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State of the art of materials' sensitivity to moisture content change

Report Nr 2

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Report Nr 2 – State of the art of materials' sensitivity to moisture change

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1 Introduction

It has been widely demonstrated that the expected life of a road depends on the subgrade's resistance modulus, and that this is highly influenced by the subgrade's moisture content. This is the reason why a good drainage system is of paramount importance in the design of a road, although not always adequate. It is estimated that about the 80% of the problems encountered in pavements is related to the presence of water (Birgisson & Ruth, 2003). This report is about the moisture content within the pavement structure, how it changes, what affects it, and what are the materials that are most influenced by its changes. The relationship between climate change and soil moisture content change has been described in the report "State of the art of likely effect of climate on current roads", and thus here it will be mentioned only briefly.

2 Main general concepts

The mechanical performance of a road subgrade depends largely on the frictional interaction developed between the grains of the soil. In fact, a greater friction means more strength, greater stiffness and thus greater resistance to rutting. The ability of a soil to sustain a certain stress is a function of its effective stress, defined as

$\sigma' = \sigma - u$

(where σ is the total stress applied to the soil and u is the water pore pressure), that is related to the soil's friction. It is clear that a well drained soil will have very low u, and thus higher strength. This is the reason why drainage is so important for efficient pavement structures.

However, a soil in a partially saturated condition is usually desired because of the presence of matric suction forces that develop in the pores between the grains due to meniscus effects at the air-water interfaces (Watmove project, 2008): the presence of suction contributes to the effective stress increase by applying a negative value of u. It should be born in mind, however, that permeability of partly saturated soils is lower than that of the same soil when saturated. This fact is due to the presence of air in the pores, which obstructs the flow of water, so that water can only move in the films around the soil particles.

The permeability of the material that constitutes a road normally increases from the top of the pavement downward until about 0.7 m depth. The asphalt or concrete layers are typically almost impermeable, while the material below should be an aggregate capable of draining more as the water moves downwards, where it eventually intercepts a path to move towards the sides and exit. This is to avoid the accumulation of water below the pavement, which otherwise would keep the subbase layer wet, with consequent high levels of moisture content, low shear resistance, and the risk of freezing of the accumulated water that might then cause heave distress in the upper layer. The only exceptions are those roads paved with porous asphalt (these will be introduced later on).

The mechanical behaviour of the road structures depends on their initial state, the hydraulic conditions and the temperature. The constitutive models that describe it are commonly used in pavement analysis and design.

3 Summary of predicted Climate changes that will affect pavement moisture content

For more details, refer to the report N° 1 "State-of-the-art of likely effect of climate on current roads".

3.1 Moisture change with temperature

The influence of the increase of temperature predicted on the moisture content, and thus on the soil properties, depends on the area that is being considered. In those areas that are normally affected by seasonal freezing, temperature has got a main role in road stability: such areas undergo periods in which the upper soil, just beneath the pavement, starts to melt (the so called spring thaw problem, described in more detail later), and water remains trapped between the pavement and the frozen soil below, increasing the moisture content and thus the pore pressure, and resulting in a decrease of effective stress. If the seasonal freeze period is reduced in length, or the temperatures are close to zero (with short cycles of positive/negative temperatures) also during winter, then much longer periods of wet, non-frozen conditions can be expected, necessitating longer drainage requirements. However, the shorter frozen period and the shallower penetration of the freezing front into the ground means that the drainage paths are free from ice also during winter and thus will operate during the whole year.

In the warmer, temperate areas, the evapotranspiration is probably the main factor that is influenced by temperature changes. In fact, when evaporation is significant, water from the watertable flows upwards in order to replace the water evaporated. This event can lead to a water movement upwards tens of metres above the phreatic surface, changing the soil's saturation, and it can also lead to salts being lifted to the surface where they can affect the soil properties.

Fig. 1: Road lifted by traffic-induced water pressure during spring-thaw in Northern-Karelia, Finland. Photo courtesy of Martti Leppänen (Watmove project, 2008).

3.2 Moisture change with rainfall

Rainfall can have very important effects because, if it reaches the road subgrade, it increases its moisture content, and cancels very rapidly the positive effect given by suction (thus suddenly reducing the effective stress). Significant moisture changes can occur immediately after rainfall, if permeable layers exist. For this reason its expected future increase has to be taken into account in order to prevent road damage. Being an intermittent supplier of water, its effects are difficult to be evaluated in a proper manner. With greater runoff volumes anticipated, the need to provide positive drainage increases. Below ground it would be wise to anticipate greater volumetric flow rates of longer duration.

4 Water in the pavement surfacing

Water on a pavement surface has got mainly two effects, a direct one and an indirect one. The direct effect is damage due to oxidation, and thus aging, of the asphalt. The second, indirect effect is the damage of water in the underlying subgrade once it passes through the asphalt. Although the presence of water in the bound pavement layers has a minor importance if compared to the effect that water has on the subgrade, nonetheless the latter is significantly affected by the surface layer, and for this reason it is important to analyse the interaction between water and pavement.

4.1 Flow through intact asphalt

The permeability of asphalt (but also of the soil below) is mainly controlled by the grading curve of the aggregate used and its level of compaction. These two factors affect the voids between the particles where water can percolate. In fig. 2 is shown the relationship between air voids and permeability: if, below 7% air voids, the permeability is almost negligible, it increases drastically if the pores increase in number/dimensions. This is due to the fact that, as the porosity increases, the voids get in connection, and thus water can pass from one to the other (fig. 3). According to Chen et al. (2004), for an air voids value higher than 12%, the voids start to be “effective”, which means the voids start to interconnect to each other, letting water pass through the entire layer. This porosity corresponds to a permeability of 10^{-2} cm/s. Such values can be considered as the minimum values for a porous asphalt. An air voids level of 8% has been recognised by many authors (Brown et al., 1989, among the others) to be a good threshold value to keep permeability low and avoid rapid oxidation with subsequent cracking and/or ravelling. Also, it is suggested that coarse mixtures with low fines content are least well-performing because they tend to have large voids.

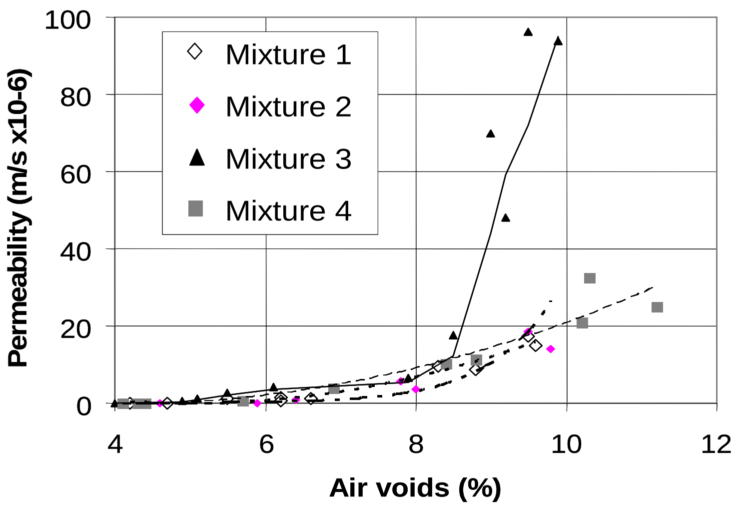

Fig. 2: Laboratory determination of the relationship between the asphalt air voids and permeability (Vivar & Haddock, 2007).

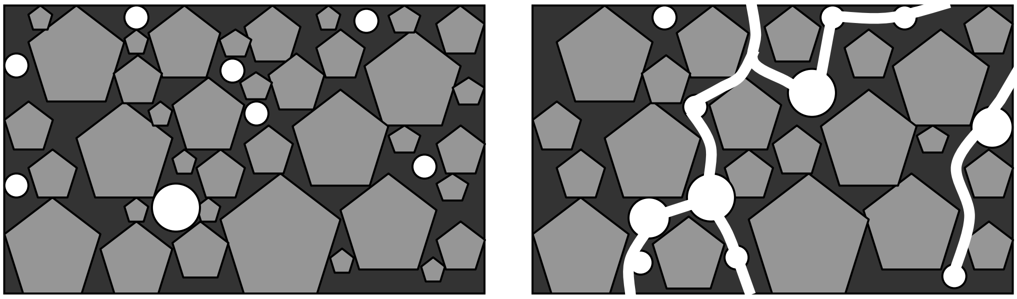

Fig. 3: If more air voids are present, they are likely to be in connection, and thus water can percolate more easily.

Ragab et al. (2003) measured the moisture content changes below different pavements, and found that, generally, between 6% and 9% of rainfall infiltrated through the road surfaces.

4.2 Flow through cracked pavements

If the asphalt layer permeability is low enough, the main path that water from the surface can follow to reach the soil subgrade it through the cracks and joints in the asphalt or through pervious surfacing. The quantity of water soaked in depends on the quality of the road surface and of its margins (where water should be routed into a drainage system). According to Ridgeway (1976), there are four factors that influence infiltration rates in cracked asphaltic pavements:

- the capacity of the crack to carry water (which basically depends on the dimensions of the cracks)
- the amount of cracking present,
- the area that drains to each crack, and
- the quantity of water (for example, the intensity and duration of the rainfall).

The permeability of an uncracked asphaltic material can be assessed through laboratory methods, in particular with the constant head and falling head laboratory tests. However, permeability loses much of its importance and becomes negligible when the asphalt suffers cracking, and thus laboratory permeability tests are not as useful as field tests.

On site, it is either possible to measure permeability on a limited area of the surface that represents the general condition of the asphalt, or, alternatively, over specific cracks or joints to assess the water that can enter through that crack or joint. Different techniques have been developed in order to assess permeability by infiltrating water into the pavement surface from a device which acts over a limited area of the surface. These techniques are based on two approaches: the first one is to keep a zone of the pavement surface wet and monitor what water supply rate is required to keep the water head constant; the second one is to provide a water head and note the rate at which such head drops. Among those field methods are the Infiltrometer used by Taylor (2004), and the device designed by the US National Center for Asphalt Technology (NCAT) (Cooley, 1999). Ridgeway (1976) performed a “constant water head” type test on a single, specific crack and he could measure a water infiltration of 100 cm^3/h/cm of crack. Thus, it is considered that such infiltration rate can be used for design purposes (Liu & Lytton, 1984). Baldwin et al. (1997) evaluated that when a road presents a surface with 0.002 cm of crack for each cm^2 of surface, then this road would needs maintenance intervention. This would mean that, before a road needs intervention to seal surface cracks, the road can potentially absorb 4.8 cm^3/day for each cm^2 of asphalt. Although this value is only an approximation and tends to overestimate the real ingress potential, it should be noticed that, considering that the average daily rainfall in UK is of about 2 mm/day (and in most of Europe is usually less than 2.5 mm/day), for not extreme events the amount of water can potentially completely infiltrate into the subgrade. Also calculations based on laminar flow theory and laboratory measurements have evaluated that cracks can potentially let almost all the rainfall that falls under normal conditions pass through (Cedergen & Godfrey, 1974). However, according to Ridgeway (1976), the majority of the cracks receive more water than they can actually carry during moderate rainfalls, and only occasionally there are cracks that can carry more water than what is supplied, as far as entry of water into and through the pavement is concerned. A consequence of this is that the intensity of rainfall is important only until the maximum pavement cracks capacity, but beyond such point the duration of the rainfall becomes more important than the intensity. If the road presents large cracks that can carry large quantities of water, then high intensity rainfalls are the most important, even if of short duration; vice versa, if the cracks are relatively narrow and thus have got low capacity, then the duration of the rainfall is more important than the intensity.

4.3 Asphalt layer damage induced by water

The asphaltic surface can be seriously damaged when exposed to high levels of water, as it can happen during heavy rains or long periods of rain. Water, infiltrating into the asphaltic mixture, weakens the mastic matrix and its bond with the aggregate particles. This phenomenon is called ravelling, or stripping, because the aggregates are “stripped” away from the mastic. The initial stripping can rapidly progress into a more severe ravelling of the wearing surface, and ultimately lead to pothole forming.

Fig. 4: An example of road subjected to ravelling (left) and to potholing (right) (Watmove project, 2008).

So far, no ideal prevention methods exist, and the only way to solve the problem is by intervening when the road shows the first signs of damage in order to maintain the road at an acceptable standard; this solution involves closure of the major highways for repair and maintenance, with consequent distress, and high costs. The main problem that does not allow taking any prevention is that it is impossible to know a priori the engineering properties of a mixture at the range of moisture contents and weather conditions at the time of purchase of the bulk materials. With this aim, in recent years, experimental and analytical investigations on water-induced damage in asphaltic mixtures are studied. Researchers at Delft University of Technology have developed a model, called RoAM (Kringos & Scarpas, 2004; Kringos, 2007), that allows a study of the interaction between physical and mechanical water damage inducing processes. Also, in order to describe fully the interaction between water and binder, asphaltic mixture needs to be considered at a micro-scale. The physical processes identified as important contributors to water damage are:

- the molecular diffusion of water through the mixture components and
- the advective transport of the mastic due to the moving water flow through the connected macro-pores.

On the other hand, the most relevant mechanical process identified is the occurrence of intense water pressure inside the mixture caused by traffic loads and known as the 'pumping action'. All these processes and their interaction are described by the RoAM model.

An experimental study to investigate the pavement distress associated with moisture, and particularly with cracks, has been carried out by Chen et al. (2004). The authors made permeability tests on stone mastic asphalt and porous asphalt at different densities; indirect tensile tests on normal and on saturated samples to evaluate the moisture-induced damage; finally, wheel-tracking tests were performed to evaluate the stripping and rutting susceptibility of cracked specimens before and after being submerged in water. The results (fig. 5) show increased water damage with increasing air voids, probably due to premature stripping and ravelling, and premature ageing. The fact that both stone mastic asphalt and porous asphalt samples curves tend to flatten at higher void ratios demonstrates that an asphalt mixture, if coated with a proper asphalt film thickness, is however able to sustain its strength in wet conditions. The tensile strength showed a reduction proportional to the cracks width, as well (fig. 5). For crack widths larger than 2 mm, the results showed a sudden increase in permeability that can cause serious problems for the subgrade; for this reason, the authors suggest immediate maintenance of 2 mm cracks are observed in a road. Finally, cracked specimens tested on the wheel-tracking device showed that the rutting rate of the samples increased of 21% for stone mastic asphalt, of 31% for porous asphalt, and of 57% for dense asphalt, the latter due to the thinner mastic film.

4.4 Porous asphalt

Porous asphalt is a relatively modern pavement surfacing material. This asphalt is designed in such a way that it deliberately allows water to pass through. The main reasons to do this are to limit spray from vehicles, tyre-pavement noise generation and to reduce the risk of aquaplaning during heavy rainfalls.

To create porous asphalt, aggregate with a medium-coarse particle size and a very steep grading curve (which means that the aggregates have got very similar dimensions, and thus the void spaces between them are not filled with finer material) is used. Such a mixture has a very high air void volume (20 – 30%), and thus water can infiltrate quite easily. The porous pavement is laid over an impermeable asphaltic base, this way water flowing in the surfacing cannot continue to flow vertically but is forced to travel sideways, exiting from the layer at its edge.

The drawbacks of porous surfaces are first of all the short durability, and, secondly, the fact that they can become clogged with fines; however, rehabilitating by removal of fines without causing premature damage is nowadays a relatively easy task.

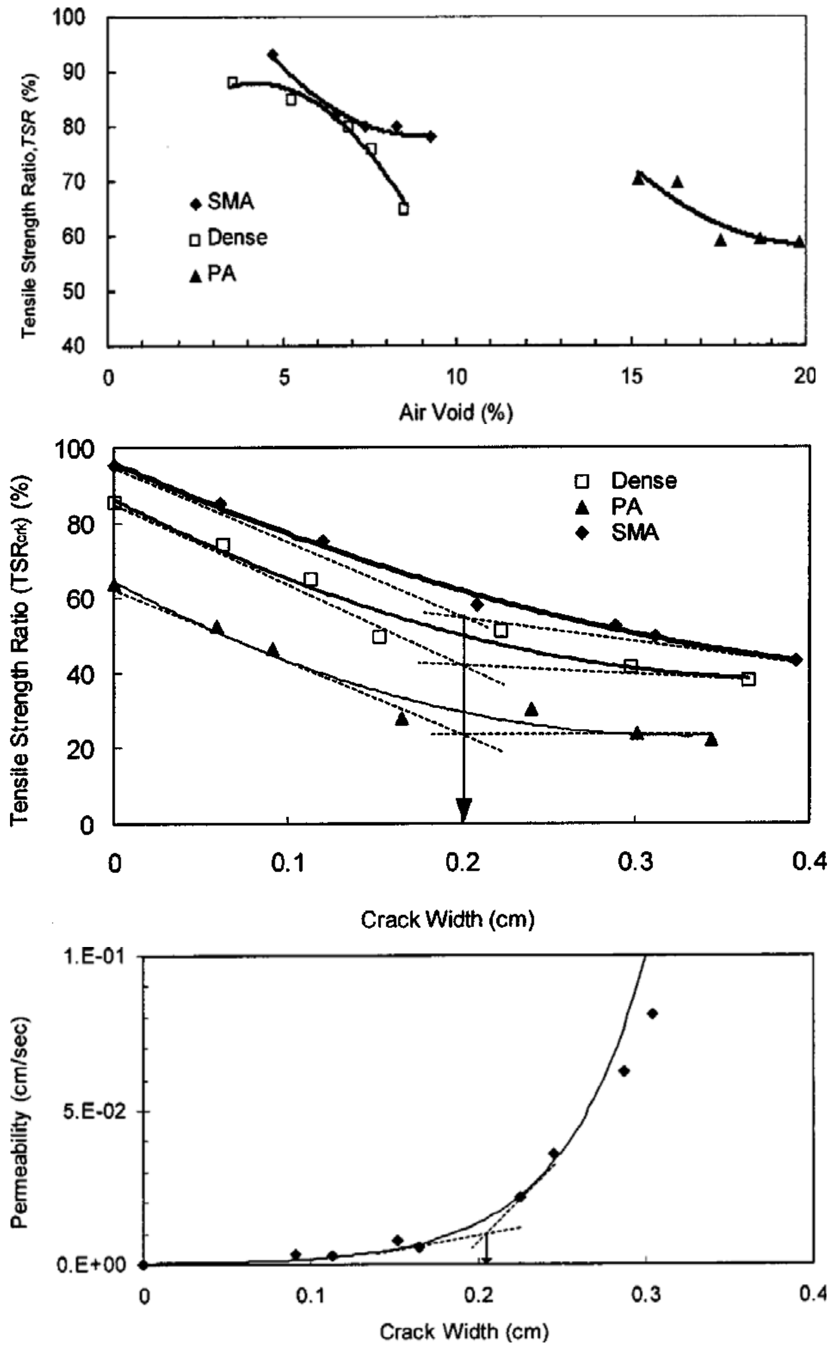

Fig. 5: From the top, tensile strength related to the air voids, to the crack width and permeability increase with the crack width (Chen et al., 2004).

5 Water in the subgrade

Subgrade moisture change usually occurs in three phases:

- water entry phase, which can occur quite rapidly, localised to the inflow boundary
- water redistribution within the material involved in response to suction and gravity
- an evaporative and departure phase when water, as vapour, leaves a material or moves to other layers in order to reach equilibrium of temperature/pressure.

Water availability in the surrounding environment depends, among others, on the season and on the weather conditions; therefore, also subgrade water content can vary seasonally, annually and over longer periods. Seasonal variations in water content commonly involve the upper 1 to 2 m.

The main factors affecting the soil moisture content, and thus its behaviour, are:

- climate and weather conditions, especially rainfall amount
- type of soil,
- groundwater depth and
- the moisture concentration in the soil itself.

Water can percolate into the subgrade in three main ways:

- Seepage into the subgrade from a high groundwater table due to capillary suction or vapour movements
- Percolation through the pavement surface, especially associated with joints, crack or other defects
- Migration laterally from shoulder slopes and verges (if the shoulders are permeable or their surface is deformed in such a way as to allow the retention of water), which depends on the material permeability, compactness of the surface, inclination and the drainage from pavement surface.

The relative importance of the different phenomena and routes depends on the materials involved, the climate and the topography of the terrain. However, according to Birgisson & Ruth (2003), pavement cracks are not the major source of water infiltration into the pavement, but rather, subsurface seepage, high water tables and moisture susceptible soils such as silty soils in the subgrade play an as much important role as the cracks.

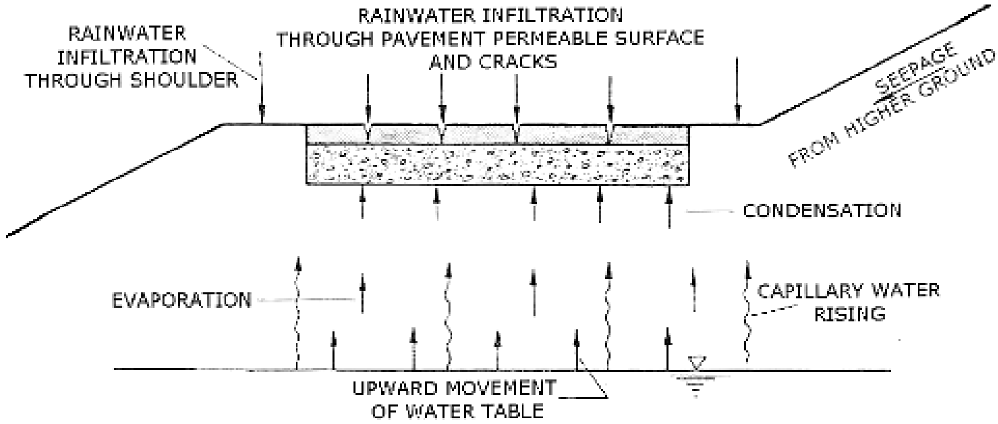

Fig. 6: Possible water movements into the pavement zone (from Moris & Gray, 1976)

The main consequence of water percolation into the subgrade, made of compacted, unsaturated material, is to increase the water pressure or decrease suction, and thus reduce the effective stress, and its elastic and plastic stiffness. The very close relationship between moisture content and soil stiffness can be understood from fig. 7, that shows the results of an accelerated load test performed with the HVS-NORDIC at VTI in Sweden in 1998 (Wiman, 2001). The rut depth measurements for a weak pavement show that, after 500 000 passes, the increase in rut depth was constant (0.88 mm/100 000 passes). An increase of the test load from 60 kN to 80 kN and the tyre pressure from 800 kPa to 1000 kPa had very little effect, increasing rut propagation only to 1.03 mm/100 000 passes. The subgrade was then made weaker by adding water to the sand layer, in order to bring the water table to a level 300 mm below the surface of the sub grade (which corresponds to the highest level permitted in the Swedish). The test load and tyre pressure were reset to the initial conditions of 60 kN and 800 kPa. As a consequence, the rut propagation increased to 4.16 mm/100 000 passes, and the first cracks could be seen at the pavement surface.

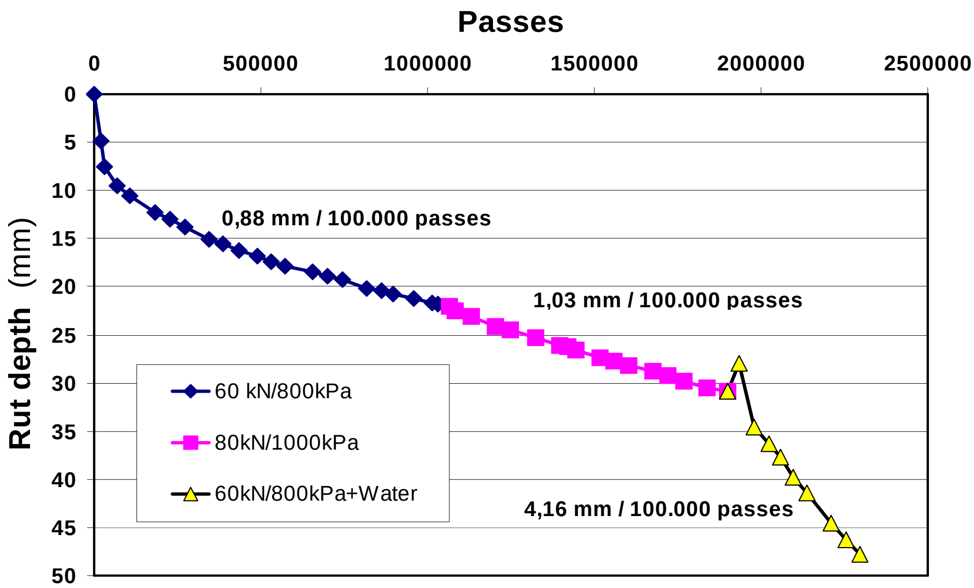

Fig. 7: Rut depth propagation rates for different conditions (from Watmove project, 2008, courtesy of L. Wiman).

According to Haynes & Yoder (1963) and Liu & Lytton (1984), the material strength is strictly related to the level of saturation (that, in a way, corresponds to the moisture content) of a crushed stone base. In particular, the total deformation tends to increase almost exponentially for a saturation level above 85%, thus accelerating the fatigue damage.

Some examples of moisture damage on roads are described by Birgisson and Ruth (2003); the cases studied involved seepage from defective culverts, slope stability problems, wrong drainage systems, pavement damages caused by soil suction. Among these, the latter is worth of note; two segments of the same road were built on different soils: one over a layer of sand below a layer of clay, the second over only clayey material. The water table was relatively high, and the portion of road built over clay exhibited pavement cracking. The two road sections and the relative water contents at the different levels are shown in fig. 8: it can be observed that the presence of the sand in correspondence of the groundwater table works as a "capillary barrier", drastically limiting the suction effect and thus reducing the water content in the upper layers.

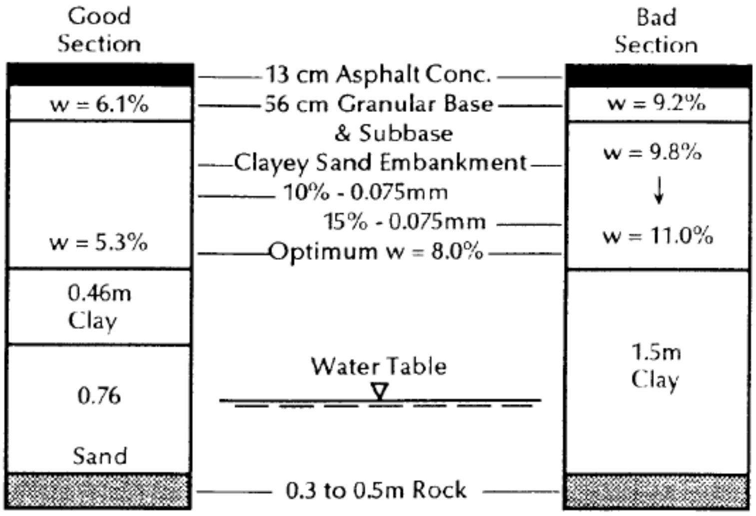

Fig. 8: Pavement distress related to soil suction: on the left, a cross section of the pavement with "good" subgrade, on the right the "bad" one (Birgisson & Ruth, 2003).

This example shows that variations in the water table level can be a potential cause of distress.

6 The frost heave and thawing problems

Frost heave is a problem that involves those subgrade soils that are fine graded (especially silts), typically called “frost susceptible”. In cold regions, very low winter temperatures can freeze the water held in the soil causing the soil to “swell”, or, more precisely, to “heave” the surface. A pavement subject to freezing tends to become uneven mainly because of the different matrials that are below, but also because snow covers the sides of the road, and thus frost depth is typically deeper in the middle of the road. Frost heave depends in large extent on the grading of the soil, and is commonly related to the presence of fines. This is shown, for example, by the results obtained by Kolisoja et al. (2002) from triaxial tests on different specimens (fig. 9). However, the same authors observed that compaction can cause excessive degradation thus transforming a non-susceptible, crushed stone subgrade into a frost-susceptible material due to the increase of fines.

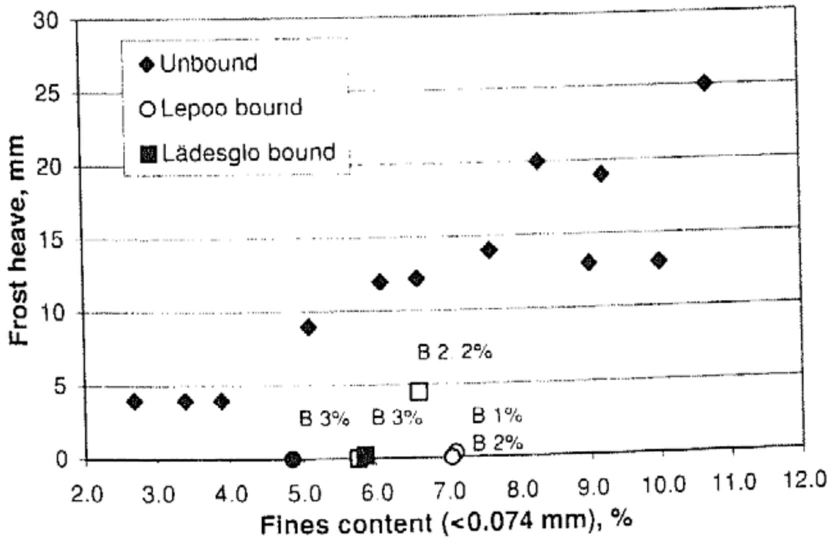

Fig. 9: Relationship between fines content and frost heave measured in the triaxial specimens during a freezing stage (Kolisoja et al., 2002).

Subgrade frost heave reduces the travelling comfort, and can cause the formation of cracking on the asphalt (see fig. 15), but does not directly affect the road strength, as the soil, being frozen, has a high stiffness. A more serious problem that reduces the road quality, instead, appears when the frozen soil starts to melt, in which case, melted water can remain trapped between the pavement surface and the ice underneath, increasing the moisture content (i.e. the saturation) and its pore pressure, and thus reducing considerably the soil’s strength and stiffness. The main forms of deterioration associated with frost heave are:

- longitudinal cracks (outside the wheel tracks),
- meandering cracks and
- medium-long distortions of the pavement surface.

Although thawing is a complex system affected by many different factors, Doré et al. (2005) recognise three main ones:

- The amount of water accumulated due to frost heave,

- The rate at which the system is thawing (especially prolonged periods in which temperature is daily ranging around 0˚C)

- The rate at which the layer expels water, i.e. consolidates.

It should be noted that the magnitude and duration of spring-thaw weakening depends on large extent on the functioning of the drainage system.

There are essentially two thawing periods; during spring, temperatures tend to increase more or less constantly day after day, and thus, when the temperature goes above the 0˚C, the soil experiences the so called “spring thaw”, a period of time during which the soil or the unbound pavement layer underneath the road is very weak while the surrounding soil conditions, being the soil still frozen, do not allow drainage of the excess pore water and until the soil regains its bearing capacity. The time that it takes to return to “normal” conditions depends, apart from the external factors, on the quantity of fines: the higher the fines content, the longer it will take. During winter, instead, some days of temperatures just above zero can bring to short thawing periods, which can last from hours up to a few days. These are potentially more dangerous because, while the spring thaw is fairly known and traffic limitations are applied, the winter, short thawing periods are not expected and, if heavy loading traffic is not blocked, it can seriously damage the road. Besides, it has been already well recognised that a high number of freeze-thaw cycles can accelerate the process of road deterioration (He et al., 1997).

Spring-thaw load restrictions are often imposed to avoid severe pavement deterioration; but changing climatic conditions are now hindering prediction of the likely thaw period, so the use of equipment that enables monitoring of the pavement strength situation is gaining importance in order to adapt restriction periods to the real pavement strength conditions. Two examples of projects aiming at doing this are being run in Sweden and Finland (Watmove project, 2008). In Finland, a Percostation is used to monitor dielectric value, electrical conductivity and temperature with depth. The data that result are very useful to impose or remove thawing traffic limitation restrictions. In Sweden, instead, only the temperature profile is monitored by means of Tjäl2004, developed by VTI. The innovative part of this project is that the collected data are distributed via the Internet enabling direct access from trucks to frost depth readings that are updated twice an hour.

7 Road bearing capacity as a function of the moisture degree

Different types of road structures can be more or less sensitive to moisture changes, depending on their characteristics. For bituminous pavements, the thickness of the asphaltic layer is an important property (together with the aggregate and binder properties, and the compaction level) that affects the sensitivity to moisture content. In fact, the thicker the bituminous base layer is, the least the stresses transmitted to the soil underneath will be; also, water will reach the subgrade soil with more difficulty, and consequently the subgrade will have higher strength. In this case, the performance of the road depends very little on the moisture content. There is evidence that suggests that water has less impact on thick (and well-construced) pavements than it does on thinner ones (Hall & Crovetti, 2007). Only after pavement cracking takes place, then water infiltration accelerates the road degradation and the subgrade will be highly affected by the presence of water. For concrete pavements and semi-rigid pavements (consisting of a bituminous surfacing over a layers treated with hydraulic binders), the main problem is linked to the response to thermal contraction and shrinkage of the cement treated materials. This can lead to transversal cracks, with consequent water infiltration. However, in concrete pavements, attempts are normally made to control thermal cracking by transverse joints.

Even more important is the choice of the material below the asphaltic surface, because their mechanical behaviour is directly connected to moisture changes. Materials used in the construction of pavement should be chosen in order to minimise the effects of excess moisture. The aggregates used within the unbound layer are the most sensitive to excess moisture content when subjected to traffic; however, some factors can reduce or increase this sensitivity; the main ones are:

- the compaction properties (a more compacted soil is less permeable),
- the amount of degradation (related to its strength),
- the grain size composition (sieving analysis) and
- the quality of fines, like their plasticity or swelling index (in some cases).

A separate analysis of the individual factors does not allow a full understanding of the behaviour of the soil or aggregate under different moisture conditions as a whole: in order to achieve this, laboratory and field tests are necessary.

7.1 Laboratory investigations of the pavements mechanical behaviour in relation to moisture content

The most straightforward way to assess the effect of moisture content of the road performance is to simulate the effects of trafficking by subjecting the material sample to a repeated loading and to simulate the different moisture conditions that can be found in the layers of the road construction and embankment by subjecting this sample to different moisture conditions, too. Most opted for this purpose is a *cyclic triaxial test* (or repeated load triaxial test), well established and widely accepted (now regulated in the European, US and Australian standards CEN 2004, AASHTO 2000 and Standards Australia 1995). The procedure for testing is simple: a cylindrical specimen is compacted to a desired level and then tested by applying confining (constant or cyclic) and vertical (cyclic) stresses. This test gives the stiffness characteristics and the ability of the material to withstand accumulation of permanent deformation during pulse loading such as that in a road (Erlingsson, 2000). Moisture/suction conditions are kept controlled.

7.2 Field investigations of the pavement's mechanical behaviour in relation to moisture content

The measurement of the pavement bearing capacity on site is the most direct measurement, and gives information on real time, for these reasons it is a very useful tool. For example, Eigenbrod and Kennepohl (1996) suggest that load restrictions (usually applied on those countries whose roads are subjected road limitations due to spring thaw) should be related to real-time field deflection measurements, for example by means of a FWD. There are different ways to evaluate the pavement capacity on site; non-destructive ones are to be preferred to make measurements on an every-day basis. The common practise is to use deflection measurements. Some examples of instruments based on deflection measurements are:

- Plate bearing test – A test plate, square or circular, is placed on the pavement layer surface and is subjected to static loading by means of a hydraulic jack. Settlement is then measured. Such a test is time consuming, which makes it not very good in practise. It can also be performed by lifting and dropping the known load from a known height and measuring the correspective deflection many times, in order to simulate the dynamic effect of vehicles to the pavement.

- The Benkelman Beam – it consists of a lever arm attached to a lightweight aluminium frame. The tip of the beam probe is placed between the tyres of a loaded (80kN axle load) truck at the point where deflection is to be determined. Then, the vehicle moves away from the test point and the dial gauge measures the upward movement of the pavement. Although the equipment is simple to operate, the test results to be quite slow.

- Curviameter – it is a dynamic deflection measurement equipment, which records the surface deflection under a dynamic load. It uses a geophone to measure the vertical acceleration of a point on the pavement surface between dual test wheels. The vertical displacement is obtained by integration of the geophone signal.

- FWD – probably the most common and effective tool to measure bearing capacity, consists of a drop weight, which falls onto a loading plate, and the response of the surface layer is automatically measured through deflection sensors positioned at specified radial distances from the centre.

When infiltrated into the subgrade and other unbound layers, water not only affects pavement's stiffness, but may also give indirect negative effects observable at the pavement surface. This is particularly true during freezing periods in cold regions, when the soil below the pavement freezes and increases in volume due to cryosuction effects. The higher the soil moisture content is, the higher the volume increase will be (however, it should be born in mind that heave strongly depends on the soil characteristics, too). As heave will not be uniform due to differences in material, water supply and thermal conduction, this will, in turn, affect the surface roughness, and thus the driving comfort and safety. Roughness is usually evaluated from the International Roughness Index, IRI and is measured on the longitudinal profile of the road with an inertial profiler. Kameyama et al. (2002) monitored the IRI of an Expressway in a cold region of Japan. The IRI measured showed an increase during winter that doubled the level measured during autumn (fig. 10, left). When spring came, the IRI decreased again to the same level reached during autumn, and the remarkable difference of the IRI observed in winter disappeared. The IRI of cut sections was the most affected by the freezing effect: in fact, although the IRI changed very little in embankment and bridge sections even in winter, it became about five times that in autumn in the cut sections. The IRI measurements were then compared with freezing index measurements, and they showed a good linear correlation (fig. 10, right).

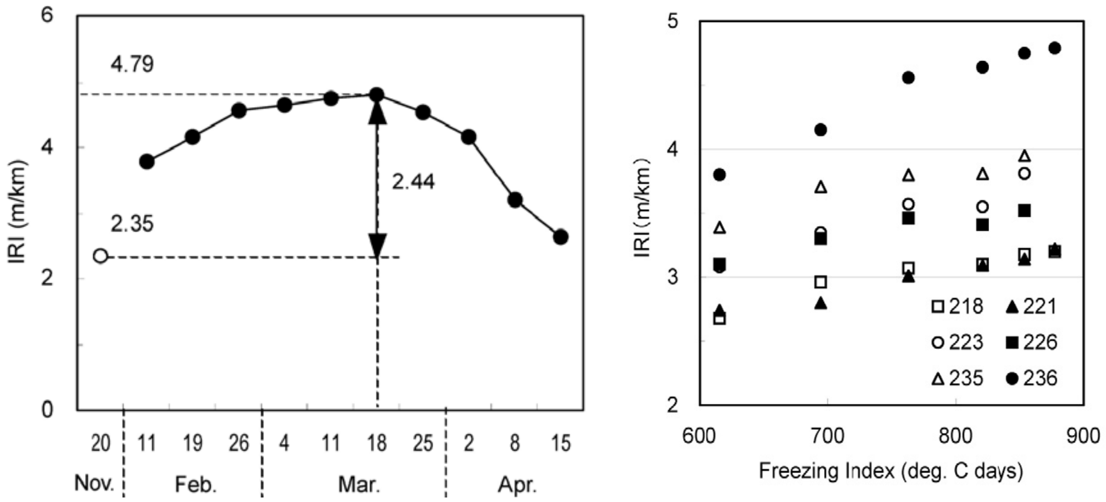

Fig. 10: Increase of IRI during the winter period (left) and its linear relationship with the freezing index (Kameyama, 2002).

8 Relationships between water, heat and pavements and their modelling

According to Hassan and White (1996), to analyse water flow in an unsaturated soil, two equations are necessary:

- The soil water characteristic function (that describes the relationship between the suction applied on a soil and the water retained in the sample at its pressure of equilibrium)

- The hydraulic conductivity characteristic function (the relationship between the hydraulic conductivity and the water content).

But, because of the difficulties met in doing it, especially in finding a reliable estimate of the unsaturated conductivity, it is usually preferred to use models. In fact, interaction of all the aspects that govern the movement of water in the pavement structure is very complex, and analytical solutions able to describe all the different physical processes and contributions are not obtainable. For this reason, numerical modelling, such as finite element methods and many others, are a good alternative to dealing with such complex problems. Some of the models that can be found in the literature are now described.

8.1 Simple relationships related to moisture content

For general modelling purposes, climate can be represented in terms of the "Thornthwaite moisture index", an index that describes the environmental moisture taking into account the function of precipitation, temperature and potential evapotranspiration. This index has been used, for example, by Austroads (2004) for modelling the influence of moisture changes on roads; in fact, roads in areas with higher values of the Thornthwaite index will deteriorate faster than those with a lower value for the same traffic loading. This method (Thornthwaite, 1948) is based on observed climatic data and allows the determination of the potential evapotranspiration (PET) through the formula:

PET_{month} (cm) = 1.6 $(10T/I)^a$;

$$PET_{year} = \sum_{1}^{12} PET_{month}$$

where T is the mean monthly temperature (°C), I is a heat index for a given area which is the sum of 12 monthly heat index values i:

$$I = \sum_{1}^{12} i\,;$$

i is derived from mean monthly temperatures using the following formula:

$i = (T/5)^{1.514}$

a is an empirically derived exponent which is a function of I:

$a = 6.75 \cdot 10^{-7} I^3 - 7.71 \cdot 10^{-5} I^2 + 1.79 \cdot 10^{-2} I + 0.49.$

Other, more sophisticated formulas have been developed since then, based on this equation from Thornthwaite. Given the data of potential evapotranspiration PET and the yearly rainfall, it is possible to estimate the water balance for each month; the Thornthwaite Moisture Index can then be calculated as:

$$TMI = \frac{100S - 60D}{PET}$$

where S is the sum of monthly water surplus during a year and is equal to the precipitation minus the actual evapotranspiration, and D is deficit, and is equal to the potential evapotransiration PET minus the actual evapotranspiration (Austroads, 2004). The TMI is used by Austroads to evaluate the present situation of subgrade moisture in Australia and the likely changes in subsurface moisture content in the future, and its consequences on the roads' life expectancy; Fig. 11 shows a map of the actual state in Australia. The same use can be hypothesised for the P2R2C2 research.

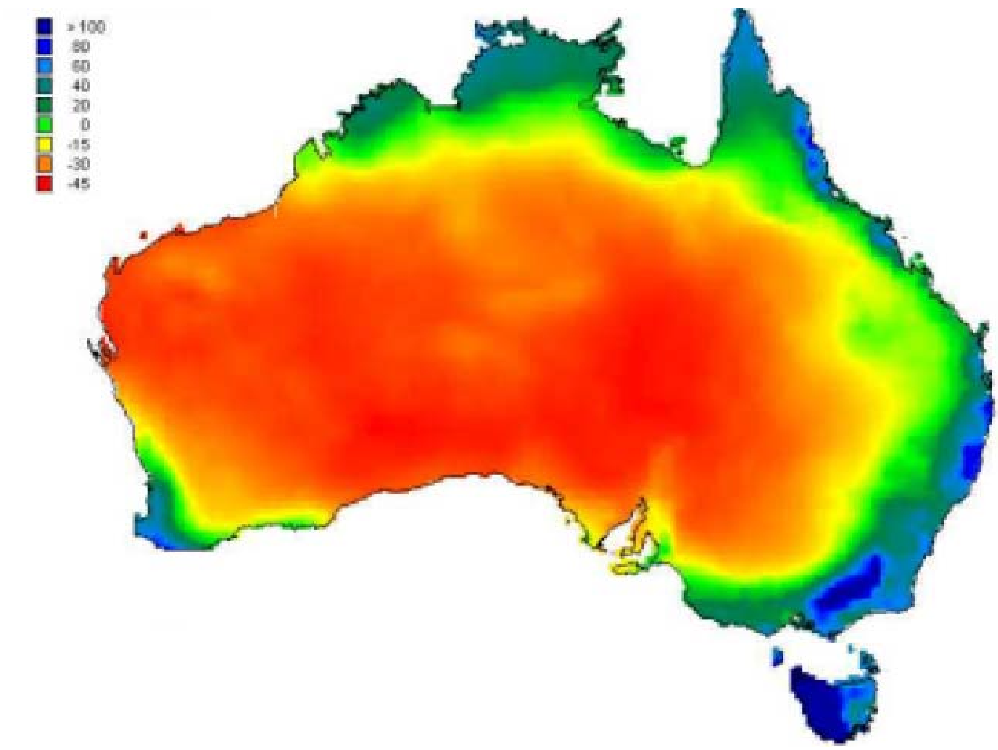

Fig. 11: Thorthwaite Moisture Index map of Australia referred to 2000 (Austroads, 2004). TMI > 100 = hyper-humid environment, 20 to 100 = humid, -20 to 20 = sub-humid, -40 to -20 = semiarid, -60 to -40 = arid environment.

Because of its strong dependency on moisture content, the resilient modulus can vary considerably with the weather and the season. In the pavement design process, a range of different values should be used in order to obtain a good estimation of the pavement life. A way to avoid this is to use a weighting factor, as Guan et al. (1998) suggest. The weighting factor can be obtained in two ways: through laboratory tests, by measuring the modulus of the subgrade soil for the range of moisture content values that is most probable to be encountered on site in different seasonal conditions; or performing non-destructive field tests in over different season, in which case the resilient moduli will be back-calculated. Then, only the modulus corresponding to a "design season", that is the season of the year that represents the equivalent damage for the pavement over the whole year, will be used in the model. If the design takes into account the maximum, or minimum water content, the result will be an over-estimation, or under-estimation, of the real situation, with consequent excessive costs, or, vice-versa, reduced life. The same concept of the weighting factor was previously used to quantify the effects of seasonal change on the pavement temperature (Gomez-Achecar & Thompson, 1984). An equation was proposed by them: for a given month,

$$WF_i = N_f / N_{ai}$$

where f is the number of years before failure, N_f is the number of load repetitions to failure under normal conditions and N_{ai} is the allowable number of load repetitions under the prevailing conditions of a given month. N_{ai} can be derived from the transfer functions of any failure criteria, and N_f can be calculated as

$$N_f = \frac{12}{\sum_{i=1}^{12} N_{ai}}.$$

This concept of weighting factor was applied by Heydinger (2003), who derived an equation for resilient modulus as a function of saturation level and deviator stress:

$$M_r = 77235.54 - 639.1\ S(\%) - 5418.3\ \sigma_d$$

and the weighting factor for each month WF_i, used to compute the weighted mean annual resilient modulus, can be calculated as:

$$WF_i = \frac{12 M_{Ri}^{-2.32}}{\sum_{i=1}^{12} M_{Ri}^{-2.32}}$$

where M_{Ri} is the average resilient modulus for each month.

The same concept of multiplying factor, but applied to the thaw problem, was used by Ullidtz and Larsen in 1983. The authors published a model that predicted the performance of flexible pavements, in terms of roughness, rutting and fatigue cracking, as a function of climatic conditions and traffic loading, based on the performance of a pavement discretised into 0.3m sub-sections. The variations in the layer thicknesses and material properties between sub-sections were described by two autocorrelation coefficients for each variable. What is interesting is the way they handle the thaw: first of all, because the damage caused by frost melting is almost negligible compared to that caused by thawing, they consider only the latter. This is done by multiplying the modulus of the unbound material by a factor R that corresponds to its frost sensitivity, and that is purely empirical:

$$R = [1- (1-R_0)] \cdot e^{A \cdot U}$$

where R_0 is the minimum factor corresponding to the week of thaw and is function of the soil type and freezing index value, A is a negative constant and U the number of weeks passed after the week of the start of the thaw.

8.2 *Simulation Modelling of water movements below pavement surface*

Alonso (1998) presents a model for the coupled analysis of transfer processes (*water and heat*) and stress-strain behaviour of unsaturated compacted soils based on in-situ measurements. This model has then been applied to make a full simulation of a modern pavement structure in a Mediterranean climate. The same author (Alonso et al., 2002) presented also an analysis of the best position and depth of longitudinal drains in pavements for three different climates: Tropical, Mediterranean and Sub-alpine. The model was based on actual data involving rainfall, temperature and relative humidity records. Five years of climate were simulated; the reaction of the selected pavement structure and drainage position were computed. Figure 12 shows some of the results: the addition of longitudinal drains has an important effect on the granular base and sub-base saturation over time, whereas their effect on the subgrade (Figure 13) was found to be of minor extent. Longitudinal drains are able to maintain a well drained subgrade layer in Mediterranean climates, but their effect was found to be more limited in sub-alpine or tropical climates.

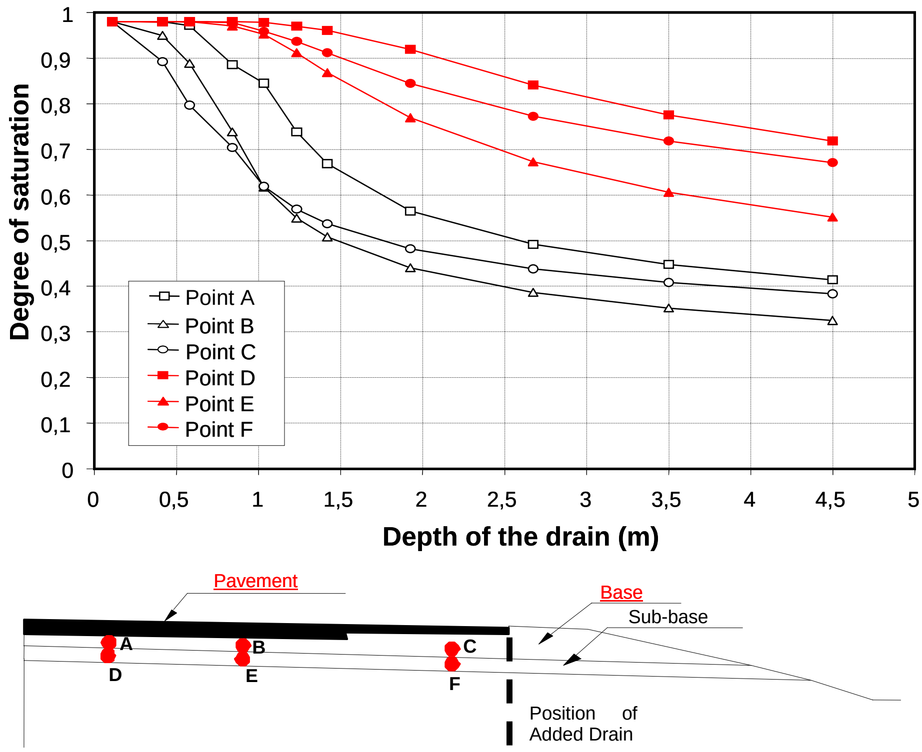

Fig. 12: Degree of saturation obtained when a drain is installed at the pavement – shoulder contact (Alonso et al., 2002).

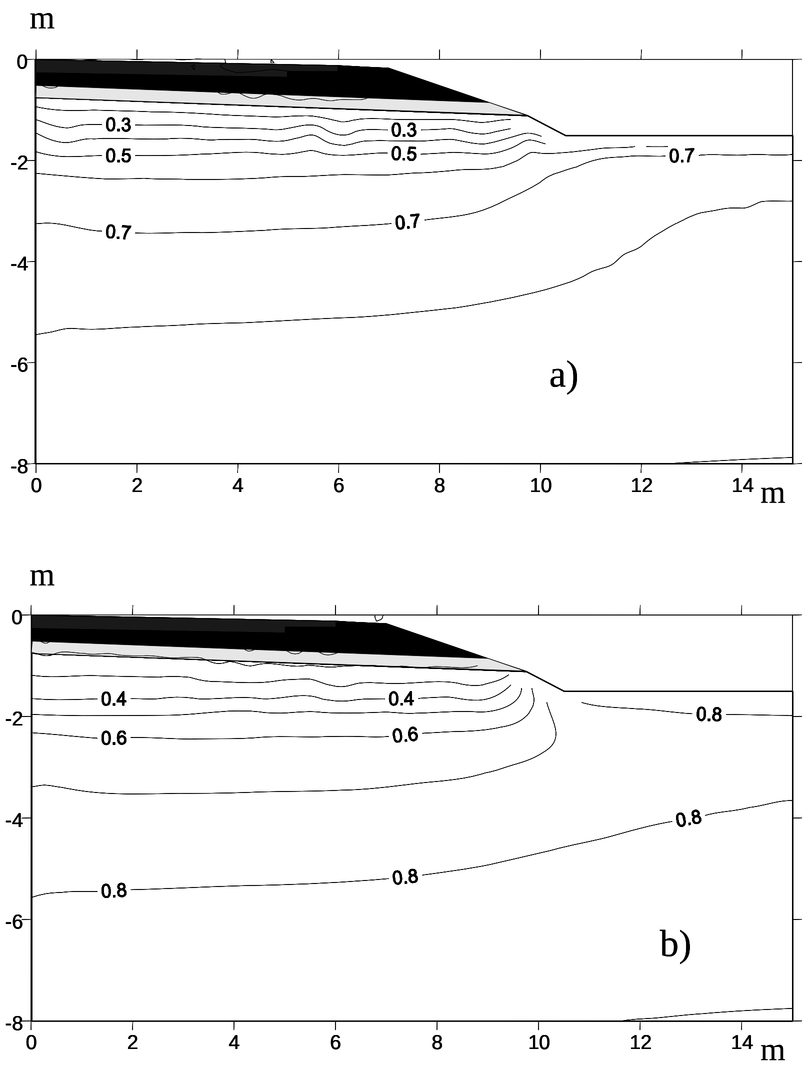

Fig. 13: Distribution of degree of saturation in a Mediterranean climate. Evaporation through pavement allowed; a) 1st July, b) 1st December (Alonso et al., 2002).

8.3 Simulation of rainfall water percolation

Hansson et al. (2005) used a two-dimensional model to illustrate the effect of a rain shower through a *fracture zone* on the subsurface. The material properties used to model the various layers of road fulfil the requirements of the Swedish road design guide. The main peculiarity of the model is the presence of “a fracture zone” where the asphalt layer had plenty of fractures over a relatively short distance (thus, an equivalent homogeneous porous media model could be used). The results (fig. 14) show that the fracture zone captures almost all the surface runoff in case of a light rainfall event as suggested earlier in section 4.2. The heavier rainfall will infiltrate much more in the road shoulder since the infiltration capacity of the fracture zone, or the granular base layer beneath it, was exceeded. As a consequence, the region of the roadside where both rainfall and surface runoff infiltrated was considerably expanded laterally. This result is qualitatively supported by the findings of Flyhammar & Bendz (2003) who measured concentrations of various solutes in the shoulder and beneath the asphalt cover in a Swedish road partly built with alternative materials, generated from waste and residuals.

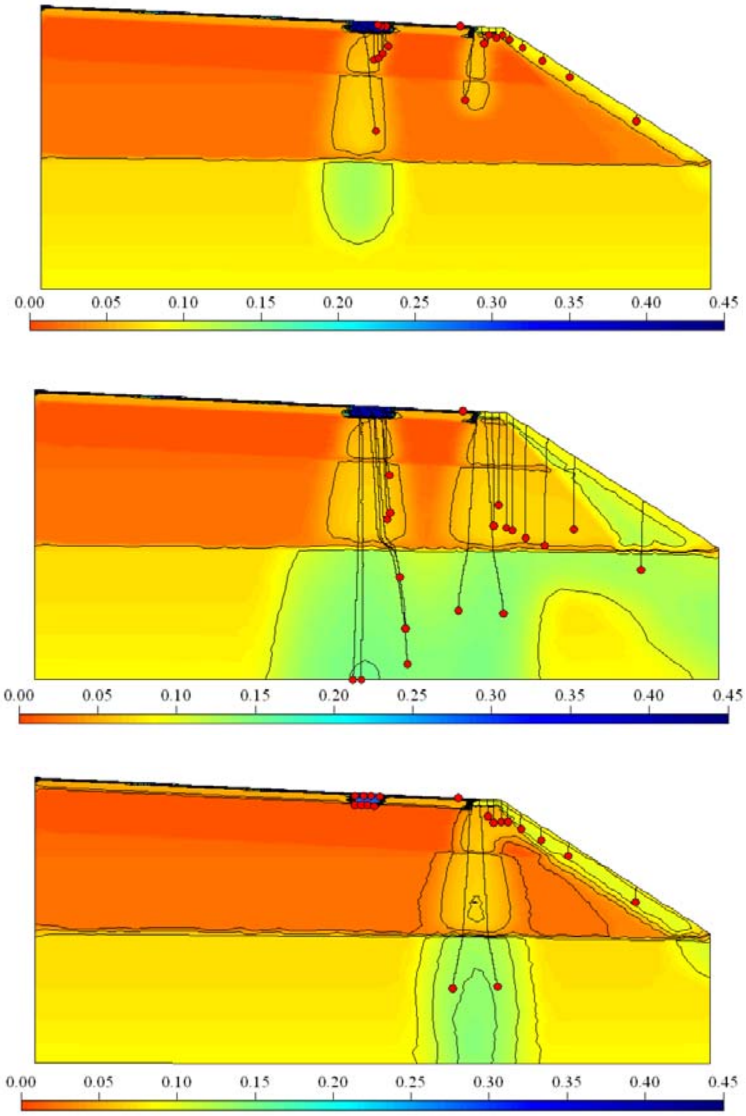

Fig. 14: The simulated volumetric water content after a light rainfall event (top), after a heavy rainfall event (middle) and after a moderate rainfall event using low fracture-zone permeability (bottom). The red dots indicate the flow paths of the infiltrated rainwater. The vertical scale is exaggerated for clarity (Hansson et al., 2005).

8.4 Simulation of pavement response at different water contents

An example of modelling of the resilient behaviour of pavements comes from the French pavement laboratory, LCPC, who developed a finite element program called CVCR, which is a part of the finite element code CESAR-LCPC (Heck et al., 1998; Heck, 2001). This program allows the modelling of the response of pavements in 3D. An application of CVCR is given by Hornych et al. (2002), who tried to model a low traffic pavement with a granular base, tested on the LCPC pavement test track, in order to simulate experimental pavement response for different load levels and different water contents of the unbound granular material. The experimental pavement structure was equipped with:

- strain gauges to measure longitudinal and transversal strains at the bottom of the asphalt layer;
- displacement transducers to measure vertical strains in the top 100 mm of the granular layer and of the subgrade;
- vertical pressure transducers at the top of the subgrade;
- thermocouples in the asphalt layer; and
- tensiometers, to measure suction in the granular base and in the subgrade.

The pavement was subject to dual wheel loads. Different load levels (45, 65 and 75 kN), and different loading speeds (3.4 to 68 km/h) were applied during the experiment. A series of calculations was performed for the 3 load levels and 3 moisture contents of the unbound granular material (w = 2.3, 3.8 and 4.8 %), at a constant loading speed of 68 km/h. The model was able to predict relatively well the strains in the granular layer and their non-linear increase with load level, while the strains in the bituminous layer were slightly over-predicted. The results showed that the water content of the granular layer has a strong influence on the vertical strains in the unbound granular material layer, in fact an increase of moisture content from 2.3 to 4.8% led to an increase of the strains by about 60 % (see fig. 15).

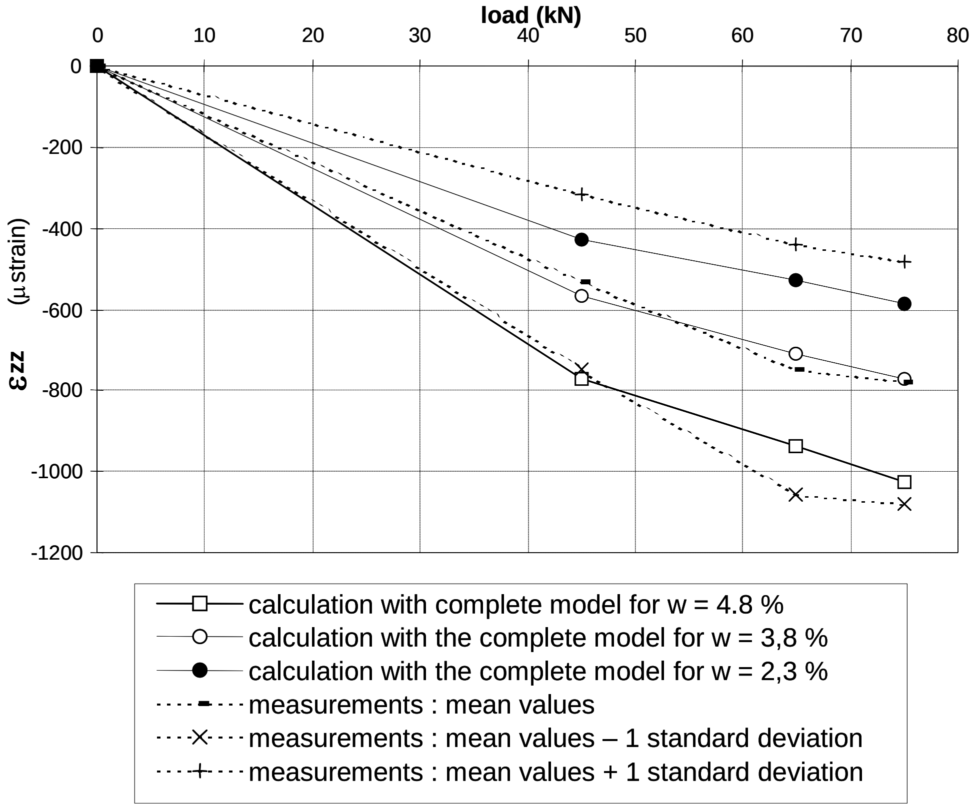

Fig. 15: Comparison of experimental and predicted maximum vertical strains at the top of the granular layer for 3 load levels (Watmove, 2008).

8.5 Simulation of pavement response in freezing and thawing conditions

A quantification of the contributions of the thawing-related factors that affect road degradation is still poor despite its importance to many pavements in Northern Europe. Deterioration models are essential in order to support pavement design and management methods, but the present information is almost only based on empirical considerations. In cold climate countries, usually, thawing is taken into account in pavement design by means of site-specific measurements and calculations to be compared with threshold values. Although some more sophisticated criteria do exist, they do not always allow quantification of life expectancy. A method to overcome these problems is proposed by Doré et al. (2002). This method for the verification of pavement structures with respect to the effects of freezing and thawing is based on an iterative procedure made of four steps. Once a preliminary structural design, based essentially on traffic considerations, is ready, the first step consists of calculating the mechanical and thermodynamic response (which means frost penetration and moisture distribution during and after thawing) of the pavement structure using site observations or models. An evaluation of life expectancy of the road with such characteristics is step 2. In the third step, it is evaluated whether such a design meets the expectation, and, in case of a negative response, the fourth step of the procedure is a decision tree suggesting improvements to apply to the pavement structure. This process is summarised in fig. 16.

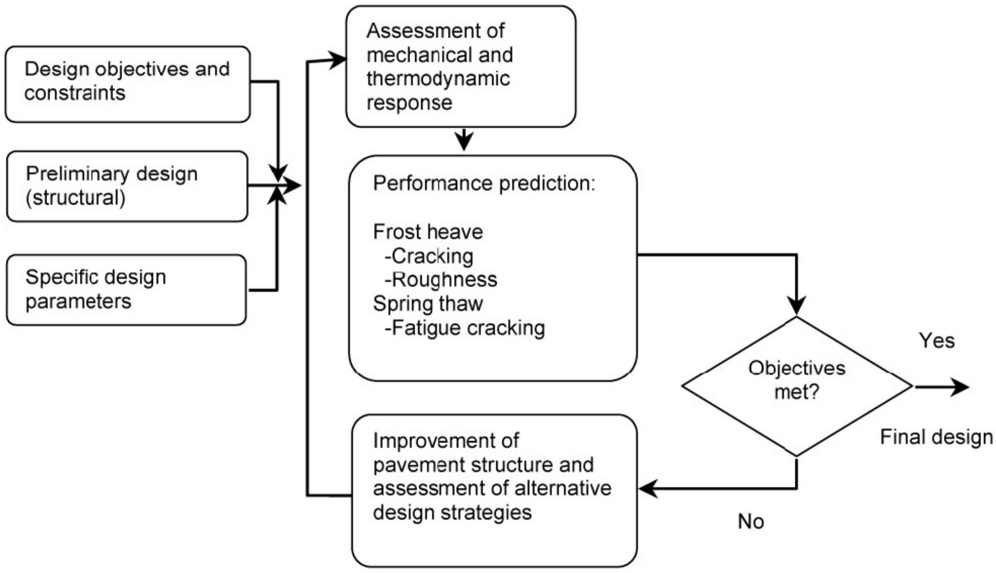

Fig. 16: Scheme of the so called “ADAAGE” procedure for the verification of pavement structures in freezing and thawing conditions (Dore’ et al., 2002).

Models were developed based on physical principles and experimental observations. The models that represent pavement performance in freezing and thawing conditions are:

Performance during freezing:

- Transverse differential heaving model (describing the cracking due to uneven subgrade freezing with consequent higher heaving in the centreline, fig. 17)
- Winter roughness model (caused by longitudinal differential heaving, fig. 17)

Spring thaw related performance:

- Fatigue cracking model (taken into account by a mechanistic-based approach using a linear elastic analysis program combined with an empirical fatigue model)
- Permanent deformation model.

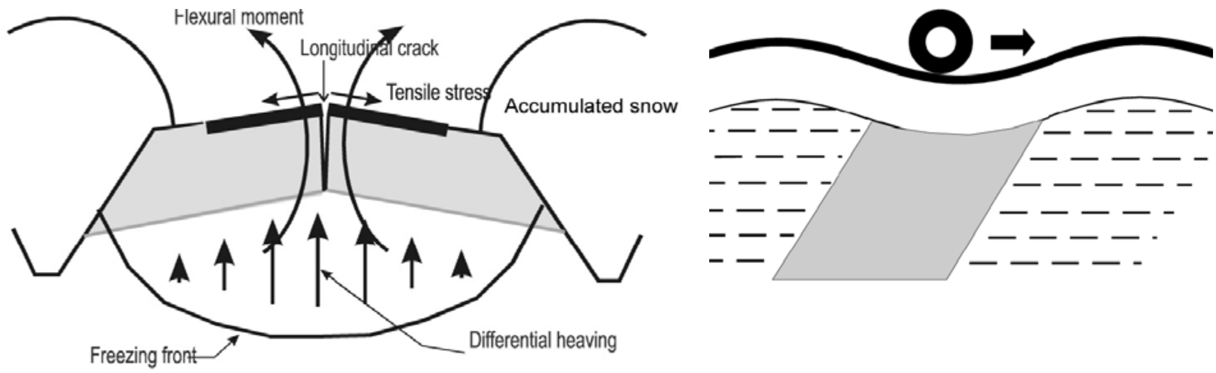

Fig. 17: Transverse and longitudinal differential heaving mechanism (Doré et al., 2002).

However, so far the method has been validated over a limited number of pavement sections of the Quebec road network, and data still need to be collected on a large number of pavement sections in order to make it more reliable.

A model able to cope with both frost heave and thaw settlement is proposed by Simonsen et al. (1997) and is called FROSTB. This model, based on coupled mass and heat transfer, was developed by the U.S. Army Cold Regions Research and Engineering Laboratory. Unsaturated hydraulic conductivity was an issue: in this regard, a database based on field measures and laboratory data was developed. Frost heave was set to occur for saturation levels over 80%. The results, compared with experimental data taken from an instrumented test road (for the results, see report No. 1), show a very good prediction of soil temperature and a fair prediction of soil moisture content during the freezing and thawing periods. An example of the results is shown in figure 18: temperatures at 15, 46 and 107 cm were simulated and compared with the measured ones.

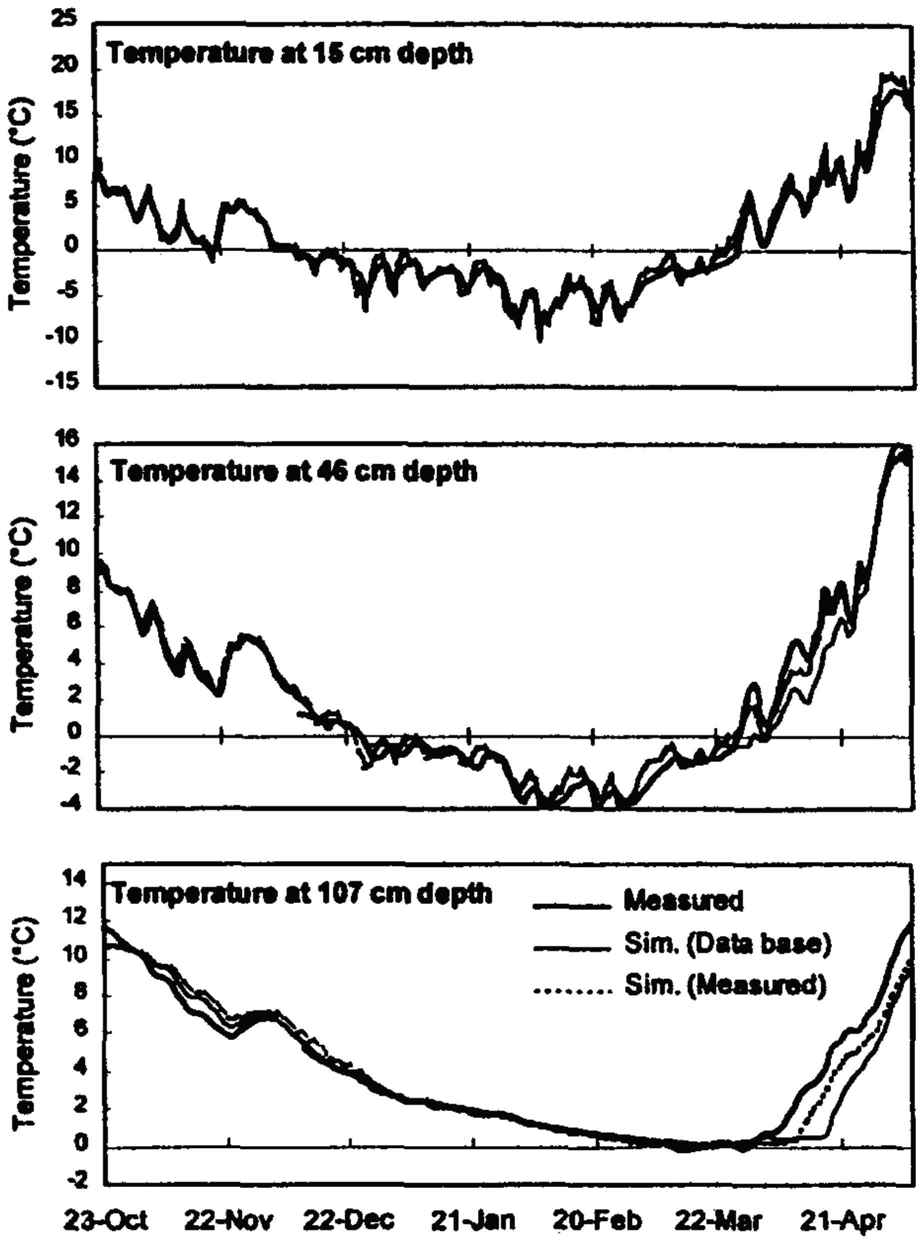

Fig. 18: Measured versus predicted temperatures (Simonsen, 1997).

8.6 Artificial Neural Networks for water infiltration modelling purposes

The use of Artificial Neural Networks (ANN) based models is becoming more end more extended and developed. ANNs are very powerful tools that allow the study of complex systems, such as those involving the external interactions with a road can be, and they usually work well in those areas where conventional models do not. They are often used in situations in which there is insufficient knowledge of the system. The name derives from the way the system works: in fact, the idea is to simulate a real neural system logic-based, where a network of simple processing elements (neurons), interacting among them, can exhibit a complex global behavior, determined by the connections between the processing elements and element parameters. As the network runs, every connection gains, with time, a different “weight” according to its importance, in order to reproduce the expected output.

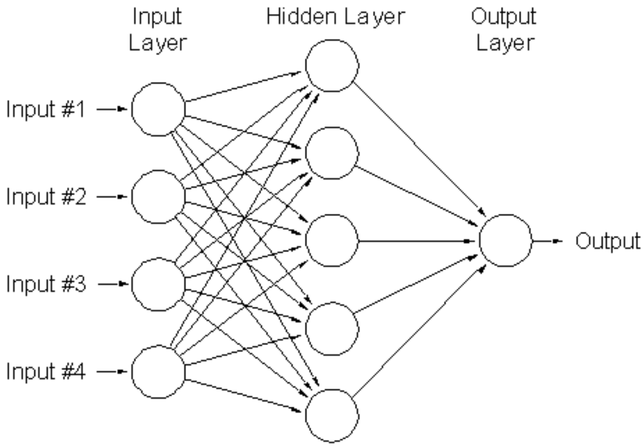

Fig. 19: Scheme of an ANN (http://smig.usgs.gov/SMIG/features_0902/tualatin_ann.fig3.gif).

Miradi (2004) employs different ANNs to predict raveling due to water infiltration into the pavement. As initial inputs, the author used data regarding climate and traffic from a porous road, and the results showed a very good prediction of the ravelling measured in such road. Results of the ANN models illustrate which parameters are more significant in development of ravelling, how these parameters interact with each other and in which conditions they are most likely to cause ravelling. The results showed that the contribution of warm days is the highest and rain fall precipitation the lowest (4% of the contribution). Cold days contribute for the 14% in raveling severity and traffic percentage up to 14%. Age contributes rarely more than 10%. All the weather factors seem to contribute for up to 57%. The author also analyzed how the parameters interact with each other for different severity levels of raveling by means of an ANN model called QNET. The results showed that the older the asphalt is, the more sensitive it becomes to cold days which lead to raveling, while roughness becomes significant when the thickness is more than 60 mm.

9 Drainage solutions

It is clear that the presence of water within the road structure, together with heavy traffic, is one of the main factors responsible of road deterioration. Even a relatively small increase in moisture level can lead to significant reductions of the road constituents' physical and mechanical properties and performance.

All the problems connected with an excess water pressure within the road structure can be much reduced, and in many cases even avoided, if the infiltration through the pavement surface is decreased and diverted through a proper drainage system. Drainage systems have two main purposes:

- To cut-off the arrival of groundwater at the pavement and
- To provide an exit route for water already in the pavement towards natural groundwater patterns.

The drainage system employed on a road needs to be chosen based on:

- The importance of the road,
- The amount of traffic,
- The sensitivity of groundwater,
- The sensitivity of the lakes and rivers in the surrounding zone.

To achieve a good drainage, a layer of highly permeable material that connects to a functioning drain is necessary to allow a good drainage and thus reduce the period that the subgrade is exposed to high levels of moisture content. This can be an untreated or treated base. If the base is untreated, the aggregate used is usually smaller in order to have a higher stability; if the base is, instead, treated with a stabiliser, it can have a higher permeability because it is the stabiliser that assures a better stability, and thus the material can be more open-graded.

The bigger the drainage system is, the more water can flow away, the better the drainage is. Sometimes a small increase in the dimension, and thus in the price, of the drainage pipes gives a much larger benefit and a much longer life for the road. Ridgeway (1976) suggests that, only for rainfall infiltration, the drainage system should be able to drain an amount of water that can be calculated as (for asphalt pavements):

$$Q = 0.1\ [N + 1 + (W/40)]$$

where Q is the amount of infiltration (cm^3/h/cm of pavement), 0.1 (cm^3/h/cm of crack) is a factor corresponding to the infiltration rate, N the number of lanes, and 40 (cm) is the evaluation of the average distance between transverse cracks.

However, in order to obtain a good drainage, not only the drainage pipes' capacity is important. The first practical precaution that needs to be taken during road design is the road's horizontal and vertical alignment: this must be chosen in a way that water can be moved from the surface to a desired outlet point where the impacts are minimised, i.e. where the proper drainage system is.

The drainage system can be on the surface, as, for example, a ditch or an open channel on the sides of the road, or in the subsurface, where a trench or pipe collects the water that is conveyed there from the porous ground. The surface drainage system is more suitable to deal with water that flows away from the pavement surface without infiltrating, while subsurface drainage collects the water that infiltrates from the surface and the groundwater. Although the open drainage systems are less expensive and require easy maintenance, they are more subject to erosion problems (fig. 20) and can affect road cracking. Subsurface drains are more susceptible to clogging and blockage. However, it is quite common to have a combination of the two drainage systems.

The choice of the drainage depth depends on the pavement thickness, the road layout (cutting or embankment), the type of soil (especially its permeability) and the climatic conditions that regulate the potential amount of water the road can be subject to. To avoid that rainfall-runoff infiltrating beneath the road can continue as a sub-horizontal subsurface flow, thus reducing the bearing capacity, subsurface drains must be able to intercept such water, and thus must be inserted in the high permeability zone, just above impermeable material. This depth is usually more than 1m. The depth is however strictly connected to the permeability of the subsoil.

Fig. 20: Excessive runoff, due to heavy rainfall, eroding the top of a drain
(Watmove project, 2008).

It is rather common to provide a permeable, granular subsurface layer, at least 10-15 cm thick and extended under the full width of the road, in order to collect the water infiltrating and convey it to the drainage system. The thickness of this layer and its permeability is imposed by the infiltration rate, i.e. by the fact that it has to be capable of containing even the largest amount of water infiltrating during the heaviest rains. A narrow-graded, coarse soil is highly permeable, and this helps drainage. Beneath this porous layer, another impervious material will make sure that water does not infiltrate more in depth.

In colder climates, deep drains are used to intercept the flow of the groundwater and thus contrast the local frost damage; the depth at which they are usually placed corresponds to the “frost depth”.

However, as Birgisson and Ruth (2003) suggest, sometimes it is not sufficient to have a proper drainage design, but rather site inspections and detailed investigations during the road construction are necessary to accommodate the drainage system to all the unforeseen conditions that are encountered.

10 Conclusions and implications

It is believed that about 80% of road distresses and pavement damages are related to the presence of excess water, water that affects the behaviour of all layers – bound asphaltic material layers, granular layers and subgrades.

The expected life of a road can be influenced significantly by the subgrade's resilient modulus, and this can be strongly affected by the presence of water. The soil is usually in a partially saturated condition, and suction contributes to the soil's strength. If the water content increases, the suction decreases until it disappears, and, in saturated conditions, the soil can experience a large loss of strength. To avoid accumulation of water below the pavement, the lower layers of the pavement must be permeable and connect to a drainage system, so that any water that infiltrates from the surface and from the lateral shoulder slopes and verges can exit as quickly as possible. The drainage system should also assist water from exiting the subgrade, although its ability to do this will be limited by the permeability of the subgrade soil.

Water can pass through the asphalt layer and reach the subbase in two ways: through the voids present in the asphalt, and through the cracks and joints. Water that passes through the air voids depends on the permeability of the pavement, and thus it is related to the grading curve of the aggregate used, to its compaction level and to the proportion of bitumen used (high volumes will fill voids better). Unless it is porous asphalt, asphalt is usually considered almost impermeable, whereas porous asphalt is characterised by a very high air void volume (about 20%), and designed with the purpose of letting water flow through.

The presence of cracks in the asphalt surface can supply large quantities of water to the lower layers, and potentially, for a road in conditions that need intervention, all the rainfall can infiltrate through the cracks. The intensity of rainfall is important only until the maximum pavement crack capacity is reached. Beyond such a point the duration of the rainfall becomes more important than the intensity. The presence of water in the pavement surface tends to increase oxidation, and thus ageing, of the bonding matrix, which in turn becomes more brittle; the consequences are stripping, ravelling and an increase in cracks. It has been shown by Chen et al. (2004) that, for cracks with a width larger than 2 mm, permeability increases suddenly, with serious problems for the subgrade strength. However, asphalt deterioration, crack formation and their dependency on water condition is not completely clear yet, and therefore will need some research during the present project.

Other than percolating through the surface, water can reach the subgrade by migrating from lateral shoulder slopes and verges, or by seepage from the groundwater. The relative importance of the different phenomena and routes depends on the materials involved, the climate and the topography of the terrain. As the subgrade weakens because of the presence of water, rut propagation takes place at much lower numbers of passes and the total deformation tends to increase almost exponentially for levels of saturation above 85%.

The presence of water in the subgrade is even more important in cold climates when the pavement temperature passes from negative values to temperatures close to zero, and the soil starts to melt; in those times of the year, thawing can develop, that makes the soil particularly weak and the road vulnerable. At temperatures below zero, water freezes, thus increasing the road stiffness, but frozen water below the road can also lead to non-uniform heave, with consequent road roughness and driving discomfort. Frost heave depends to a large extent on the grading of the soil, and is commonly related to the presence of fines that do not allow fast drainage but which do permit sufficient permeability for water to be drawn from an adjacent water source towards the freezing front by cryo-suction effects. Thawing is a typical phenomenon that occurs during spring in cold climate regions, but because of the increasing tendency of the temperatures, it tends to appear earlier in the year and, often, also during warm winter days. Some regions, traditionally suffering from intermittent freezing (e.g. UK, northern France, Belgium, Netherlands, northern Germany, Denmark) are expected to benefit, in this respect, under climate change with frost penetration (and, thus, thaw problems) being reduced.

Pavements with thick asphaltic layers transmit less stresses to the soil underneath and are less affected by cracks through the whole depth, and thus are less sensitive to moisture changes. A study of the extent to which the asphalt thickness relates to the sensitivity to moisture content needs to be addressed during the P2R2C2 project, and this will be done by means of models. The hypothesis of changing the present guidelines will then be taken into consideration. Also the sensitivity to moisture change of the material beneath the surface will need to be investigated, and this will be done mainly with laboratory tests.

However, a lot of work has already been done in the past regarding the study of the pavements' mechanical behaviour in relation to moisture content, and can be found in the literature. The most frequently used instrument to measure pavement capacity *in-situ* is the Falling Weight Deflectometer (FWD). Based on field data, some analytical studies on the relationship between water and pavement performance have been performed in previous researches.

Experimental field and laboratory data have allowed the development of models aimed at describing the various aspects of the water infiltration/road performance relationship. Among these, Alonso (1998) presented a model that simulates water movement below the pavement surface and in the presence of drains, and the results showed that the addition of longitudinal drains has an important effect on the granular base and sub-base saturation over time, whereas their effect on the subgrade was of minor extent. Hansson et al.'s (2005) simulation of rainfall percolation into cracks showed that a fracture zone in the main part of the pavement can capture almost all the surface runoff in case of light rainfall event. In the case of heavier rainfall, more water infiltrated into the road shoulder since the infiltration capacity of the pavement-edge fracture was exceeded. Heck (2001) modelled the response of a pavement at different water contents, and found that an increase of moisture content from 2.3 to 4.8% led to an increase of the strains by about 60 %.

Frost heave and thaw weakening are phenomena particularly difficult to model, due to the complex processes involved. Nonetheless, some attempts have been successfully made. One of them is the FROSTB model (Simonssen et al., 1997), and the results showed a good prediction. Finally, worth mentioning are the so called Artificial Neural Networks' based models that have been developed in order to model water infiltration.

As the presence of water within the road structure is one of the main factors responsible for road deterioration, good drainage is very important. This can be achieved mainly:

- with a granular layer at the bottom of the construction that is permeable enough to drain water as quickly as possible;
- with a drainage pipe system of adequate capacity and having adequate falls to outlets;
- with a proper road surface shape, able to let rainfall water flow away and not infiltrate.

Different drainage systems will be investigated during the P2R2C2 project.

References

Alonso E., (1998). “Suction and moisture regimes in roadway bases and subgrades”. Proc. International Symposium on Subdrainage in Roadway Pavements and Subgrades, Granada, Spain, pp. 3-56 & 57-104.

Alonso, E.E., Cañete, A. & Olivella, S., (2002). “Moisture transfer and deformation behaviour of pavements: effect of climate, materials and drainage”. Proc. 3rd International Conference on Unsaturated Soils, Recife, Brazil, 2, pp. 671-678.

Austroads Incorporated (2004), “Impact of Climate Change on Road Infrastructure”. www.austroads.com.au .

Birgisson, B. and Ruth, B., (2003). “Improving performance through consideration of terrain conditions”. Transportation Research Record 1819, TRB, National Research Council, Washington, D.C., 2003, pp. 369-377.

Brown, E.R., Collins, R & Brownfield, J.R., (1989). “Investigation of segregation of asphalt mixtures in the State of Georgia”. Paper presented to 68th Annual Meeting of Transportation Research Board, Washington DC.

Cedergren, H.R. & Godfrey, K.A., (1974). “Water: key cause of pavement failure”. Civil Engineering, pp. 78-82.

Chen, J., Lin, K., Young, S., (2004). “Effects of crack width and permeability on moisture-induced damage of pavements”. J. of Materials in Civil Eng., 16, 3, pp. 276-282.

Cooley, L.A., Jr., (1999). “Permeability of Superpave Mixtures: Evaluation of Field Permeameters”. National Center for Asphalt Technology, Auburn University, NCAT Report No. 99-1, February.

Doré, G., Riuox, N., Pierre, P., (2002). “Development of a rational design procedure for pavements subjected to frost action”. 9th Int. Conf. on Asphalt pavements, Copenhagen, TRB.

Doré G., Droiun P., Pierre P., Desrochers P., (2005). “Estimation of the relationships of road deterioration to traffic and weather in Canada”. Final report, BPR reference: M61-04-07 (60ET). Available: http://www.tc.gc.ca/pol/en/Report/FullCostInvestigation/Road/r004/r004.pdf .

Eigenbrod K.D. & Kennepohl G.J.A., (1996). “moisture accumulation and pore water pressures at base of pavements”. TRB n. 1546, pp. 151-161.

Erlingsson, S., (2000). “Dynamic triaxial testing of unbound base course materials”. Proc. XIII Nordic Geotech.l Conf., NGM 2000, Finnish Geotechnical Society, Helsinki, pp. 69-76.

Gomez-Achecar M., Thompson M. R., (1984). “Mechanistic design concepts for full-depth asphalt concrete pavements”. Civil Engineering studies, Transportation Engineering Series n. 41. Unversity of Illinois.

Guan, Y., Drumm, E.C., and Jackson, N.M., (1998). "Weighting Factors for Seasonal Subgrade Resilient Modulus." TRB Session on Resilient Modulus, Transportation Research Record 1619, TRB, National Research Council, Washington, D.C., 1998, pp. 94-101.

Hansson, K., Lundin, L-C. & Siminiek, J., (2005). “modelling water flow patterns in flexible pavements”. Transportation Research Record 1936, TRB, National Research Council, Washington, D.C., pp. 133-141.

Haynes, J.H. & Yoder, E.J., (1963). “Effects of repeated Loadings on gravel and crushed stone base course materials used in the AASHTO Road Test”. HRB, National Research Council, Washington D.C., pp. 82-96.

He, Z., Kennepohl, G., Cai, Y. and Raas, R., (1997). “Development of performance models for Ontario’s new Mechanistic-Empirical pavement Design method”. Vol. 1, Proc. of the 8th

International Conf. on Asphalt Pavements, Seattle, Washington, pp. 43-60.

Heck, J.V., Piau, J.M., Gramsammer, J.C., Kerzreho, J.P. & Odéon, H., (1998). “Thermo-visco-elastic modelling of pavements behaviour and comparison with experimental data from the LCPC test track”. Proc. 5th Conference on Bearing Capacity of Roads and Airfields, Trondheim, Norway, July.

Heck, J.V., (2001). “Module CVCR version expert”. Documentation du code de calcul César-LCPC.

Hornych, P., Kerzrého, J.P. & Salasca, S., (2002). “Prediction of the behaviour of a flexible pavement using finite element analysis with non-linear elastic and viscoelastic models”. 9th Int. Conf. Asphalt Pavements, Copenhagen, August.

Kameyama, S., Kato, M., Kawamura, A., Himeno, K. and KasaharaA. (2002). “Effects of Frost Heave on the Longitudinal Profile of Asphalt Pavements in Cold Regions”. 9th Int. Conf. Asphalt Pavements, Copenhagen, August.

Kolisoja, P., Saaranketo, T., Peltoniemi, H., Vuorimies, M., (2002). “Laboratory testing of suction and deformation properties of base course aggregates”. Transportation Research Record 1787, Transportation Research Board, Washington, DC., pp.83-89.

Kringos, N., (2007). “Modeling of Combined Physical-Mechanical Moisture Induced Damage in Asphaltic Mixes”. PhD dissertation, Delft University Press.

Kringos, N. & Scarpas, A., (2004,). “Development of a Finite Element Tool for Simulation of Ravelling of Asphaltic Mixes”. Proc. 2004 Int. Conf. Computational & Experimental Eng. & Sciences (ICCES ' 04), Madeira, Portugal, July, Tech Science Press, in CD ROM

Liu, S.J. & Lytton, R.L., (1984). “Rainfall infiltration, Drainage, and Load-carrying Capacity of Pavements”. Transportation Research Record 993, Transportation Research Board, Washington, DC., pp.28-35.

Miradi, M., (2004). “Neural Network models for analysis and prediction of raveling”. Proc. Of the 2004 IEEE Conf. on Cybernetics and Intelligent Systems. Singapore, 1-3 Dec..

Moris, P.O. & Gray, W.J., (1976). “Moisture conditions under roads in the Australian environment”. Australian Road Research Board. Research Report, ARR No. 69.

Ragab, R., Rosier, P., Dixon, A., Bromley, j. & Cooper, D., (2003). Experimental study of water fluxes in a residential area: 2. Road infiltration, runoff and evaporation”. Hydrol. Process. 17, pp. 2423-2437.

Ridgeway, H.H., (1976). “Infiltration of Water through the Pavement Surface”. Transportation Research Record 616, Transportation Research Board, Washington, DC., pp.98-100.

Simonsen, E., Janoo, V.C., Isacsson, U., (1997). “Prediction of temperature and moisture changes in pavement structures”. Journal of Cold Regions Engineering, Vol. 11, No. 4, pp. 291-307.

Taylor, J.V., (2004). “Migration of Contaminants Associated with Pavement Construction”. PhD thesis, School of Civil Engineering, University of Nottingham.

Thornthwaite, C.W., (1948). “An Approach Toward a Rational Classification of Climate”. The Geographical Review, pp.55-94.

Ullidtz P., Larsen B.K., (1983). ”Mathematical model for predicting pavement performance.” TRR, Vol. 949, pp. 45–55.

Vivar, E. & Haddock, J.E., (2007). “Hot-Mix Asphalt Permeability and Porosity”. Paper to 82nd Annual Meeting of Association of Asphalt Paving Technologists, San Antonio, Texas.

Watmove team, Dawson A. editor (2008). “Water in road structures – movement, drainage & effects”. Springer, XXVI, 438.

Wiman, L., (2001). “Accelerated Load Testing of pavements, HVS-Nordic Tests in Sweden 1999”. VTI report 477A-2001; available at: http://www.vti.se/templates/Page____3250.aspx .