ABSTRACT: The paper describes the results of a study, based on literature review and interviewing of practicing engineers, examining pavement subsurface drainage systems in the UK. Details are provided of the most common drainage systems, the problems frequently encountered and methods by which these problems can be remediated and prevented. Case studies have been included to provide examples of the detection, remediation and cost of drainage failures. The impact of drainage conditions on the subsurface moisture regime is discussed, including an assessment of the possible impact on pavement performance.

1 INTRODUCTION

Engineers have long held the view that the drainage of pavement bases and sub-grades improves their mechanical properties, and increases their service life. However, the veracity of this belief is dependant upon the assumption that the drains function as designed, and that the resultant reduced saturation produces the desired results, in terms of improved mechanical properties. Several studies, both laboratory and site based, have shown that good drainage does reduce pavement deterioration. There have also been several studies looking at the effectiveness of subsurface drainage. However, these studies are only valid for the areas in which they were conducted. Local variations in regulations, material availability, quality and skills of workforce, climatic conditions and many other factors result in a wide variety of drainage systems and maintenance practices being employed in different locations.

The objective of this study was to investigate the reality of pavement subsurface drainage in the UK; i.e. which drainage systems are used, do they function successfully, are they sufficiently maintained, and what are the typical problems and how can they be countered? These questions are to be answered by reviewing previous literature on the topic, interviewing practicing maintenance engineers, and collecting data on specific case study sites. The results of this study are to be used to assess the level of drainage that can be expected by designers in practice (as opposed to ideally), to provide a foundation from which more practical drainage ideas may be formulated and to ensure that research into pavement and earthwork behaviour will model as accurately as possible, the genuine in-situ conditions.

2 PREVIOUS STUDIES

There have been several studies looking at the effect of moisture on pavements. Experimental studies have shown that excess moisture can have a detrimental effect on the modulus, and other mechanical properties, of base course materials (Cawsey et al 1987, Thom & Brown 1987, Dawson et al 1996), and in-situ studies have shown that pavements without adequate drainage often deteriorate more quickly than those with good drainage (Hall & Correa 2003, Harrigan
Dunnam & Daleiden (1999), Hassan et al (1996) and Hall & Correa (2003) carried out studies that have involved looking at the condition of pavement subsurface drainage in the US. In these studies a range of common problems with drainage systems were identified, these included:

− Overgrown vegetation clogging drainage outlets.
− Penetration of roots into drainage pipes, leading to clogging of pipes.
− Crushing of drainage pipes by signposts and barrier posts.
− Collapse of drainage pipes - most common in pipes with lower strength and rigidity.
− Planned drainage outlets not found, indicating that the drainage system may not have been installed in many cases.
− Accumulation of silt in drainage pipes.
− Rodent nests blocking drainage pipes.

Dunnam & Daleiden (1999) reported that although several recurring problems were found the general condition of the drains inspected was good, and that the drainage system was functioning adequately. Hall & Correa (2003) inspected drains constructed on test sections of roads in 18 states, and their results show drainage performance varied significantly from state to state. In several states drainage was rated as poor at all test sections. From this it seems likely that many of the failures with drainage encountered in these were not due to random events. It implies that the test sections investigated in some of the areas studied either have environmental/climatic conditions that make the maintenance of an effective drainage system more difficult or poor construction/maintenance practices that result in an increased failure rate.

3 DRAINAGE SYSTEMS IN USE

Many of the problems identified in previous studies were dependent upon the type of drainage system in use. Therefore, in order to identify which of the previously identified problems are likely to occur in the UK (the topic of this paper) it was necessary to find out which drainage systems were most commonly used.

To find out, and to determine other issues, pavement engineers responsible for the primary road network in England were interviewed in person or by telephone. Interviews with the initial respondents allowed the questions posed to later respondents to be adapted.

Engineers responding to this study reported subsurface drainage to be provided, on most roads, by high permeability sub-base layers running into fin drains, and that subsurface drainage is retrospectively added to older roads if investigations reveal that they were not fitted during construction. In some cases French drains are used instead of fin drains. Water entering these lateral drains is normally outlet into a combined drainage system that also collects the run-off from the surface drains. On most UK roads this consists of a piped drainage system leading to final outlets into streams, rivers and soakaways. Less frequently fin drains outlet into ditches and swales to be transported to final outlets.
Figure 1. Typical pavement section showing the positioning of fin and French drains.

Figure 2. Typical designs of fin drains constructed with geotextiles.  
1 indicates the permeable aggregate filler, 2 the geotextile membrane of the geosynthetic, 3 the core of the geosynthetic, 4 a drainage pipe and 5 a porous drainage pipe.
Figure 3. Typical designs of conventional fin drains. 

*Key for numbering is as given for Fig. 2.*

Figure 4. Typical design of French drains. 

1 indicates topsoil, 2 the pavement wearing course, 3 the base courses, 4 a permeable filler, 5 the permeable aggregate, 6 the porous drainage pipe, 7 the geotextile membrane, 8 the impermeable cap and 9 the sub-grade.

4 FUNCTIONALITY OF DRAINAGE AND COMMON FAILURES

The respondents considered drainage failures to be relatively uncommon, and that highway sub-surface drainage systems in their regions were functioning well.

Where failures did occur, these failures were often in the drainage pipes diverting water from the permeable drainage layers and edge drains, and could be divided into 4 major categories; complete and partial blockage, fracturing of pipe and collapse of pipe.
Drainage pipes that have been partially blocked restrict the flow of water from the pavement base. Although this does not prevent the base courses from draining, it does increase the time period required for them to drain. This increases the amount of time that the pavement base is saturated, and therefore in many cases increases the rate at which they deteriorate.

Complete blockage of drainage pipes either completely prevents or significantly reduces the rate at which water drains from the pavement base courses. In regions with high permeability soils, water can infiltrate through the sub-grade, but even under these circumstances the rate of drainage usually will be significantly lower than when the drainage is functioning correctly. In regions with low permeability soils the sub-grade can become practically impermeable and base course drainage is prevented. In all cases the subsequent increased saturation of the pavement sub-grade is likely to increase the rate at which the pavement deteriorates, the lower the permeability of the sub-grade the greater the increase in deterioration.

Where blockages occur in combined surface and subsurface drainage pipes the blockage will also prevent water draining from the pavement surface. As a result ponding will occur on the highway surface during storms. This ponding will be observed by users of the highway and is likely to instigate investigations of the drain system and clearing of the blockage. As, in these circumstances, the drainage failure is likely to be rectified within a shorter period of time the long-term impact on pavement performance may be less than less noticeable failures.

Where the drainage pipes are fractured they may leak small amounts of water. If enough water is leaking it can lead to the erosion of sandy and silty soils around the pipe, or the softening of clay soils. This reduces the ground support of the pipe and can lead to the pipe deteriorating at an increased rate and, if the affected soil extends to the highway sub-grade, this can increase the rate of deterioration of the pavement. Fractures may also allow roots to enter the drainage pipe, restricting flow and further damaging the pipe, in some cases leading to the collapse of the pipe.

The impact of the collapse of drainage pipes depends upon the nature of the soil in which the pipe is situated. In most cases collapse of the pipe will simply cause a blockage as described above. However, in some soils, in particular sandy/silty soils, collapse of the pipe can lead to erosion of the soil around the collapsed section of pipe. In these cases large cavities can be formed in the ground that eventually collapse themselves, at which point the formation of a new cavity often occurs. The formation and subsequent collapse of these cavities can cause significant subsidence damage both to the highway and to surrounding structures.

4.1 Previously encountered drainage failures
As has been stated a range of drainage failures have been identified in previous studies (based in the US). The occurrence of these failures in drainage systems in the UK is discussed below, as well as, conditions under which they can occur, potential impacts of the failure, and possible methods to minimise the probability of failure occurring.

4.1.1 Vegetation clogged outlets
One of the most common failures identified by previous studies was the clogging of outlets from edge drains into ditches by overgrown vegetation. This is not a failure mechanism that has been identified by responding engineers in this study. The main reason for this is that, due to constraints on space availability, it is much less common for drainage systems in the UK to have outlets into ditches. Instead it is much more common for subsurface drainage to run into combined piped systems that collect both subsurface drained water and surface run-off. These generally lead to much larger outlets that are less likely to become blocked by vegetation.

This form of drainage failure can be avoided by using drainage systems that do not have small outlets into ditches that are able to be blocked. The possible alternatives include having fewer outlets, each with a larger flow capacity, to drain the base layer. Although vegetation could still grow around the outlet it would be less likely cause a complete blockage. The second
method to prevent vegetation clogging is to use an alternative outlet; if the sub-grade is sufficiently permeable this could be done using soakaways. The third alternative is to use a daylighted drainage layer (drainage blanket); in this case the drainage layer extends beyond the pavement to the ditch. As a result it is of little consequence if at points the outlet is blocked, as the water can drain along the entire length of the drainage layer and can therefore go round the blockage.

4.1.2 Root intrusion into drains
This failure mechanism, identified in the previous studies, was the most common failure identified by engineers responding to this study. Root intrusion into drainage pipes occurs most frequently where the drainage runs close to trees, as a result of this it is a high risk failure in the UK as trees are regularly planted alongside highways, for amenity reasons, close to the drainage system.

When roots first penetrate into a pipe they are likely to cause small amounts of damage, fracturing it where they enter. Once in the pipe the roots can cause two types of failure; they can trap fines leading to a build-up of sediments partially or completely blocking the pipe, or as they grow they can increase the size of the fractures through which they entered eventually causing the pipe to collapse.

Reducing the probability of root intrusion can be achieved most economically by designing the drainage system to avoid trees and other plants that may cause damage. However, this is not always a simple solution as trees are often planted along the sides of trunk roads to reduce noise and light pollution to the surrounding countryside, and to reduce the negative aesthetic impact of the highway. In cases where trees cannot be avoided it is possible to limit root intrusion by reducing the joints in the pipe through which the roots initially enter. This can be achieved by using longer sections of pipe, and by using pipes more flexible and hence able to tolerate settlement and loading without cracking.

4.1.3 Crushing of drainpipes by sign and barrier posts
The installation of posts through drainage pipes was identified as a cause of pipe collapse by Dunnam & Daleiden (1999). One case of this has been experienced by responding engineers (see Case Study 1) in the UK. Clearly this failure occurs when contractors installing the posts are either unaware of where the drainage pipes run, or alternatively install the posts in the wrong position.

Where damage to drainage systems due to sign and barrier installation is due to the contractors being unaware of the location of the drainage pipes, then provision of up-to-date details of the drainage systems in place has been omitted. For new highways, or new sections of drainage, surface markers should also be used to indicate the lines along which drainage pipes run. Where the error is found to be due to contractors installing the posts in the wrong position, then post-construction checks by the client are required to locate defects and arrange remedial work by the contractor.

4.1.4 Collapse of drainage pipes
In previous studies some drainage pipes were found to have collapsed under pressures exerted during installation, traffic accidents and normal repose. These collapses were reported to be more common in corrugated drainage pipes with a lower structural strength. Similar failures were also identified by respondents to this study. The most significant causes of collapse identified were pressures exerted by vehicles leaving the carriageway and due to subsidence.

Due to the random occurrence of events causing the collapse of drainage pipes it is difficult to prevent such collapse. To limit the damage to pavements, due to vehicles leaving the carriageway, drain investigations post-recovery of the vehicle should be instigated.

Where collapse is caused by subsidence this often indicates poor construction practice/workmanship. For example voids may have been left adjacent to drainage trenches or in-
adequate compaction may have been applied to fill in the drain. The solution to this is probably better training of operatives, better supervision and better quality management.

4.1.5 Drainage not found
A major failure identified in previous studies was that drainage on many highways was not found. This indicates that the drainage was either not installed as designed, or that the outlets were heavily overgrown and difficult to find. Respondents to the study reported here did not identify this as a major issue. Some sections of older roads had been found without drainage, however, when these were found, drainage was retrofitted. All new roads are built with drainage.

4.1.6 Silt accumulation
A common failure method identified by in previous studies was the blocking of drainage pipes with silt. This failure mechanism has also been identified by respondents in this study. The blockages are only partial in the majority of cases and therefore have limited effect on pavement drainage.

Prevention of the accumulation of silts in drainage pipes is difficult, however, where silts have accumulated the blockage can be removed using a water jet. Design with appropriate falls and construction quality to prevent low spots will also help avoid this problem.

4.1.7 Rodent Nests
A common failure method identified by in previous studies was the blocking of drainage pipes with rodent nests. This failure mechanism has also been identified by respondents in this study. As with silt accumulation the blockages are only partial in the majority of cases and therefore have limited effect on pavement drainage.

Rodents can be prevented from nesting in drainage pipes by using grills and guards to prevent them from entering the pipes. The disadvantage of this approach is that the grills and guards may cause silt to accumulate and thus create a blockage themselves. Oversize grills/guards will help alleviate this problem. Where rodents have built nests the blockage can be removed using a water jet.

4.1.8 Infiltration of fines into drainage layers
Another failure identified in previous studies is the infiltration of fines into drainage layers. The presence of fines in the aggregate matrix reduces the size of pores which in turn reduces the permeability of the base layer and increases the matrix suction. The result of this is that the base layer drains more slowly and retains increased moisture content, both of which may increase the rate of pavement deterioration.

Preventing fines infiltrating into the base course layers can be achieved by installing either geotextiles or filter layers above and below the base course. If installed correctly these trap the fines before they enter the base course.

4.2 Drainage failures specific to this study
During this study a range of issues and drainage failures were identified that were not reported in previous studies.

4.2.1 Lack of information on existing drainage systems
A lack of available information has been highlighted as a major source of problems by almost all engineers contacted during this study. In recent decades there have been regular changes of the format in which information records are kept, and in the contracting of maintenance work. The result is that when companies take over a maintenance contract for a region's highways they do not receive all information about the network, and a substantial portion of what they do receive may be in a format that is no longer accessible.
The result of this lack of information is that problems previously identified are not addressed, some parts of the drainage system miss being monitored, road sections known to frequently experience a particular distress don't receive preventative treatment or the appropriate investigatory check.

4.2.2 Long term changes in climatic conditions
Changes in global climate are affecting both long term precipitation as well as the magnitude of design storms. Predictions by the UK Climate Impact Program (Hulme et al 2002) indicate that, in the future, average annual precipitation will reduce but intense storms will occur more frequently and will be of a greater magnitude.

The reduction in average annual precipitation is likely to have a positive effect on pavement drainage. It is likely to reduce the level of water tables allowing water in the pavement base to infiltrate with greater ease into the sub-grade, and increase the capillary pore pressures in the base course reducing the saturation. The increase in regularity and magnitude of intense storms on the other hand is likely to have a negative impact on pavement drainage. With intense rainfalls exceeding the drainage capacity of pavements occurring more frequently.

Currently drainage systems are being designed to account for these changes, allowing an increased capacity of 40%. Older drainage systems were not so designed and, hence, are likely to suffer from erosion of drain surrounds and adjacent soil as excess water has to find an alternative route to the outlet.

5 CASE STUDIES OF EXAMPLE DRAINAGE FAILURES

Two case studies of drainage failures have been undertaken.

5.1 Case Study 1 - A14 Clayden

This first case study refers to a drainage failure that occurred on the A14 near Clayden (South East England). The section of highway where the failure occurred was on a bypass constructed circa 25 years ago. The highway at this point is a two lane dual carriageway. The drain affected in this case was the carrier drain running underneath the central reserve, that collected water from gully and filter drains.

Early in 2004 a series of holes was spotted in the central reserve of the highway during routine monitoring runs. Following this observation a cctv investigation of the drainage pipe running along the central reserve was quickly arranged to try and discover the source of the problem. The cctv footage showed that at many locations along the pipe it had been cracked or crushed by traffic barrier posts. At many of these points barrier posts could be seen on the cctv footage passing right through the pipe.

Where the posts had damaged the drainage pipe the soil above had collapsed into it. At some points the flow of water through the pipe washed away the soil that had collapsed into it. However, at many points the pipe was blocked by the collapsed soil. At these points the water backed up behind the blockage and rose up above the level of the blockage. Once above the level of the blockage the water could continue along the drainage pipe, however the swirling motion of the water as it passed over the blockages eroded cavities in the soil above the pipe. These cavities then collapsed at which point the process of water backing up and creating cavities started again. The construction date of the barrier that damaged the drainage system is unknown, but it is believed to have occurred shortly after the construction of the highway.

The damage caused by this drainage failure was significant. As well as the damage to the drainage system these failures may well have had a negative impact on the pavement's resistance to rutting and cracking. The cavities formed under the central reserve were large and extended almost to the pavement. Had the failure not been detected at that stage there is little
doubt that some of the cavities would have extended beneath the pavement, and may have caused substantial damage.

Figure 5. Soil erosion due to barrier post installation.

The repair of this drainage failure includes laying a new drainage pipe, filling the cavities, and reinstalling a barrier. The total cost of these repairs, over a length of circa 400m, is estimated at circa £100,000. Due to safety regulations regarding the dismantling of the safety barrier on the central reserve it was not possible to carry out all repair works at one time, as a result the work took place over several weekends, and therefore had a significant cost in terms of increased inconvenience to road users as well as its financial cost.

Without being able to contact the contractors who carried out the installation of the safety barrier it is impossible to determine what the exact circumstances were leading to the failure. However, it is clear that the contractors were not aware that the drainage pipe was running underneath the barrier that they were installing. This is a situation that could easily reoccur given the current unavailability of drainage information, and as a result this case can be considered an illustration of the potential consequences of carrying out maintenance and construction work without knowledge of the in-situ drainage system.

Preventing errors of this nature relies upon ensuring that accurate records are maintained detailing the type and location of drainage systems. Not only should this information be recorded, but it should be recorded in a format that is easily transferable between contractors and agents, and can be easily updated. The Highways Agency could consider including conditions ensuring the successful transfer of data to future contractors as part of their standard contracts for area maintenance.

5.2 Case Study 2 - A14 Snailwell Flooding

This second case study refers to a second drainage failure that occurred on the A14 near Snailwell. The section of highway where the failure occurred was on a bypass constructed in 1975. The road is a 3 lane dual-carriageway, and the area where the failure occurred was in a cutting.
in a chalk bedrock. Information for this case study has been taken from a report produced for the Highways Agency (Birch 2001).

In this case the road is situated in a lowland area with a water table that is close to level across a large area. As a result of this water drained from the pavement has to be transported over a large distance prior to being discharged. Consequently the hydraulic gradient in the drainage system is insufficient to reduce the water table.

On 8th February 2001 the highways maintenance team were contacted by the local police force reporting that 1 lane had been closed due to flooding and requesting that pumps be brought to site. By the time pumps had been taken to the site 2 lanes in the eastbound carriageway and 1 in the westbound carriageway had already been closed.

This incident of flooding was not the first to have occurred at the site. Previously flooding had occurred in 1981/82, following which a pumping chamber were designed and installed, and again in 1987 and 1994. The failures have all occurred as a result of significant rises in the ground water table following particularly wet years (the autumn of 2000 was the wettest since 1766). The water table has risen on these occasions above the level of the pavement surface.

The most significant damage caused by this drainage failure is the inconvenience it causes users of the road, on each occasion lanes were closed for as many as 6 weeks. The elevated water table will also increase the saturation of the base course. This is likely to have little impact on the pavement’s service life when the lanes are closed to traffic while the pavement is flooded. However, immediately before surface flooding and immediately afterwards, high saturation levels in the pavement and associated pavement deterioration are expected.

As has already been stated, after the first set of floods a pumping chamber was installed at the site at a cost of about £195,000. A report was carried out after the 2001 flooding with a range of options as to how to deal with potential future flooding.

The first option was to do nothing. Dealing with flooding only when it occurs would be the cheapest solution. However, this would result in the road being closed again in the future when flooding occurs. There would also be a risk of fatalities during the period between the start of flooding on the highway surface and the closure of flooded lanes. Also if the water table were to remain high it would be likely to increase the damage to the pavement.

The second was to request the cooperation of the local water authority (AWA) in controlling the level of groundwater in the area. AWA already have pumping wells from which they abstract water during drought periods. It was suggested that they could be requested to continue pumping if the water level rose above a certain level. If this option were to be implemented AWA may insist on the Highways Agency contributing towards the maintenance costs of the pumps.

The third option was to raise the level of the carriageway above the level to which the water has been rising. This would effectively resolve the problem provided that the water table does not rise to levels exceeding those recorded in the past, however, it would be the most expensive solution costing over £750,000, the construction works would cause significant disruption to highway users, and there would be no guarantee that the water table would not rise to even higher levels in the future and cause flooding despite the works.

The fourth option was to install larger ground water pumps capable of pumping both the surface and groundwater in the vicinity of the problem area. This solution cause minimal disruption to highway users, and would be significantly cheaper than the previous option, costing circa £166,000.

As yet a final decision has not been made on which of the options provides the best value solution.
This case highlights the possible failures and options for remediation when encountering extreme or unexpected hydrological conditions that raise the level of the water table. The low available hydraulic gradient means that, even if the capacity of the drainage pipe system was increased, pumping is required to effectively drain the site. However, in many cases it is possible to reduce the water table simply by increasing the flow capacity of existing drains, across much of the UK this provides a cheaper method to reduce the level of high water tables.

6 CONCLUSIONS

The main conclusion that can be drawn from this study is that respondents have reported drainage systems in the UK to be effective with few failures. However, there are various reasons that this may be the case. One is that the drainage system may be in good condition and working effectively. Another is that the many of failures that occur do not completely prevent the drainage system from working; they simply reduce its effectiveness and are therefore not always rapidly detected. Monitoring of drainage systems is currently undertaken at a maximum interval of 10 years; and should ensure that all failures are detected even if they are present for several years beforehand.

According to Harrigan (2002) the impact of poor drainage depended upon the type of pavement. It was found that for flexible pavements, and non-doweled jointed concrete pavements drainability was important for the performance. For well designed and constructed doweled jointed concrete pavements drainage was found to have little impact on pavement performance. In the UK the majority of pavements are flexible pavements, and as a result their performance is likely to be affected by poor drainage. If, as the above indicates is a possibility, pavement bases are saturated for extended periods of time there is likely to be an increase in the rate at which rutting and cracking of pavement surfaces occurs.

Because of the uncertainty regarding the condition of in-situ drainage, designers and researchers should be cautious when making assumptions about moisture conditions. While it appears unlikely that base layers will become permanently fully saturated it is possible that degradation in the drainage system may increase the period of saturation after rainfall, and infiltration of fines will increase the residual moisture content.

There is potential for a more detailed study looking at drainage system failures. A comprehensive survey of drains, classifying their type, age, local conditions and the number of failures that have occurred on each, would help to identify both the frequency and the conditions under which failures occur. This could aid in identifying the most cost effective drains for a range of conditions, as well as providing an improved understanding of the extent of drainage failures and their impact on pavement performance.

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