. It is practically impossible in most cases to remove the trapped water by any nondestructive means. Repair of affected pavements is also not straightforward. No standard repair procedure can be formulated because each case is likely to be different. An effective corrective repair can be achieved only when the exact causes and mechanism of the distress in question are determined.

Certain preventive maintenance activities may be useful in reducing the likelihood of water intrusion into pavements. Cracks and joints in pavement surfaces should be sealed watertight. Drainage facilities such as gutters, ditches, and pipes must be inspected and maintained regularly. Underdrains can be installed along edges of those pavements with poor surface drainage. Standing water in ditches and storm drains is a sign of potential water-induced problems. Areas of pavement surface that stay damp for a long period of time after the rest of the pavement surface dries after a rainfall deserve additional attention. A poorly compacted longitudinal joint will also appear damp long after the adjacent pavement surface dries.

CLIMATIC FACTOR

The occurrence of water-induced distress depends on two factors, the climate and the pavement. Good pavement design, construction, and maintenance practices cut down the number of cases of pavements with entrapped water. Areas of wet climate with frequent rainfall tend to be affected more by water-induced problems than are dry climatic regions, although the possibility of water-induced problems occurring in an arid climate after heavy rainstorms, which might occur only a few times each year, must not be ruled out. As long as a pavement is capable of trapping water within it, water-induced problems may arise whenever rainwater is available.

The threat of water-induced problems is ever present for the pavements in Singapore and Malaysia because of the abundance of rainfall. The region generally has rainfall throughout the year but tends to be particularly wet during the monsoon season from November to January. The average annual rainfall is around 2,000 mm (79 in.), and the average number of days with rain each year is about 155. The pavements in the region are also exposed to extensive sunshine each year. The annual average number of hours per day under bright sunshine is more than 5. Table 1 gives the yearly temperature range and rainfall data of Singapore for the past few years.

The general climatic pattern all year round is that of relatively hot days followed by cool nights. On a typical day, the maximum temperature is around 30°C and the minimum is 24°C *(3)*. The temperature variations on most road pavements are much larger than the changes in air temperature, ranging from around 25°C in the early morning to as high as 75°C on a hot afternoon. Three important characteristics of the wet tropical climate of Singapore and Malaysia can therefore be identified: *(a)* frequent rainfall with high precipitation throughout the year, *(b)* alternating rain and sunshine leading to a large number of wetting and drying cycles, and *(c)* repetitive daily cycles of cooling and heating due to temperature changes.

These three conditions present to pavement engineers a difficult task in keeping pavement surfaces watertight and resistant to stripping or disintegration of surface materials. Surface runoff and infiltration water, coupled with favorable temperature changes, wetting and drying, and traffic loading effects, are constantly causing deterioration of pavement materials and creating void spaces within pavement structures.

Pavement crown, cross section, and structural thickness usually receive the greatest attention from designers in Singapore and Malaysia. In the light of the highly favorable environment for the development of water-induced problems, it is thought that inadequate attention has been paid to the climatic factor in design to guard against water-induced problems. More emphasis should be placed on drainage considerations during pavement design as well as during construction and maintenance of pavements. On the basis of experience observing the performance of pavements in this region, some measures are recommended in the following section for the prevention of water-induced problems in flexible pavements.

RECOMMENDATIONS FOR PREVENTIVE MEASURES

Pavement design and construction practices in Singapore and Malaysia generally provide for side-drains to remove surface water and to lower the groundwater table. Cut-off drainage systems such as French drains are usually installed along edges of pavements constructed on cut sections. Unfortunately, rarely do pavement designers and constructors carry out detailed studies to guard against possible storing or holding up of rainwater within a pavement structure after a heavy rainstorm. Permeability requirements of base, subbase, and subdrain materials are not strictly specified and controlled.

Figure 14 shows one of the crushed-stone gradation limits commonly adopted in Singapore and Malaysia. Laboratory falling-head permeability tests were conducted using four different sets of samples with Gradations A, B, C, and D as shown

TABLE 1 RAINFALL AND TEMPERATURE CHARACTERISTICS OF SINGAPORE *(5)*

Year	Average Daily Temperature (°C): High	Low	Rainfall: Total (mm)	Daily Maximum (mm)	Rainy Days	Daily Mean Hours of Sunshine
1979	31.0	23.9	2168	91	168	5.7
1980	31.0	23.9	2326	134	176	5.7
1981	31.3	24.2	1463	72	145	5.8
1982	31.4	24.6	1582	109	130	5.7
1983	31.7	24.9	1994	182	145	5.6

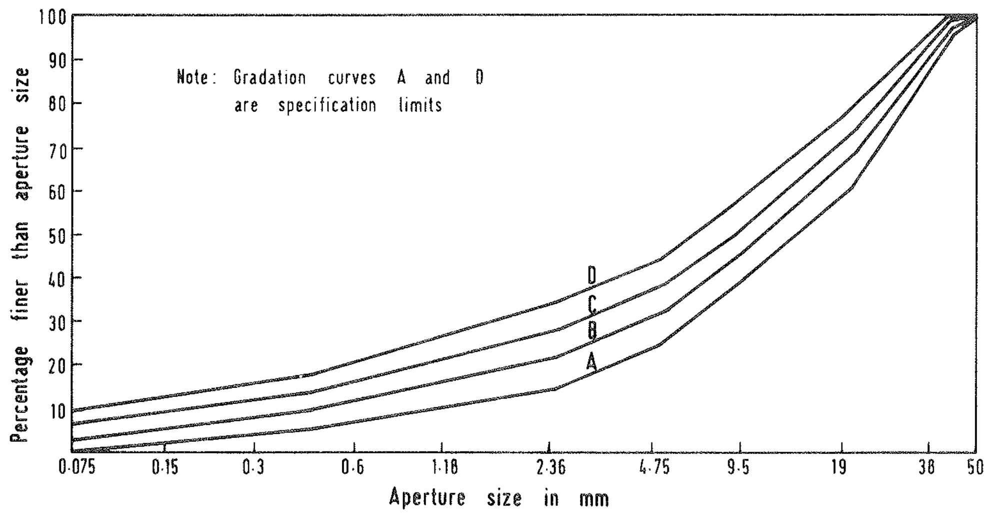

FIGURE 14 Aggregate gradations for base course materials.

in Figure 14. The results of these tests are given in Table 2. It is noted that materials that fall within the specified gradation limits could have permeability values varying from 1.57×10^{-1} cm/sec to 2.42×10^{-3} cm/sec. It appears that the gradation specification alone is insufficient from the point of view of pavement drainage.

TABLE 2 PERMEABILITY VALUES OF BASE MATERIALS

Gradation (see Figure 14)	Permeability cm/sec	ft/sec
A	1.57×10^{-1}	5.15×10^{-3}
B	1.73×10^{-2}	5.68×10^{-4}
C	1.01×10^{-3}	3.31×10^{-4}
D	2.42×10^{-3}	7.94×10^{-5}

NOTE: Permeability for each gradation obtained as average of six laboratory falling-head tests.

Specification of permeability requirements for base and subbase in a comprehensive pavement design represents only one preventive measure against water-induced pavement distress. In light of observations and investigations made on the pavements in Singapore and Malaysia, the following measures appear appropriate for controlling the occurrence of water-induced problems in construction of new bituminous pavements:

- Base and subbase materials should be sufficiently permeable to drain off surface water infiltration or other inflow of rainwater.
- Each pavement layer must be more permeable than the layer immediately above so that draining off of infiltrated water will not be impeded and no water will be held up in the upper layer.
- Good geometrics should be provided for pavement and adjacent features to aid drainage. Roadside drainage systems must be constructed and maintained such that flooding will not occur on the borders of the pavement. In areas where the surrounding land is flat and where standing water cannot be discharged quickly, the level and the cross section of the road must be such that lateral flow of water into the adjacent pavement structure will not take place.
- Along a cut section, French drains or other subdrainage systems may be used to discharge surface runoff and to lower the groundwater table.
- Full-width paving is desirable because it eliminates longitudinal joints that are potential points of moisture infiltration. Where such joints cannot be avoided, they should be properly constructed and sealed, if necessary, to remain watertight.
- On secondary roads and some primary roads where shoulders are not provided, the use of curbs as edge restraints is recommended. Sufficient drainage facility should be provided so that water will not accumulate at the curb line.
- When a thick bituminous layer is compacted in lifts, it is important to monitor the construction closely to ensure that the interfaces between lifts are intact and watertight.
- In areas where subbase and base may be clogged by fine subgrade soil brought up by a fluctuating water level, a filter layer is needed to protect the drainage layers.
- Close tolerance of subgrade grading should be achieved to prevent depressions that could trap water.

Proper drainage maintenance plays a vital role in preventing the occurrence of water-induced problems. Regularly scheduled inspection and maintenance of drainage features is a must. Timely maintenance and sealing of joints and cracks offer long-term benefits by cutting off possible inflows of water.

One of the cases presented in this paper suggested that paving a dense overlay on a porous wearing course would lead to water-induced pavement damage. This is particularly relevant in the tropics where many old road surfaces are badly stripped and eroded. If the cavities and voids in these weathered surfaces are not removed or filled before overlay construction, there is a high probability that infiltration water will eventually get trapped in the old weathered wearing course. It therefore makes good engineering sense in the tropics to investigate the drainage condition and permeability properties of an old pavement, in addition to the commonly performed structural evaluation, before constructing an overlay.

Poorly constructed utility trenches present a tremendous potential for the development of water-induced problems. Utility patches and surrounding pavement sections may be damaged by water intrusion from the boundary joints or by backfill that interrupts the subsurface drainage of the original system. Intrusion of water can be checked by sealing the edges of trench patches. Poor backfill can be avoided by proper supervision and control during construction.

CONCLUSIONS

The climate of wet tropical regions provides an environment that is conducive to the development of water-related distress in flexible pavement. Surface deterioration such as stripping and raveling is visible and can be easily detected. Another form of water-induced flexible pavement distress, which is caused by the presence of trapped water within the structural system of a flexible pavement, has been described in this paper. Detection of such distress is difficult until an advanced stage when an elaborate repair of the affected pavement is required.

Several cases of distress in Singapore and Malaysia have been presented to illustrate the circumstances in which such distress occurs. These cases were selected to reveal the various mechanisms by which water-induced problems could develop. An important lesson learned from the study of these cases is that there is a need for a thorough material permeability and drainage analysis to be carried out during the pavement design phase, and that it is equally important for site supervisors of construction work and pavement maintenance staff to be aware of the significance of providing proper drainage to suit actual ground conditions.

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