DRAINAGE CONSIDERATIONS TO MINIMIZE DISTRESS AT THE PAVEMENT-SHOULDER JOINT

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SYNOPSIS

The highway system in the United States includes a significant mileage of portland cement concrete pavements with adjoining asphaltic concrete shoulders. The resulting joint formed between the pavement and shoulder has proved to be one of the weakest parts of the pavement-shoulder system. Leakage of excessive amounts of surface water through this joint leads not only to early cracking, settlement, and structural deterioration of the shoulder, but ultimately to cracking, transverse-joint faulting, spalling, and settlement of the pavement itself. Infiltrating water has also contributed to frost heave in northern climates and to heave of expansive subgrade soils in both warm and cold regions. This joint has proved to be a costly maintenance problem, an inconvenience to the traveling public and, in some instances, a serious safety hazard

Results of the study indicate that deterioration of the shoulder in the vicinity of the longitudinal pavement-shoulder joint is considerably more severe when a significant quantity of water is present beneath the pavement and shoulder structure. Important factors that affect the severity of the water-associated problems include the amount and distribution of rainfall, temperature, expansive clay subgrades, and the strength and type of the structural shoulder section. Rapid removal of water from beneath the pavement structure is an excellent method for minimizing water-related deterioration. For the drainage system to function properly, it must have sufficient permeability and a positive outlet.

Although groundwater is frequently the source of pavement and shoulder problems, infiltration of surface water into the pavement structure can be just as important as subsurface water. A typical open crack or joint with an unfilled reservoir beneath can remove 70 to 97 percent of the rainfall flowing across the joint. Field infiltration measurements performed as a part of this study indicate that even under prolonged wet conditions a pavement resting on a moderately impermeable subgrade can have an average infiltration capacity of approximately 30 percent of the rain falling on the pavement.

To substantially lower the water level in the vicinity of the longitudinal pavement-shoulder joint in 5 to 30 minutes, 50 percent of the available free water should be removed from a drainage blanket in 0.05 to 0.20 days. For a typical two-lane divided highway, a drainage blanket having a minimum permeability on the order of 200 to 800 ft./day can generally satisfy this proposed drainage criterion for surface infiltration. Open-graded, asphaltic concrete base course mixes can be designed which exhibit good stability and also have relatively high permeabilities varying between approximately 800 and 2,000 ft./day. More use should be made of these materials which can serve both as a structural load carrying component and also as a drainage blanket or drainage layer. Sections having both full-width permeable asphalt concrete bases and also permeable shoulder drains of limited width are proposed for providing efficient collection and removal of infiltrated surface water. Water can be collected from these permeable layers by either conventional trench drains or a mini-drain system consisting of small-diameter slotted or perforated pipe placed in the drainage layer.

INTRODUCTION

The highway system in the United States includes a significant mileage of portland cement concrete pavements with adjoining asphaltic concrete shoulders. The resulting joint formed between the pavement and shoulder has proved to be one of the weakest parts of the

pavement-shoulder system. Leakage of excessive amounts of surface water through this joint leads not only to early cracking, settlement, and structural deterioration of the shoulder, but ultimately to cracking, transverse-joint faulting, spalling, and settlement of the pavement itself. Infiltrating water has also contributed to frost heave in northern climates and to heave of expansive subgrade soils in both warm and cold regions. This joint has proved to be a costly maintenance problem, an inconvenience to the traveling public and, in some instances, a serious safety hazard.

Although the rate of deterioration of the pavement and shoulder at the joint varies widely with respect to locality, materials used, and construction practices, the basic mechanisms of deterioration are generally the same. Further, each mechanism's importance may vary considerably. Without a positive seal at the joints, surface water infiltrates into the subbase, subgrade and shoulder.

The distress manifestations normally associated with the pavement-shoulder joint problem are quite widespread; however relatively little formal research has been conducted in an attempt to develop and evaluate design criteria or joint sealants to minimize intrusion and detrimental effects of water. As the cost of maintenance has increased and delays to motorists have become a more important consideration, the need to develop reasonably effective sealing systems for the joint, and to identify suitable design and construction techniques to minimize the effects of water has become considerably more important than in the past.

This paper discusses the occurrence and removal of water which gets beneath the pavement. The research described is a small portion of NCHRP Project 14-3 [2] which involved developing an improved pavement-shoulder joint design; a design that will both minimize the intrusion of water through the joint and, at the same time, minimize the deterioration of both the roadway and paved shoulder caused by water which does get beneath the pavement.

CURRENT DRAINAGE PRACTICES

Problems experienced in the vicinity of the pavement-shoulder joint have frequently been related to water which enters through the pavement surface or gets beneath the pavement due to ground water movement. The surface and subsurface drainage practices used to control water by the state highway and transportation organizations interviewed during this study are summarized in Table 1.

Surface Drainage

Typical transverse surface slopes being used vary from 1/8 in./ft. to 1/4 in./ft. for the pavement and between 1/4 and 1-1/2 in./ft. for the shoulder. Only Ohio uses a reverse transverse pavement slope to limit the amount of pavement surface water draining across the outside longitudinal pavement-shoulder joint (Fig. 1). The performance of Ohio shoulder sections having reverse slopes appeared to be better than for sections sloping toward the outside edge.

Subsurface Drainage Practices

A number of years ago Hveem [3] concluded that slab pumping would not be a serious problem if water did not accumulate beneath the pavement. Of the state transportation organizations interviewed, ten of the thirteen indicated that specific measures had been adopted to remove water from beneath the pavement (Arizona, Texas and Utah did not). With the exception of Illinois, these states were relying on granular base or subbase materials having from 0 to 20 percent fines to remove the water. Six of these states were using a "daylighted" base extending out to the edge of the side slope. None of the states interviewed were using a high permeability, asphalt-stabilized aggregate drainage layer as a standard section. In general, longitudinal drains and drainage blankets were being used only in critical areas where water was found to be a problem, such as in cuts or where subsurface water conditions are encountered. Only Georgia (Fig. 2) and Pennsylvania were using longitudinal drains as a routine design practice.

Illinois [4] has reported the use of three open-graded subbases that have improved shoulder performance, particularly with full-depth asphaltic concrete shoulders. Fewer transverse cracks also were observed where the open-graded subbase was used under PCC shoulders. All shoulder subbase materials were extended to the side slopes for drainage. No difference in performance was observed for the three gradations studied. Problems in

keeping the washed sand (similar in gradation to PCC fine aggregate) in place during succeeding construction operations has, however, resulted in discontinuing the use of this material in base or subbase construction in Illinois.

Edge drains are used in Michigan where the drainage path is greater than 30 ft., or where underground water problems are encountered. A 4 in. thick aggregate base is placed beneath the concrete pavement and extended 3 ft. out from the edge on each side. A 10 in. sand subbase is placed beneath the aggregate base and carried out to the side slopes.

During the field inspections in Michigan and elsewhere, daylighted bases and subbases were generally found to be covered with topsoil at their junctions with the sideslopes. Because of this and the common use of a relatively high percent fines, these bases as presently constructed are believed in general to have a low capacity for draining water from beneath the pavements and shoulders. A similar conclusion has also been reached by Cedergren et al. [1].

Most pavements in Ohio constructed from 1967 until recently have had a granular base under the pavement and shoulder having approximately 0 to 10 percent fines. This layer was drained by a longitudinal pipe underdrain located 2 ft. from the edge of the pavement. Use of this underdrain system was discontinued as stabilized subbases under the slab and full depth asphaltic concrete shoulders came into use.

Pennsylvania uses a 6 in. dia. longitudinal pipe underdrain system on all Interstate highways, with cross drains every 200 ft. Pennsylvania reported good performance of this underdrain system. Use in Pennsylvania of underdrain systems may be one reason for the good performance of shoulder sections with unstabilized bases.

Stabilized Drainage Layers

Gray, Hannon and Forsyth [5] have described the construction and performance of seven open-graded, stone drainage blankets stabilized with 1.5 to 2 percent asphalt. The asphalt-stabilized drainage blankets were used by California in localized areas where subsurface ground water was found to be a problem. This type layer has been found to have a drainage capacity of up to 100 times that of the California standard Class 2 permeable drainage material, and a field efficiency of approximately 10 times that of the conventional drainage layer. A comparison between the asphalt-stabilized drainage layer and the Class 2 permeable aggregate base material is given in Table 2. The asphalt-stabilized drainage layer has a very high laboratory permeability that varies from about 7,500 to 10,000 ft./day. A filter layer consisting of a relatively permeable, non-stabilized stone was used at locations where the asphalt stabilized drainage layer did not satisfy the filter requirements for placement directly on the subgrade.

Special techniques that can be used to construct asphalt-stabilized drainage blankets have been described elsewhere [5,6]. Though little or no compaction has been used on the asphalt-stabilized drainage blanket, the drainage layer has been found in the field to perform quite well structurally when placed beneath conventional flexible pavement structures. Problems with rutting of the surface have not been reported by California for this type construction although some field compaction apparently has been observed in the drainage blanket. Field investigations of completed projects indicate that infiltration of fines has not occurred where filter criteria have been satisfied.

Cedergren [7] has described several examples of the use of stabilized and nonstabilized high permeability drainage layers as load carrying components of pavement structures. The U.S. Forest Service has constructed over 600 miles of logging truck roads in the Pacific Northwest consisting of a thin chip seal overlying an emulsified, asphalt stabilized, open graded base course. These roads have supported trucks up to 200,000 lbs. in weight without significant shoving or rutting. Further, a heavy-duty military airfield pavement having an open graded, unstabilized crushed rock base whose permeability is greater than 100,000 ft./day has not undergone any rutting or other type damage after over 15 years of carrying heavy aircraft loadings.

The performance of an open graded, asphalt-stabilized drainage blanket has also been studied by Tayabji and Barenberg [6] using a small, circular test track facility. A 3 in. layer of asphaltic concrete was placed over the 4 in. asphalt-stabilized drainage blanket and subjected to 246,000 repetitions by a dual-wheel assembly loaded to 6,400 pounds. The drainage blanket was stabilized with approximately 2 percent asphalt. Although the

materials tested had gradations similar to those of the blankets used by California, the initial permeabilities were approximately 2 to 3 times the permeabilities of the California drainage blankets. A reduction in permeability in the drainage layer as well as considerable surface rutting occurred under traffic. Intrusion of fines was apparently not a primary factor in the reduction of the permeability. Also, asphalt stripping occurred in the drainage blanket. Because the primary purpose of the asphalt is to stabilize the stone during construction, stripping was not considered to directly effect performance. A significant stripping problem could, however, in at least some instances, lead to additional densification of the drainage blanket and consequent surface rutting. The problems experienced with rutting and stripping in the test track study may have been at least partially related to the very high initial permeability of the drainage layer and to the fact it was located directly below the 3 in. asphaltic concrete surfacing.

Neither surface rutting nor stripping was found to be a problem in the experimental sections used in California where the drainage blanket was placed below the conventional pavement structure. The study in California has shown that a high-permeability, open-graded asphalt-stabilized drainage blanket can be constructed to perform satisfactorily in the field. However, as found in the test track study and also in a full scale experiment in Louisiana, an open-graded drainage blanket having an initial permeability greater than about 10,000 ft./day can in some instances result in an unstable material and excessive rutting. It should, however, be emphasized that permeability alone does not indicate an unstable mix, and that high permeability mixes which are stable can be designed. It appears that mixtures used in bases must have higher stability with, in some instances, a sacrifice in permeability compared with mixes used in drainage blankets located below a conventional pavement structure.

DRAINAGE CONSIDERATIONS

For many years highway engineers have realized the importance of limiting the amount of water entering the pavement structure. Cedergren and Godfrey [8] have recently concluded that from 80 to 90 percent of the major premature failures in pavements are attributable primarily to the presence of excess water. Furthermore, evidence was presented indicating that when free water is present, each wheel-load repetition can cause at least forty times and possible considerably more structural damage than would occur when the pavement is in a relatively dry condition.

In the past, structural distress of pavements due to water has been usually attributed to the presence of subsurface water. Although subsurface water is indeed frequently the source of the problem, a recent study by Cedergren, O'Brien, and Arman [1] found that infiltration of surface water into the pavement structure can be just as important as subsurface water. Cedergren et al. studied the probable causes of premature structural distress at eight selected locations in different states. At seven of these sites, the presence of excess water was found to be the cause of the premature structural distress. Since all eight sites were located on fills, surface infiltration must have been the primary source of the water. Water entering a pavement through the surface has a tendency to move down longitudinal grades beneath the pavement to a low point. Since the test sites were located in the middle or lower segments of longitudinal grades, the source of water probably extended some distance upgrade from the actual distressed area.

Infiltration of Surface Water Into the Pavement Structure

Surface water can get into and below the pavement through transverse joints, random cracks and through the longitudinal pavement-shoulder joint. Water can also penetrate the shoulder at cracks and the outside edges. Field observations during the site inspections indicate that an open joint has a large capacity for accepting surface water at the beginning of a rainfall. Experiments conducted at the University of Maryland and reported by Cedergren et al. [1] confirm this observation. These tests show that from 70 to 97 percent of the rainfall can enter open joints between 0.035 and 0.125 in. in width for slopes varying between 1.25 and 3.75 percent when an unfilled reservoir exists beneath this joint. Therefore, at the beginning of a rainfall on a poorly sealed pavement, a high percent of the water falling on the pavement surface can be expected to enter the cracks and joints. Eventually, the cracks in the pavement and the pores of granular material immediately beneath the pavement will become filled with water. By this time the amount of water running off the pavement will have significantly increased, and the infiltration into and below the pavement will become dependent upon the rate at which water flows down-

ward through the subgrade and laterally through the base and subbase.

Infiltration tests at two locations (designated A and B) on I-85 approximately 25 miles southwest of Atlanta, Georgia were conducted to obtain an indication of the percent infiltration of surface water that actually occurs in the field. The PCC pavement at test location A is 9 in. thick and at location B 10 in. thick. At both locations sealed 1/4 in. transverse joints were located 30 ft. on center. The pavements were placed on a stabilized base course overlying a micaceous silty sand subgrade. The pavements are 24 ft. wide and the outside asphaltic concrete shoulders are 10 ft. wide. The average measured width of the longitudinal crack between the pavement and the outside shoulder was 1/4 in. at Site A and less than 1/8 in. at Site B. The pavement-shoulder joint was not sealed at either site. The pavements had longitudinal slopes of slightly less than 1 percent. The mainline transverse slopes were approximately 1 percent, and the transverse shoulder slopes were 4 percent. Both series of infiltration tests were performed during periods of greater than average rainfall. For example, the month of January which just preceded the time of the first measurements had 6.44 in. of rainfall compared with a long-term average rainfall of 4.79 in. Therefore, the base and subgrade would be expected to be in a relatively wet condition. Runoff was measured at each site for a period of 1 hour in 5 minute intervals during two different periods of rainfall.

At Site A, the average total infiltration into the pavement and shoulder within the drainage area studied was approximately 1 percent of the total rainfall while at Site B the average infiltration was 59 percent. From a visual inspection of the pavements, Site B appeared to be in better condition that Site A from the standpoint of removing surface water from the area, and hence was expected to have a lower infiltration value than Site A. However, field measurements made on two separate dates indicated that Site A had a lower infiltration value than Site B. These results appear to indicate that conditions existing beneath the pavement may in at least some instances have more affect on infiltration than the visually observable conditions on the surface. Because of the many variables present in these tests which could influence the results, probably a reasonable value of the effective infiltration is 30 percent which is the average of the infiltration values measured at each site. A greater number of trucks passing the test sites made the infiltration values appear higher whereas a greater number of cars made the infiltration values appear smaller. The passage of trucks apparently caused water to be splashed outside the drainage area whereas cars splashed water closer to the collection trough located on the edge of the shoulder making runoff appear to be greater during the measurement interval.

An average infiltration of 30 percent would apply only to pavements having similar characteristics to those in the study and constructed on a micaceous silty sand subgrade. Further, average infiltration greater than 30 percent would be expected at the beginning of a rainfall for dry base and subgrade conditions.

Subsurface Drainage

To develop typical shoulder sections which permit drainage, the design of the subsurface drainage system should be approached in a rational manner using the fundamental principals of hydrology and the flow of water through porous materials [1,2]. The time required for water to drain from beneath a pavement structural section is influenced by the following factors: (1) rainfall intensity and duration of the selected design storm, (2) percent of the total rainfall entering the pavement, (3) quantity of groundwater seepage reaching the pavement, (4) permeability and thickness of the relatively free draining layers and the permeability of the subgrade, (5) longitudinal and transverse slope of the drainage layers, (6) width of the pavement structure, and (7) construction variables that can influence the performance of the drainage system. Shoulders located in areas having as low as 20 to 30 in. of rainfall each year can undergo significant structural damage due to surface and subsurface water particularly when distinct wet and dry seasons occur. Some indication of the relative magnitude of water-associated problems in the shoulder can be obtained from Figure 3 which shows the average annual distribution of precipitation within the contiguous portion of the United States.

Open-graded drainage layers in a pavement structure must have a permeability sufficiently great so that water is removed before a significant amount of damage occurs. Cedergren et al. [1] have made the following recommendations for designing a subsurface drainage system to rapidly remove surface water: (1) use a one-hour design rainfall having a frequency of occurrence of 1 year; (2) assume for portland cement concrete pavements that from 0.50 to 0.67 of the total rainfall will enter the pavement (multiply the rainfall

intensity by this factor to determine the amount of infiltration) and, (3) design the drainage system to have an outflow rate equal to the infiltration rate into the pavement. This approach has been described in detail and design charts are presented in the comprehensive report on subsurface drainage by Cedergren et al. [1].

The removal of water from beneath the pavement as rapidly as it enters is highly desirable and would certainly minimize structural damage from water. However, for handling primarily surface infiltration water the above criteria give sections having very high drainage capacities. Sections meeting these criteria would probably remove the water more rapidly than is necessary to reduce the structural damage caused by water to a very small percent of that which presently occurs. Furthermore, by using somewhat less stringent requirements a structural section can be readily utilized that has a relatively free-draining, porous asphaltic concrete base with sufficient strength to also be considered an integral structural component of the system.

Most of the problems associated with water usually develop within 24 in. of the longitudinal pavement-shoulder joint. Further, relatively little structural damage occurs in the inside lane of a two-lane divided highway. Consider what happens if a drainage layer is placed beneath the pavement with a collector pipe system located under the shoulder near the longitudinal joint. Due to the transient nature of the flow of water from this layer, the water level in the vicinity of the drain and also the longitudinal joint is lowered in a relatively short time compared with the total time required to remove all of the water from the layer. The actual variation with time of the free water surface as observed during field experiments is illustrated in Figure 4. Because of the rapid lowering of the water surface near the drain, drainage layers having permeabilities on the order of 100 to 800 ft./day have sufficient capacity to lower the free water in the upper part of the drainage layer in the vicinity of the shoulder in approximately 5 to 30 minutes after rainfall has ended. Drainage times of this magnitude in the vicinity of the shoulder correspond to the removal of 50 percent of the available free water from the permeable layer in approximately 2 to 6 hours after the layer has been saturated. In areas where problems with frost action or expansive clay soils exist, consideration should probably be given to removing the water even more rapidly than this from the pavement structure.

This somewhat simplified approach allows the base during extended periods of rainfall to become saturated. As a result, hydrologic considerations such as design storms and rainfall intensities do not have to be analyzed. For a given set of hydrologic conditions, a study could be made to determine if the design structural section would actually become saturated although this would not be necessary following the proposed approach.

The time required for drainage of 50 percent of the available free water from the layer can be estimated using the drainage theory developed by Casagrande and Shannon [9] some years ago for airfield pavements. This theory considers the transient lowering of the water within the drainage layer and was developed assuming a straight-line free surface. The theoretical solution was verified using both laboratory models and full-scale field tests. The theory was then adjusted so that the calculated time required for 50 percent drainage agreed with the corresponding experimentally observed times. Using this theory, the time required for 50 percent drainage of the free water from the layer can be arrived at as follows:

1. Calculate the effective length of the drainage path, L_e and the effective slope, g_e, for pavement sections having both longitudinal and transverse slopes:

$$L_e = W\sqrt{\left(\frac{g_\ell}{g_t}\right)^2 + 1} \qquad (1)$$

where
W = width of the tributary drainage area perpendicular to the edge of the pavement.
g_ℓ = longitudinal grade of drainage layer (expressed as a fraction).
g_t = transverse grade of drainage layer (expressed as a fraction).

2. Determine the effective porosity of the drainage layer. The effective porosity, n_e, is defined as the ratio of the volume of voids that can be drained to the total volume of voids and solids. Because of capillary effects, all of the moisture will not drain from a granular layer having some sand and silt size parti-

cles. The degree of saturation at the time of compaction of a granualar layer having some finer material will typically be between approximately 50 and 65 percent. From actual field measurements Casagrande and Shannon found for sandy graval (k = 765 ft./day) an average effective porosity of 0.07.

3. Calculate the slope factor, $\overline{S}$:

$$\overline{S} = \frac{H}{L_e g_e} \tag{2}$$

Where H is the thickness of the drainage layer (Figure 4) and L_e and g_e are determined from Step 1.

4. Calculate the time required for 50 percent of the total free water to be drained from the layer as follows:

$$t_{50} = \left[\frac{c\, n_e L_e^2}{2\, k\, H}\right] T_{50} \tag{3}$$

Where n_e, L_e and H are determined in steps 1-4. The parameter, c, is obtained from Figure 5 and the dimensionless time factor, T_{50}, from Figure 6. The permeability of the drainage layer is k. Consistent units are used throughout the above expression.

Filter Design Criteria

The presence of a small quantity of fines in a drainage layer can result in a poor draining material which cannot remove the free water in a reasonable length of time. The substantial effect of fines on permeability is clearly illustrated in Figure 7. The presence of an excessive amount of fines can be caused by the following factors: (1) unsatisfactory initial gradation, (2) intrusion of finer material into an open-graded drainage layer, (3) segregation of the finer sizes during movement and placement of the material, and (4) degradation of the material during compaction and under traffic.

To prevent intrusion of fines into an open-graded drainage layer, a filter layer must be placed over silt and clay subgrades. Intrusion of fines into a filter layer is caused by both the repeated application of wheel loadings on the surface and also the upward seepage of water into the drainage layer.

Filter criteria frequently used in the design of highway subsurface drainage systems were developed for a steady-state, upward flow of water and do not consider the effect of repeated wheel loadings. A good general review of these filter criteria has been presented by Spalding [10]. Based on a review of available test results, Spalding concluded that the Corps of Engineers filter criteria should be used to protect an open-graded drainage layer from clogging. The criteria can be summarized as follows:

$$D15F \leq 5 \times D85S \tag{4a}$$
$$D15F \leq 20 \times D15S \tag{4b}$$
$$D50F \leq 25 \times D50S \tag{4c}$$

where D15, D50 and D85 indicate the grain diameter for which 15, 50 and 85 percent, respectively of the material is finer. The filter material is indicated by "F", and the soil being filtered by "S". For soils to be filtered having a uniform gradation (D60S/D10S $\leq$ 1.5), equation (4a) should be replaced with D15F $\leq$ 6xD85S. For well-graded soils (D60S/D10S $\geq$ 4.0), equation (4b) should be replaced by the slightly less severe requirement of D15F $\leq$ 40xD15S. Frequently, only the criteria given in equations (4a) and (4c) are used. Finally, to insure that the filter layer has adequate drainage capacity:

$$D15F \geq 5 \times D15S \tag{5}$$

The preceding filter criteria are based on the results of approximately 100 laboratory tests and in general have been found to be in agreement with the results of several other investigators. These criteria tend to be slightly conservative for the steady state seepage conditions for which they were derived. The results of the laboratory study of intrusion of fines into drainage layers [2] and also the tests conducted by Tayabji and Barenberg [6] indicate that when relatively open-graded drainage layers are placed

directly on silt and clay subgrades, intrusion of fines can occur under simulated traffic loading conditions. The results presented by Tayabji and Barenberg showed that a sand filter placed between a clay subgrade and an open-graded drainage layer effectively prevented intrusion of fines for the 246,000 wheel-load repetitions applied during the investigation. Because filter criteria were not quite satisfied, the criteria given by equations (4) and (5) may at least for some gradations be conservative under conditions similar to those that existed during the test. A lime-modified clay subgrade and a filter cloth were found not to be effective in preventing intrusion into an open-graded, asphalt-stabilized drainage layer.

The preceding filter criteria should not be applied to gap-graded materials because they will not adequately control the grain size distribution of the filter layer. Also, gap-graded filter materials tend to segregate badly during movement and placement. If the soil to be filtered is gap-graded, the filter criteria should be applied to the grain sizes finer than the gap in the grading. To prevent the possibility of clogging due to movement of fines from the filter into the drain pipe, the fines (minus No. 200, U.S. Standard Sieve Size) in the filter should be limited to 5 percent. In addition, the hole size in drainage pipe should at least meet the following criteria [1,10,11]:

$$\text{Diameter of Circular Perforations} < D85F \qquad (6)$$
$$\text{Maximum Width of Slot} < 1.2 \times D85F$$

Spalding [10], however, has recommended the following somewhat more conservative criterion for pipes having slots:

$$\text{Maximum Slot Width} = 0.83 \times D85F \qquad (7)$$

Openings in the pipe should be placed in the bottom to reduce the chance of erosion of fine particles into the pipe and to lower the depth at which the water is intercepted. Compacting the backfill around the pipe has also been found to reduce the possibility of erosion of the filter material into the pipe [10]. Schwab and Kirkham [12] have found that increasing the number of holes up to approximately 20 perforations/ft. results in increasing the flow of water into the pipe. The effect of the number of perforations was found to be less at greater depths below the water table.

DRAINAGE SYSTEMS

Field studies of distressed areas in pavements performed by Cedergren et al. [1] and the field inspections conducted as part of this investigation indicate that most of the conventional pavement structures constructed at the present time do not allow the free drainage of surface and subsurface water from beneath the pavement. One important cause of poor drainage is the almost universal use of base and subbase courses having low permeabilities. A base course having even a small amount of fines will, in general, be too impermeable to result in the drainage of 50 percent of the free water from the base in even 3 to 5 days. The effective in situ permeability would have to be at least 15 to 20 ft./day to allow drainage in this time for a typical two lane pavement.

Another very important factor in restricting the drainage of pavement structures as they are presently constructed is the use of "bath tub" sections which do not have pipe underdrains or a permeable layer extending out to the edge of the shoulder. Even if a relatively permeable layer is extended out to the edge of the pavement to give a "daylighted" section, a relatively thin cover of topsoil and sod on the surface of the shoulder can effectively block drainage. Consider a typical 24 ft. wide pavement with a 10 ft. wide paved shoulder on the outside. If a 3 in. thick layer of clayey silt covers the outlet end of a drainage layer having a permeability of 1,000 ft./day, the resulting effective permeabilitiy of the layer would be reduced to approximately 0.5 ft./day due to the clogged end. Therefore, in addition to a drainage layer having high permeability, provisions *must* also be made for an effective outlet to ensure that water flows freely from the permeable layer.

Construction of a compacted, unstabilitzed granular layer that has a permeability greater than approximately 5 to 10 ft./day can be difficult because of instability due to a lack of fines. Such an open-graded material also tends to segregate badly unless carefully placed using a spreader. If the open-graded layer is used as a base or subbase course,

densification using a suitable vibratory roller is required. In some instances, for ease of construction, an open-graded drainage layer may receive little or no compaction when placed beneath a conventional structural pavement section [5]. To minimize shoving and lateral displacement of an open-graded cohesionless material, considerable care must be exercised by operators of equipment working on it, avoiding sudden stops or sharp turns.

Several state highway and transportation agencies, including those of Indiana, New York, Tennessee and Vermont [1] have developed open-graded, asphaltic concrete base-course mixtures that exhibit good stability, and also have relatively high permeabilities varying between approximately 800 and 5,000 ft./day. It appears that full advantage could be taken of these properties in developing a base section that can be used both as a structural load-carrying component and as a drainage blanket. The drainage theory described previously indicates that a permeability of 600 to 800 ft./day is all that is required to result in relatively free drain of surface water from beneath the pavement and shoulder.

Typical drainage sections recommended by Cedergren and Godfrey [8] are illustrated in Figure 8. Where filter criteria for the drainage layer are not satisfied, a filter layer should be used to prevent intrusion of fines into the drainage blanket. A positive system of collection and removal of the water must also be provided to ensure that the water is removed from the drainage blanket. Either asphalt-stabilized or non-stabilized stone can be used for the drainage blanket provided the material has the required permeability to satisfy design requirements for drainage. In cut sections, where ground water problems are encountered, a high-permeability asphalt-stabilized drainage layer probably should be provided.

RECOMMENDATIONS

Observations made during the field inspections of this study and also by previous investigators [1,13] indicate that in many instances deterioration of the shoulder in the vicinity of the longitudinal joint is considerably more severe when a significant quantity of water is present beneath the pavement and shoulder. In the past, structural distress of pavements due to water has been usually attributed to the presence of groundwater. Although subsurface water is indeed frequently the source of the problem, these findings indicate that the infiltration of surface water into the pavement structure can be just as important as subsurface water.

The following three factors were found to be particularly important and must be given special attention to ensure that a subsurface drainage system functions properly: (1) permeable materials must be free draining as established by permeability tests performed on the actual materials used, (2) a positive method must be provided for removing water from the drainage layer, and (3) underdrain pipes must have a discharge outlet that is designed and maintained so that it will not become clogged. To prevent clogging of the drainage layer, the filter criteria given by equations (4) and (5) should be satisfied. Intermediate filter layers must usually be placed over silt and clay subgrades to prevent intrusion of fines into open-graded drainage layers (Table 2). The filter material should not be gap-graded.

Groundwater

Subsurface water should in general be controlled by the use of a drainage blanket and/or an interceptor drainage trench. The drainage blanket (Fig. 9) can be constructed using either an unstabilized or asphalt-stabilized open-graded stone. The drainage system should be designed to have sufficient capacity to remove the expected quantity of groundwater.

In general, use of an asphalt-stabilized granular drainage blanket is recommended for high drainage capacity to control groundwater and to minimize construction problems. The blanket should be stabilized with 1.5 to 2.0 percent asphalt and placed beneath the normal structural section. A gradation similar to the one given in Table 3 is recommended for the stabilized drainage blanket. Use of this gradation should result in a laboratory permeability of approximately 7,500 to 10,000 ft./day. Mixes more open-graded than this having higher permeabilities are not recommended for general use until further studies indicate rutting and stability would not be a problem.

Surface Infiltration Water

Due to the transient nature of the flow of water from the drainage layer, the water level

in the vicinity of the drain and hence the longitudinal joint is significantly lowered in a relatively short time compared with the total time required to remove all of the free water from the layer. Since most of the structural damage in both the mainline pavement and shoulder occurs near the longitudinal joint, advantage can be taken of this transient flow of water in developing design criteria for the drainage system. To substantially lower the water level in the vicinity of the joint in 5 to 30 minutes, 50 percent of the available free water should be removed from a blanket drainage layer in 0.05 to 0.20 days.

The pores of a structural section designed using the recommended criteria may fill with water during high-intensity storms. Excess water, however, would simply run off the surface of the pavement, and the water stored within the structural section would be rapidly removed as the storm subsides. As a result of this assumption, hydrologic data such as design storms and rainfall intensities do not have to be analyzed. The recommended drainage criterion is admittedly somewhat less conservative than that proposed by Cedergren et al. [1]. The proposed drainage criterion, however, should result in removal of water at least 200 to 800 times faster than in most presently used bases and subbases, and should reduce the structural damage caused by water to a very small percent of that presently occurring.

For a typical 2-lane divided highway, 50 percent of the available free water in the drainage layer can be removed in approximately 4, 0.2 and 0.05 days for permeabilities of 10, 200, and 1,000 ft./day, respectively. These results show that drainage layers which have permeabilities less than 10 ft./day drain slowly even for the ideal assumption of free flow from the drainage layer. For typical conditions, drainage layers having minimum permeabilities of 200 to 800 ft./day can generally satisfy the proposed drainage criterion. Open-graded, asphaltic concrete base-course mixtures used for example by New York, Tennessee and Vermont have permeabilities of 800 to 5,000 ft./day. This type base can serve as an integral structural component of the system and also a drainage layer. A typical open-graded asphaltic concrete base course should have 3 to 5.5 percent asphalt content and a gradation similar to that given in Table 3. To ensure sufficient stability under heavy traffic, the permeability of the base should generally be limited to approximately 800 to 1,000 ft./day. Bases with permeabilities greater than about 2,000 ft./day should not be used at this time as a structural component because of potential stability problems. Additional studies may show under certain conditions that more open mixes can also be used as part of the structural section. General recommendations for the drainage system design for surface water are given in Table 4.

Removal of Surface Water

Water collected by permeable drainage layers must be removed rapidly from beneath the pavement. The most positive method of removing this water is to use a longitudinal perforated or slotted collector pipe placed along the edge of the drainage layer. An excellent design alternative to a conventional trench drainage collection system for controlling surface infiltration water consists of placing 2 to 2-1/2 in. diameter, slotted or perforated pipe within the drainage layer (Fig. 9). If the openings in the pipe are designed using equation (6) or (7), the drainage pipe will not become clogged with finer material. This underdrain system has the advantage of being relatively simple to construct, thereby minimizing the possibility of a poorly functioning drain. Transverse outlet pipes should be provided approximately every 200 to 300 ft. to remove the water. For this spacing of transverse drains, the relatively small 2 to 2-1/2 in. diameter pipe will have sufficient hydraulic capacity to handle surface water for most conditions.

A 2 in. diameter pipe collection system placed on a 1 percent slope has a discharge capacity of approximately 10,000 to 15,000 gal./day. During short periods of peak rainfall a mini collection system might not remove water from the permeable layer as rapidly as it enters. The water which would back water up in the system, however, would very quickly drain from the permeable layer as the rainfall intensity subsided.

Transverse Drains

Water that has infiltrated beneath the pavement moves in the direction of the steepest slope. As the longitudinal slope of the pavement increases, the length of the flow path to the edge of the pavement also increases. Due to the longitudinal component of flow, water collects at low points in the vertical alignment and can frequently be seen seeping from the cracks and joints in pavements near the bottom of hills.

Positive removal of this flowing water from low points is therefore recommended in areas

having an average annual rainfall greater than about 20 to 30 in. A single transverse drain is recommended at the low point for two lane pavements having longitudinal slopes equal to or less than 2 percent. For longitudinal grades between 2 and 5 percent, a transverse drain should be located at the low point and also 100 ft. to either side. These recommendations should be considered as minimum requirements if other provisions are not made to prevent the accumulation of water at low points in the longitudinal grade.

SUMMARY

In most instances, deterioration of the shoulder in the vicinity of the longitudinal pavement-shoulder joint is considerably more severe when a significant quantity of water is present beneath the pavement and shoulder structure. Important factors that affect the severity of the water-associated problems include the amount and distribution of rainfall, frost heaving, expansive clay subgrades, and the strength and type of the structural shoulder section. Rapid removal of water from beneath the pavement structure is an excellent method for minimizing water-related deterioration. For the drainage system to function properly, it must have sufficient permeability and a positive outlet.

Although groundwater is frequently the source of pavement shoulder problems, a recent study by Cedergren et al. [1] found that infiltration of surface water into the pavement structure can be just as important as subsurface water. Field infiltration measurements indicate that even under prolonged wet conditions a pavement resting on a moderately impermeable subgrade can have an average infiltration capacity of approximately 30 percent of rain falling on the pavement.

The occurrence of significant quantities of subsurface ground water should in general be controlled by the use of a drainage blanket and/or an interceptor drainage trench. An excellent approach in controlling this type water problem is by use of a high capacity granular drainage blanket stabilized with 1.5 to 2 percent asphalt. This blanket should be placed beneath the normal structural section and have a permeability of approximately 8,000 to 12,000 ft./day.

To handle surface infiltration water in the vicinity of the longitudinal joint, 50 percent of the available free water should be removed from an open-graded layer in approximately 0.05 to 0.20 days. For a typical 2-lane divided highway, a drainage blanket having a minimum permeability on the order of 200 to 800 ft./day can generally satisfy this proposed drainage criterion for surface infiltration. Open-graded, asphaltic concrete base course mixes can be designed which exhibit good stability and also have relatively high permeabilities varying between approximately 800 and 2,000 ft./day. More use should be made of these materials which can serve both as a structural load carrying component and at the same time rapidly remove surface infiltration. Sections having either full-width permeable asphalt concrete bases or permeable shoulder drains of limited size are proposed for providing efficient collection and removal of infiltrated surface water. Water can be collected from these permeable layers by either conventional trench drains or a mini-drain system consisting of small-diameter slotted or perforated pipe placed in the drainage layer.

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TABLE 1 DRAINAGE PRACTICES OF STATES INTERVIEWED

HIGHWAY ORGANIZATION	SURFACE DRAINAGE		SUBSURFACE DRAINAGE LAYER			PIPE SHOULDER DRAIN	
	Pavement Slope	Shoulder Slope	Material	Thickness	Extent	Type Location	Size (in.)
Arizona	1/4 in/ft	1/4 in/ft	Granular Base or Subbase	4 in. (min.)	Daylighted	None Provided	-
California	1/4 in/ft	$1\frac{1}{2}$ in/ft	Granular Base Beneath Shoulder	5 in. (min.)	Edge of Paved Shoulder	Wet Conditions Only	-
			Asphalt Stabilized Drainage Blanket (exp. only)	5 in. (min.)	Full Shoulder Width	1 in. PVC (exp. only)	
Georgia	1/8 in/ft	1/2 in/ft	-	-	-	Longitudinal Drain Standard Design	
Illinois	1/4 in/ft	1/2 in/ft	Open Graded Aggregate Subbase	4-6 in.	Daylighted	Wet Conditions or During Shoulder Rehabilitation	-
Louisiana	1/4 in/ft	$1\frac{1}{2}$ in/ft	Experimental Only	-	-	Experimental Only	-
Michigan	-	-	Granular Base and Subbase	14 in.	Daylighted	Use Edge Drains Where Drainage Path > 30 Feet	-
Minnesota	3/16 in/ft	1 in/ft	Granular Base	6 in.	-	Cuts Only	-
New York	1/4 in/ft	1 in/ft	Granular Base and Subbase	12 in.	Daylighted	Low Points Only	-
North Dakota	1/8 in/ft	1 in/ft	-	-	-	Seldom Used	-
Ohio (1)	3/16 in/ft (reverse slope)	1/2 in/ft	Granular Subbase	$7\frac{1}{2}$ in.	Daylighted	For Subgrade Soils A-4, A-6, A-7-6	6 in. dia. Clay or Metal Pipe
Pennsylvania	1/4 in/ft	1/2 in/ft	Granular Subbase	6-12 in.	Daylighted	18-in. From Pavement Edge	6 in. dia. Clay or Metal Pipe
Texas	1/4 in/ft	3/8 to 1/2 in/ft	Not Normally Used	-	-	Wet Conditions Only	-
Utah	1/4 in/ft	1/4 in/ft	Not Normally Used	-	-	Not Used	-

1. New pavements will have stabilized base. No provision for drainage.

TABLE 2 COMPARISON OF GRADATIONS OF CALIFORNIA CLASS 2 DRAINAGE MATERIAL WITH ASPHALT-STABILIZED DRAINAGE MATERIAL

Sieve Size	Class 2 Permeable Drainage Materials	Asphalt Stabilized Drainage Blanket
2		
1 1/2		
1	100	100
3/4	90-100	90-100
3/8	40-100	40-70
4	25-40	0-10
8	18-33	0-5
30	5-15	
50	0-7	
200	0-3	

TABLE 3 ALLOWABLE GRADATION LIMITS FOR BOTH GRADED BASE AND BINDER COURSES USED IN NEW YORK

Screen Size (inches)	Base Course	Binder Course
2	100	
1-1/2	75-100	100
1	55-80	90-100
1/2	23-42	35-65
1/4	5-20	10-35
1/8	2-15	5-20

TABLE 4 RECOMMENDATIONS FOR DRAINAGE SYSTEMS TO REMOVE PRIMARILY INFILTRATED SURFACE WATER

Design Activity	Recommendation
Drainage Layer (Infiltrated Surface Water)	1. Remove 50% of available free water in 0.05 to 0.20 days. 2. Typical minimum permeability of 200 to 800 fpd. 3. Use open graded asphalt concrete base course with 3 to 5.5 percent asphalt. 4. Measure permeability of unstabilized and stabilized drainage layer materials.
Mini-Drain Collector System	1. Install at slope paralleling grade of road centerline. 2. Minimum grade: 1% for smooth pipe; 2% for rough pipes. 3. Minimum diameter of 2-in. (I.D.) for slotted and perforated pipe.
Outlets	1. Outlet pipe end should be 12-in. above flow line of roadside ditch and 6-in. above base of clean-out box if used. 2. Outlet marker should be 3 to 5-in. diameter (or square) wood or concrete post protruding not less than 4-ft. above the surface. 3. Use for mini-drain system precast concrete outlet designed so pipe is slightly above shoulder slope and erosion does not occur.

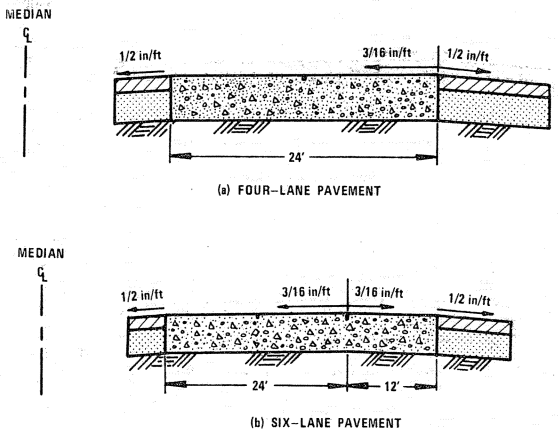


FIGURE 1 REVERSE SURFACE DRAINAGE USED IN OHIO ON DIVIDED HIGHWAYS

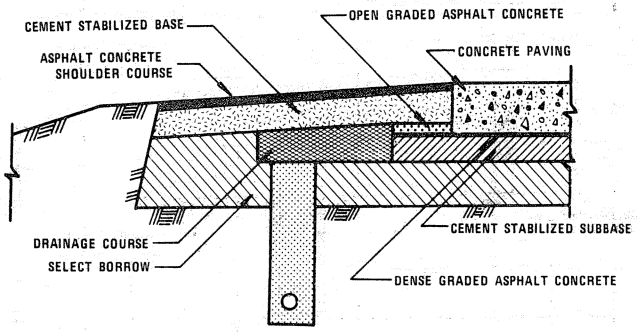


FIGURE 2 IMPROVED PAVEMENT-SHOULDER DRAINAGE SYSTEM USED IN GEORGIA

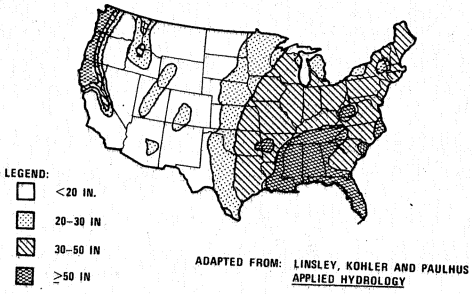


FIGURE 3 DISTRIBUTION OF AVERAGE ANNUAL PRECIPITATION WITHIN THE CONTINENTAL UNITED STATES

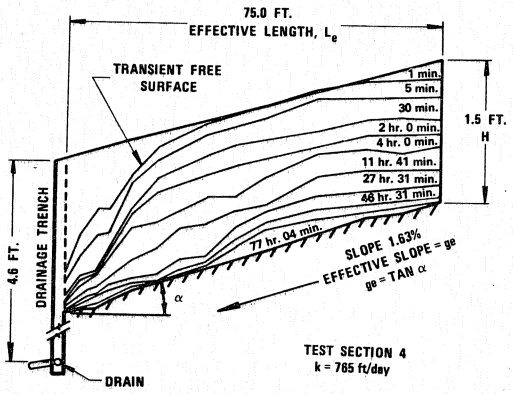


FIGURE 4 VARIATION OF THE FREE SURFACE WITH TIME FOR A PERMEABLE DRAINAGE LAYER (ADAPTED FROM REFERENCE 9)

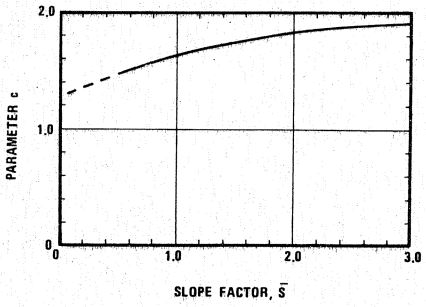


FIGURE 5 VARIATION OF PARAMETER "c" WITH SLOPE FACTOR (ADAPTED FROM REFERENCE 9)

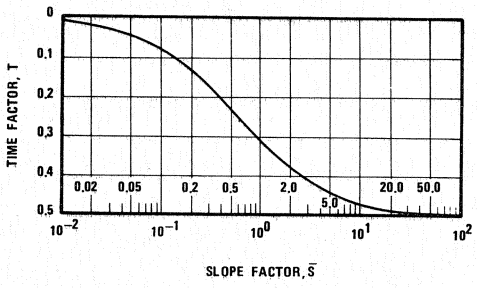


FIGURE 6 TIME FACTOR FOR 50% DRAINAGE AS A FUNCTION OF THE SLOPE FACTOR (AFTER REFERENCE 9)

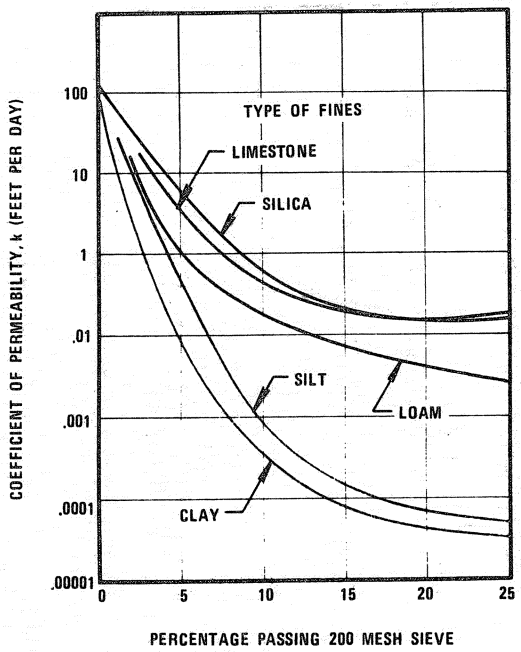


FIGURE 7 EFFECT OF FINES ON THE PERMEABILITY OF GRADED AGGREGATE

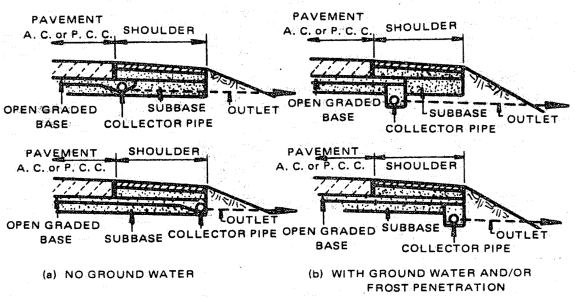


FIGURE 8 TYPICAL HIGHWAY DRAINAGE LAYERS (AFTER REFERENCE 8)

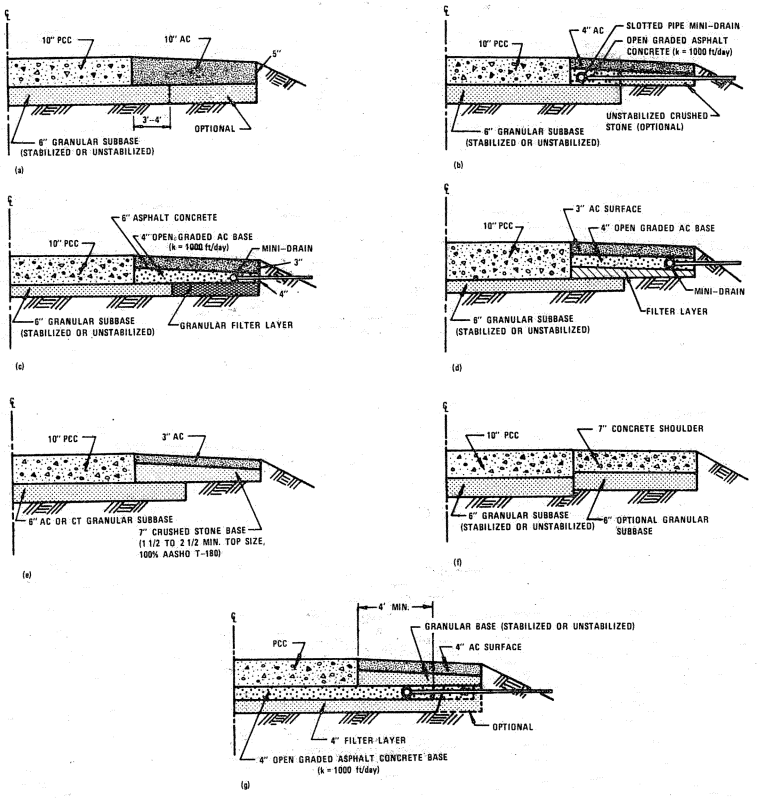


FIGURE 9 TYPICAL IMPROVED SHOULDER SECTIONS