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Alternative materials and methods to enhance resistance to climate change

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Project Coordinator
University of Nottingham, UK

ZAG, Slovenia

VTT, Finland

SINTEF, Norway

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Authors:
Alessandra Carrera, University of Nottingham
Andrew Dawson, University of Nottingham

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1 Introduction

The study of the influence of climate change on the pavement structure, performed in the first part of the current project, highlighted the strong correlation between temperature and rainfall changes and the pavement performance. In particular, the temperature is likely to rise in the future, and extreme temperatures will occur more often; the consequences will be observed mostly on the surface of the road, the most important of which will be the increase of rutting and the ageing-related increase in brittleness and eventually in cracking. Also rainfalls are likely to change; for the central-northern part of Europe, although the predictions show that the average quantity of water might not change substantially, extreme events such as storms will be more likely. The presence of high quantities of water that storms can bring, leads to a loss of substructure strength, but also to stripping, fatigue cracking, faulting, pumping and so on (see Reports 1 and 5).

For the surface course, the reasons that cause its deterioration are, apart from the loading caused by traffic, basically always climate related, independently of the climate change. Thus, all the research made nowadays is aimed at creating asphalts less and less influenced by climate and, generally speaking, more resistant to external factors. Less research has been made concerning the subbase material, which, therefore, needs more attention.

This report shows a summary of the alternative ways and materials that can be used in order to reduce the negative effects of climate on the road, with particular attention to the subbase layer. The influence of the temperature on this layer, at least for temperatures constantly above zero, is sensibly minor compared to its influence on the surface course, and for this reason temperature will be only partly covered in this study. When temperatures go below zero, problems related to the freezing-thawing phenomenon may arise; these are treated in W.P. 2.3. The main problems treated in this report will be, therefore, how different types of alternative base and subbase materials can reduce the influence of water on the strength.

2 Literature review – pavement surface modification to withstand temperature and moisture changes

In Table 1, below, taken from Doré & Pierre (2003), are listed the most common road damages that can be caused by climatic factors and their possible solutions.

Anticipated problem	Predicted life	Proposed solution (new pavement)	Proposed solution (existing pavement)
Longitudinal cracking	Close to the objective	1) Increase subbase thickness 2) Increase width of lane cleared of snow 3) Stabilization of subgrade soil	1) Increase width of lane cleared of snow 2) Increase base thickness 3) Improve drainage quality
	Far from the objective	1) Pavement insulation* 2) Increase width of lane cleared of snow 3) Stabilization of subgrade soil	1) Pavement insulation* 2) Increase width of lane cleared of snow 3) Reinforcement of the asphalt concrete (mesh grid)
Winter roughness	Close to the objective	1) Increase subbase thickness 2) Uniformization of subgrade soil	1) Increase base thickness 2) Improve drainage quality
	Far from the objective	1) Pavement insulation* 2) Uniformization of subgrade soil 3) Stabilization of subgrade soil	1) Pavement insulation*
Fatigue cracking	Close to the objective	1) Increase subbase thickness	1) Increase asphalt concrete thickness
	Far from the objective	1) Increase subbase thickness 2) Increase base thickness 3) Increase asphalt concrete thickness 4) Pavement insulation* 5) Stabilization of granular base 6) Stabilization of subgrade soil	1) Increase asphalt concrete thickness 2) Increase base thickness 3) Pavement insulation* 4) Stabilization of granular base

* : pavement insulation involves partial reconstruction of the pavement structure to allow for the installation of an insulation layer at sufficient depth to minimize the risk of differential icing at the pavement surface.

Table 1: list of the most common climate-related problems and their possible construction solutions (Doré & Pierre, 2003).

2.1 Increasing temperature

Possible solutions suggested in the literature as a remedy to the problems that increased pavement temperature causes have been to include sacrificial, *anti-oxidation additives* in the bitumen aggregate mix. This would serve a similar purpose as that of steel galvanization in that the added particles would be more easily oxidized and thus prevent the bitumen from oxidation (Vind, 1967).

Another suggestion is to add a *light reflective coating*, or use light-colour aggregate for the asphalt surface to reduce the overall pavement temperature and avoid potential deformations such as rutting (Vind, 1967). A similar product, but more refined, seems to be the so called *heat-shield pavement*. This is obtained by a special paint that reflects the near-red radiation (Kawakami & Kubo, 2008). The application of this cool pavement technique has increased recently in Japan in order to try to contrast the so called “heat island effect”, a phenomenon in which air temperatures in the cities are much higher than the surrounding area. Cool pavements have shown to give temperature decreases of 0.7 to 2.3˚C if compared to a normal pavement. An example of product created to obtain heat-shield pavements is described by Iwama et al. (2008). This product, developed in Japan, is solar reflective, and is characterised by high reflectivity for near infrared rays and lower for visible rays. In addition, fine hollow ceramic particles were mixed with the spray pigment in order to reduce the thermal conductivity. Such a product gave very good results: a reduction in surface temperature of about 20˚C was measured, and did not show any problem regarding weather resistance, skid resistance and interference with porous asphalt. Another cool pavement technique is the so called water-retention pavement, described by Kawakami & Kubo (2008). This pavement has water-retentive materials mixed into it, thus allowing the pavement to reduce road-surface temperature through the evapotranspiration of moisture (energy being lost due to the latent heat of evaporation) – Fig. 1.

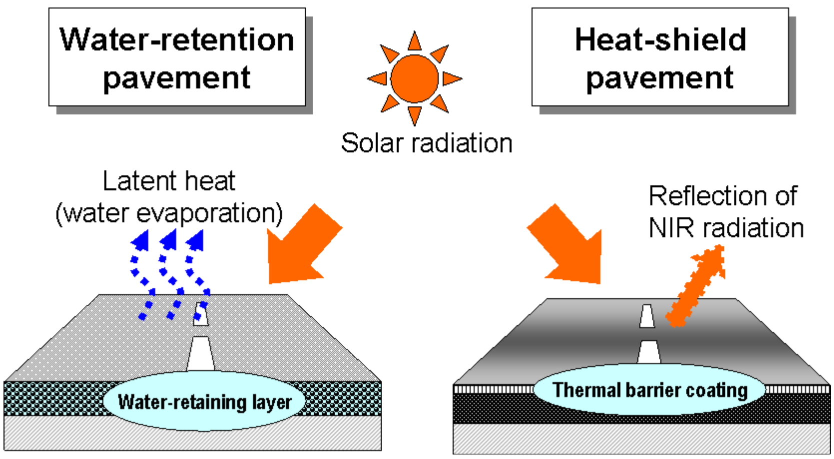

Fig. 1: Schematic of the two cool pavement techniques: water-retention and heat-shield pavements (source: http://www.pwri.go.jp/eng/activity/pdf/reports/kawakami.080929.pdf).

However, such products only serve to partly protect the asphalt from the effects of solar radiation, and an increase in pavement temperature due to hotter air temperatures might still be a problem. For this reason, it is suggested that the *design mix* might need to be altered. The amount of permanent deformation (e.g. rutting) seen after an increase in pavement temperature will be a combination of the maximum subgrade strain and the stiffness of the asphalt mix. Under design conditions, the desired design life of the pavement (to critical or failed conditions) is worked out in millions of standard axles (MSA). By using this and the stiffness of the mixture (converted into a rut factor “f_r”), it is possible to figure out the allowable strain of the subgrade using analytical pavement design procedures. However, if it is assumed that the allowable strain for the subgrade is met or exceeded, it is then possible to vary the asphalt concrete mixture in order to make it stiffer and less susceptible to deformation. These variations are numerous but generally include: increasing the binder stiffness, decreasing the size of the aggregate used in the mix and heavily compacting the mixture during construction to get a void content of around 10-20%. Such alterations to the general hot asphalt mix are known as *close-graded* or *dense bitumen macadam* (McCormack, 2009).

2.2 Increasing moisture content

Construction solutions available to engineers to counter the effects of moisture damage on roads are numerous and vary depending on the responses of the pavement. For instance, no one mechanism is agreed upon as the cause of stripping. What is known, however, is that stripping eliminates the bond between the aggregate and mastic. The effect of water on asphalt and porous asphalt is treated in more detail in W.P. 2.3.

It has been shown that using *crushed angular aggregate* helps to form a better bond with the asphalt, and bond strength was further increased when the aggregate was washed and dried before mixing to get rid of smaller dust particles (Kennedy, 1985). The *mastic* can also be chemically altered to provide a stronger more water-tight bond with the aggregate. Another method to contrast the problem of stripping that is widely used and agreed is the use of *additives* with the mix. These include hydrated lime in slurry form, liquid anti-stripping agents and sometimes even Portland cement, to strengthen and seal the bonds and reduce stripping (Kennedy, 1985).

Water ingress into the road foundations through the pavement is largely related to the presence of cracks on the surface or via malfunctioning drains at the pavement edge. Regarding the first of these, it has already been shown that cracking depends both on temperature and water. Rubberised asphalt has given very good results concerning crack prevention, as it develops much less cracks than normal asphalt. For this reason, the use of rubberised asphalt might be considered as an indirect way to reduce water infiltration, and thus high moisture contents, in the soil beneath the road surface.

Nowadays the use of porous asphalt as an alternative to the traditional impervious asphalt is more and more common. Porous asphalt has an average void ratio typically of 15%, against the 5-8% of a common asphalt, and this allows contact between the voids so that water can infiltrate into the sub-soil or be stored in a subsurface storage zone and then be removed through the drainage system. Porous asphalt is particularly effective during medium-heavy rainfalls, as water is quickly removed from the surface, thus avoiding aquaplaning, stripping and all the related problems. As rainfalls are likely to become heavier in the future, the use of porous asphalt should be supported, but only if the lower layers are rendered impermeable to prevent ingress to the subgrade.

The issue of malfunctioning lateral drainage systems is partly addressed in the following section and partly in Report No. 9.

3 Literature review – alternative materials for base and subbase

The strength of the subbase is strictly related to the presence of water. The infiltration of rainfall water from the surface, the increase of the groundwater level, or water coming from a flood event, can reach the subbase and subgrade, saturating the material, and reducing its strength. In materials such as soils and aggregates, where mechanical performance is dependent on a combination of frictional interaction and cohesion between constituent particles, water can have a major influence. In the short-term, it is the frictional element that is affected as matric suctions are reduced and, perhaps, pore water pressures increased. In the longer term, softening of soils can occur as clay minerals interact with available water. Where there is adhesive bonding, water, typically, has less effect – although water may cause such bonding to decay as in the stripping of aggregate from asphalt surfacing.

For this reason, more and more importance is being given to the appropriate design of drainage systems, which have to be able to remove water that reaches the subbase pavement as quickly as possible (but maintaining the minimum costs and the maximum road structure stability). However, when infiltration occurs, good drainage will never be able to completely avoid water from passing through the material, even if just momentarily, and thus increasing its moisture content with consequent reduction of mechanical performance. Good drainage can only try to reduce to a minimum such time. In addition to this, drainage pipes are often subject to obstruction with time, and thus their effectiveness will tend to reduce.

From these considerations, it is clear that, although an appropriate design of the drainage system is fundamental for road stability, a good design of the subbase and subgrade material can significantly reduce the loss of strength in presence of water. Materials that differ from the standard aggregate prescribed by the specifications have thus been taken into consideration and their effectiveness has been studied by a number of researches. These materials, that can be named as “alternative” materials, include, among the others, unbound aggregates with variations in their grading curve, aggregates of various gradings treated with additives such as cement, lime, ashes, bitumen, fibres, polymers and so on. A brief review of the past researches and of the results obtained is now presented.

In order to evaluate the different types of materials available, it is important to draw attention to the future needs in terms of climate changes. It is likely that, in the future, events of heavy rain, with large amounts of water potentially infiltrating beneath the surface in a relatively short time, will occur more often. The total amount of rainfall yearly is not going to change considerably, so it is probable that prolonged periods of light rain will occur more rarely. For these reasons, the pavement needs to be able to deal with large amounts of water coming in a relatively short period of time, and consequently with the presence of water within the pavement structure until it flows away through the drainage pipes, evaporates or filtrates into the groundwater; the time required for water to leave the structure needs to be reduced to the minimum.

An analysis of the alternative materials available to withstand this problem is performed in the next sections.

3.1 Cementitious stabilisation

The use of cement mixed with base and subbase aggregates to modify and stabilise the material and thus increase its strength has been known for a long time. Nowadays, it is a widely used and accepted method, probably the most widespread in the world. Cement is usually associated with stabilisation of sandy to gravelly soils, while the cementitious bonding created in clayey soils tends to be lower. The addition of cement in quantities from 1.5% to 4.5% have shown to improve markedly the performance of an aggregate, the strength being proportional to the quantity of cement added (Guthrie et al., 2002).

However, lately its use has decreased due to several factors (Guthrie et al., 2002). One of the main drawbacks related to the use of cement is the shrinkage that accompanies the cementing process and the consequent shrinkage cracking that leads to pavement failure. This is expected to be of particular concern in the context of climate change in that cracks would allow water to reach sensitive underlying subgrades. Another, more important problem is fatigue cracking that can be caused by the high rigidity of the treated material. Even a small localised deficiency in thickness can be the weak point from which cracking develops. According to Guthrie et al. (2002), a stiff layer characterised by a high resilient modulus does not guarantee good long-term performance, and thus more importance has to be given to the performance rather than to the material strength. According to Wilmot & Rodway (1999), the design of a cementitious stabilisation does not depend on a subgrade rutting criterion, as the high stiffness resulting allows the use of thin layers; instead, the design must be based on a fatigue criterion, for which much thicker layers will be required.

Cement shrinkage is the result of the drying phase that follows its hydration, and depends on several factors, among which are the cement/aggregate proportions and the properties of the material. For example, cement-treated materials with high fines content are usually more subject to shrinkage than coarse soils (Guthrie et al. 2002). This problem is usually managed by the addition of products that reduce it, such as fly ash, expansive cement, but also by pre-cracking operations. Cement-soil cracking can be contrasted with the addition of fibres, as it will be seen in section 3.2.

On a long term, the presence of water can be detrimental when the cementing component of the mixture suffers leaching problems.

3.2 Fibre reinforcement

Poor quality soils may be treated with various improvement techniques, among which the most widely used is by far cement mixing. As already mentioned, one of the drawbacks of cement treated soils is their tendency to brittle failure. To try to overcome this problem, various researches have studied the use of other additives. Fairly good results have been reported by Kaniraj & Havanagi, 2001 who used fibres of various types. Yin and Yu (2009) used 10mm long glass fibres in addition to cement to treat a soft clay from China. The soil was treated with cement in quantities of 12% and 15% by weight of the soil, and the fibres were added in quantities between 0 and 3%. The results from unconfined compressive strength tests (Fig. 2) showed that, independently of age, the specimen treated with 12% cement and 3% glass fibre (E on the graph) has the highest strength, higher than the sample treated with 15% cement but no fibres (B). But the most important aspect is that, observing the failure mode, the number of cracks and their width were much less in the samples treated with fibres compared to those treated only with cement. Therefore, glass fibre helps to reduce the brittleness of cement treated materials.

3.3 Foam bitumen stabilisation

Foam bitumen stabilisation is a method that is gaining more and more importance nowadays, especially thanks to its higher flexibility compared to the other stabilisation methods. Foam bitumen consists of foam created by adding a small amount of cold water (about 2%) with hot bitumen; the latter will consequently expand by rapid boiling up to a volume that is 10 to 15 times the initial volume of bitumen (Wilmot & Rodway, 1999), see Fig. 3.

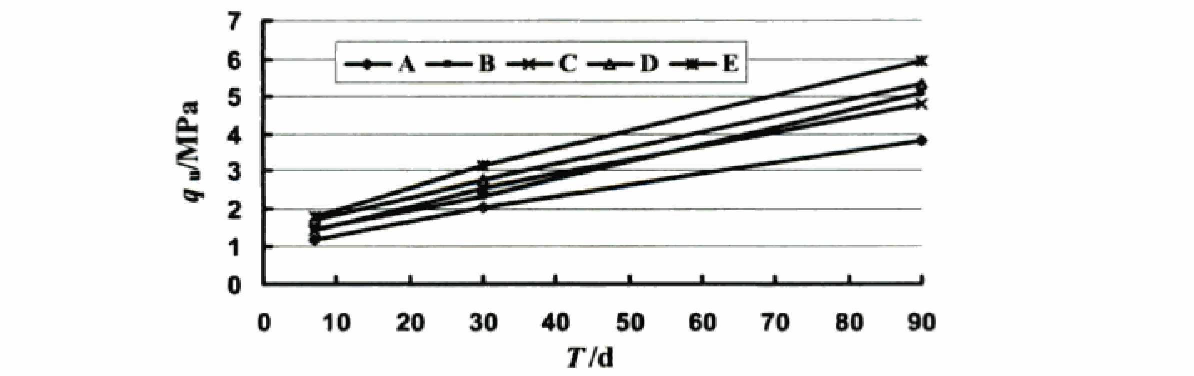

Fig. 2: relationship of unconfined compressive strength (Yin and Yu, 2009).

In this state it can be easily mixed with aggregate, provided that the mixing takes place in the next few seconds after the foam is created, as the life of the foam is very short (10 to 30 seconds). Usually a quantity of bitumen between 2 and 5% in weight is used. The aggregate does not need to be heated before being mixed with the bitumen, and this not only makes the product more environmentally suitable, but also sensibly reduces the production costs usually linked to standard asphalt production. Foam bitumen is also more environmentally friendly if compared to lime and cement, as it does not increase the pH of the groundwater as most other stabilisation methods do (Saleh, 2006). Other positive sides of its use are:

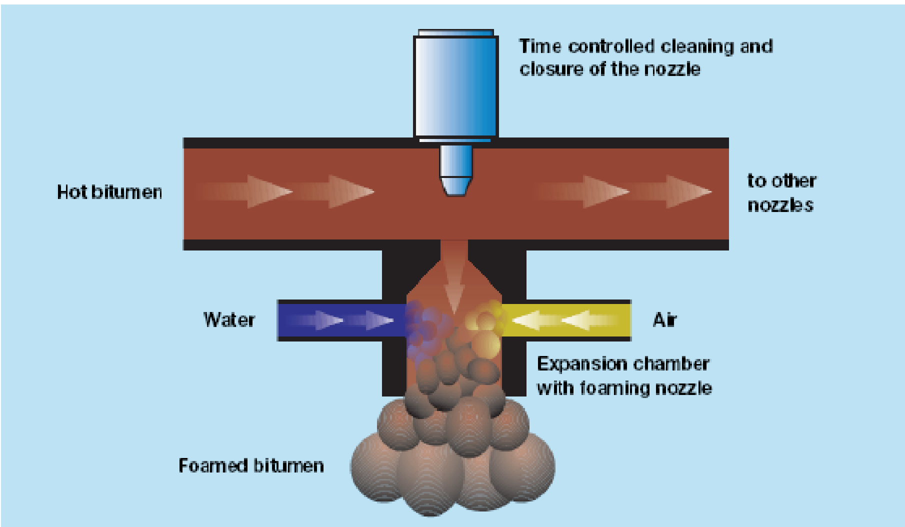

Fig. 3: production of foam bitumen (Ramanujan et al., 2009).

- the possibility to treat the subsoil directly on site
- its minor dependency on the thickness of the layer (whereas this is very high in cement treated soils)
- its rapid strength gain that allows the road to be re-opened soon after compaction.

When mixed with soil, foam bitumen tends to coat finer particles and thus form an impermeable matrix that bonds the larger particles together. Foam bitumen works better with well graded aggregates, crushed rocks, and material of low plasticity (PI<10). It seems that foam bitumen is very sensitive to the grading of the treated aggregate; in particular, the fines (diameter < 0.075 mm) should be between 5 and 15% (Ramanujam & Jones, 2000). Plastic fines can adversely affect the foam bitumen stabilisation. When the soil contains plastic fines, it is common to add some quicklime or hydrated lime (1 – 2% by mass of soil) to counteract the effects of plasticity. The effect of lime is to flocculate the clay fines, but it also acts as an anti-stripping agent by helping disperse the foam bitumen evenly around the aggregate.

Drawing on information obtained from treated graded aggregates (Fig. 4), Saleh (2006) observed that one drawback of foam-bitumen-treated soil is their moisture sensitivity, as the stiffness of a wet specimen can be 50% lower than that of a dry specimen. This fact is very important, as the need in light of the future climate change is that of an alternative material able to sustain even high levels of moisture content. To overcome this problem, the author proposes instead the stabilisation of foam-bitumen soil with cement. According to the author, a small quantity (1 to 2%) of Portland cement is enough to reduce the asphalt's sensitivity to moisture (Nataatmadja, 2002; Saleh, 2004). Saleh (2006/2) found very good values for soaked specimens stabilized with foamed bitumen and treated with fly ash or cement (1-2%). The ratio between the soaked modulus, after 5 days soaking, and the dry modulus (called the Index of Retained Strength, IRS) was, on average, 86%. Similar results were found, among others, by Kanussi and Hashemian (2004).

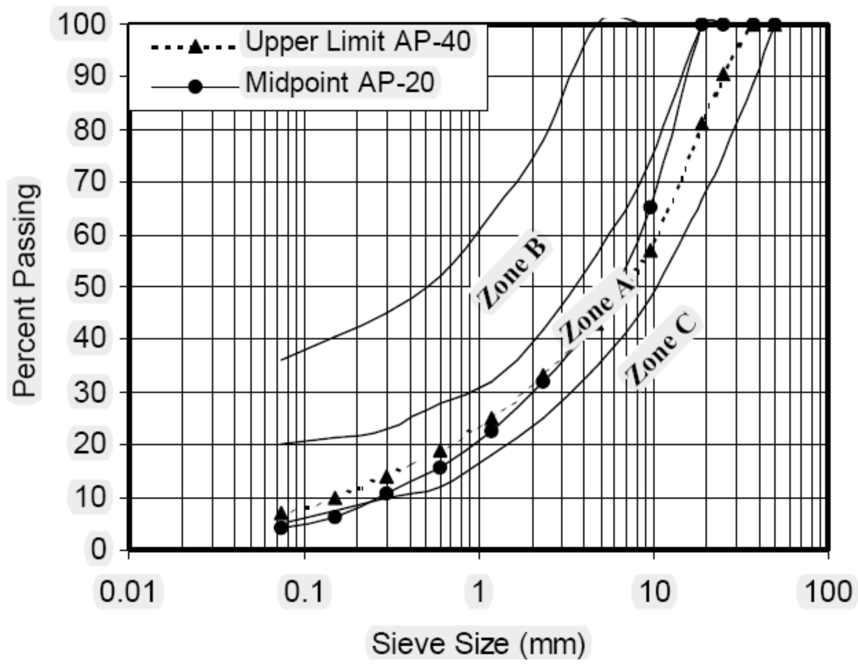

Fig. 4: aggregate gradation of mixes and their suitability to use in foamed bitumen mixes (Saleh, 2006/2). Gradations in zone A are the most suitable for this type of stabilisation.

The temperature susceptibility of foamed-bitumen-treated material was also investigated by Saleh (2006/2). The authors found (Fig. 5) that, as the testing temperature was increased, the samples modulus was inferior, and that a higher temperature susceptibility was shown by those samples that experienced a longer curing time. However, it should be noted that, according to the authors, Hot Mix Asphalt (HMA) undergoes much higher decreases in modulus as the temperature increases, compared to a foamed-bitumen-treated aggregate, although the latter can achieve greater stiffnesses when cool. The foamed-bitumen-treated material's response is reasonable, as those aggregates are not completely coated with bitumen so can still preserve a good friction at higher temperature.

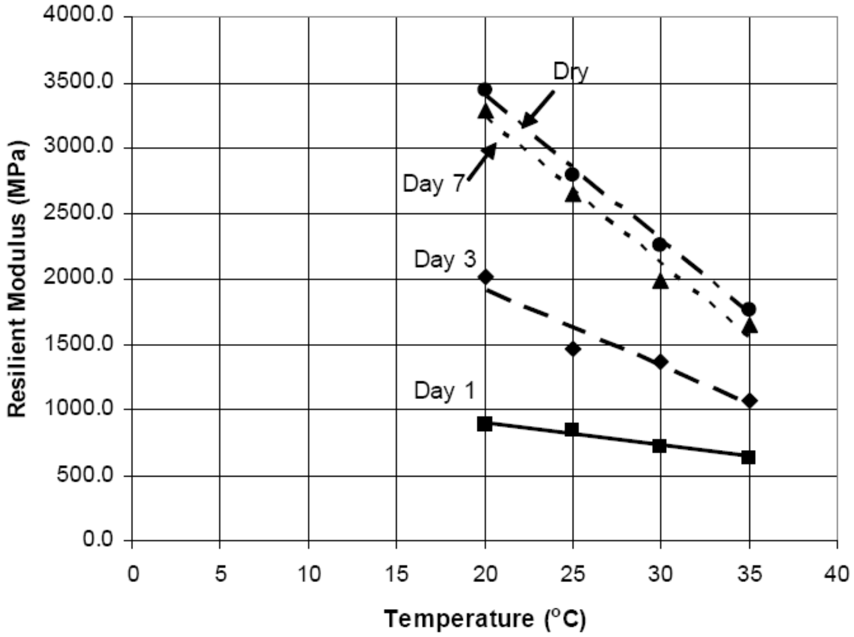

Fig. 5: temperature susceptibility of a specimen treated with foamed bitumen for different curing periods (Saleh, 2006/2).

The presence of small amounts of lime or cement in foam bitumen mixes not only increases the strength of the material, necessary especially in the early stages, but also reduces the curing time. However, it must be taken into account that the addition of strengthening agents decreases the workability of the mix, although the effect on workability of lime is minor compared to that of cement (Kavussi and Hashemian, 2004).

Lastly, the presence of cement, although in very small amounts, assures a very good rutting resistance, even in the presence of water (Hodgkinson and Visser, 2004).

3.4 Asphalt and cement treated bases - comparisons

The different importance that subsurface drainage and type of base material used have for the performance of a road has been investigated by the National Cooperative Highway Research Program (NCHRP, Hall & Correa, 2003; Hall & Crovetti, 2007). The study involved the analysis of both asphalt and concrete pavement sections throughout the U.S. The observations started in 1995, therefore a time-dependent analysis was possible. HMA pavement performance was evaluated through an analysis of rutting and cracking, while for concrete pavements the International Rutting Index (IRI) and the longitudinal and transverse cracking were the performance indicators used.

From a deflection analysis, it was found that, under an asphaltic surface, pavements with undrained, untreated aggregate bases were the weakest, while undrained, dense graded asphalt treated bases gave the best performance. The undrained sections with asphalt-treated base over aggregate and the drained sections with permeable asphalt-treated base over aggregate or over permeable asphalt-treated base fell between these two in terms of pavement performance.

For a concrete-surfaced pavement, the results (see Fig. 6) showed that the undrained sections with lean concrete base were more rigid than the drained sections with permeable asphalt-treated base, the latter ones corresponding to the highest increase in joints with load transfer.

The long-term IRI values were usually more strongly correlated to the initial values than to the ageing of the material; however, while those sections paved with HMA did not show any dependence of IRI on the type of base used (i.e. the base did not have any effect in the development of roughness) the concrete pavement sections had significant variations of initial IRI with the base type. In particular, the lean concrete base had the highest initial IRI values, while the dense aggregate base was associated with the highest long term IRI values.

However, the lean concrete base used in concrete pavements also exhibited a high tendency to crack. Undrained aggregate bases were even weaker, while sections with undrained hot-mix asphalt concrete and cement-aggregate mixture bases had even less cracking than sections with drained permeable asphalt-treated base. These facts suggest that cracking might be due more to base stiffness than to drainage differences. This finding might mean that more importance has to be given to the design of the materials used than not to the subsurface drainage conditions – at least for thick pavements as observed in these studies.

Overall, the asphalt surface pavements that performed best were those with the stiffest bases (i.e. with a dense-graded asphalt-treated base layer), whether drained or undrained, while the best performance for concrete pavements was given by roads with bases that were neither too weak (untreated aggregate) nor too stiff (lean concrete).

Some interesting observations about asphaltic materials were pointed out by Kandhal et al. (1989). The authors noticed a general higher stripping in binder course mixtures compared to wearing course mixtures. Based on the findings of Hallberg (1950), who reported that “the required internal water pressure causing an asphaltic mixture to have adhesive or interfacial tension failure (stripping) is inversely proportional to the diameter of the pores”, the authors hypothesised that this is probably due to larger diameters of the pores in the binder course, and thus densely graded aggregates should help to eliminate stripping in these layers.

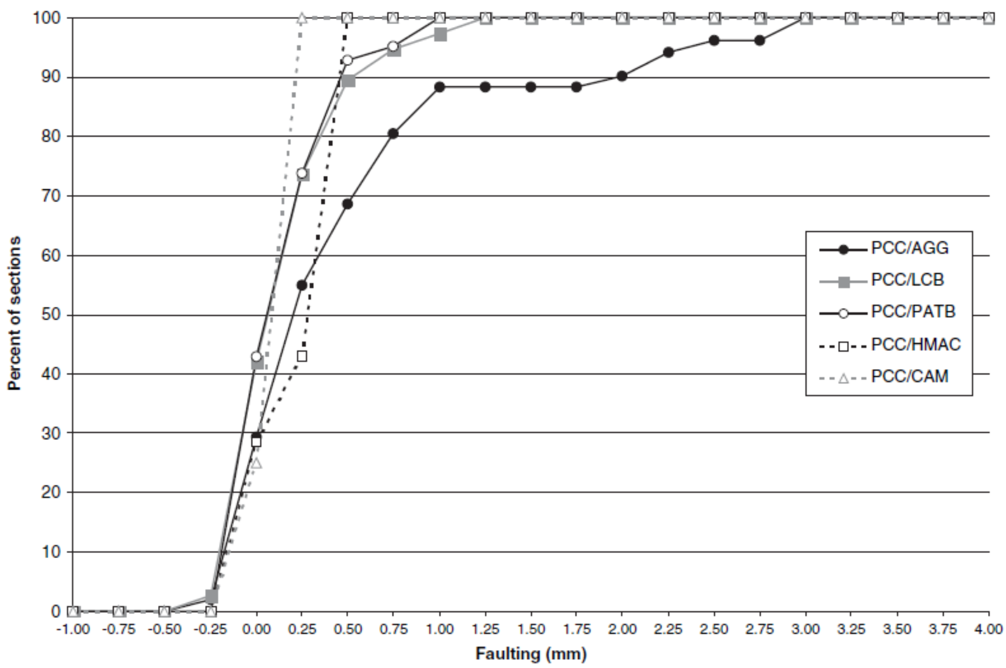

Fig. 6: cumulative frequency distributions of faulting for pavement sections (Hall & Crovetti, 2007). (PCC = Portland Cement concrete, AGG = unbound aggregate, LCB = lean concrete base, PATB = permeable asphalt-treated base, HMAC = hot-mix asphalt concrete base, CAM = cement – aggregate mixture).

3.5 Dry powdered polymers

Dry powdered polymers (DPP) were first developed in Australia, and their use is nowadays spreading in other countries. They are defined as a dry powdered road stabilising binder consisting of an insoluble polymer thermally bound to a very fine carrier such as fly ash. DPPs work particularly well with clay grain sizes as they create a hydrophobic soil matrix between the particles that avoids water ingress, thus creating a waterproofing barrier around the fines. It is suggested to use it with soils comprising at least 35% of material passing through the 2.36 mm sieve. The use of DPPs with fly ash or similar material is common.

The ingress of water in a clayey material causes an increase in moisture content, reduction of pore suction, and softening of the interaction between the particles, causing plastic deformation, and all these factors decrease the strength. DPPs tend to counteract the water ingress, and thus the strength reduction. If compared with the results obtained using cement, DPPs do not show those problems that are usually related to the presence of cement, such as cracking and, because the clayey particles are now protected by the polymer, water cannot ingress and they do not swell.

The DPP is usually associated with the addition of small quantities of hydrated lime; its function is not to generate cementitious bonds, but rather to flocculate with the clay and make it more suitable to be protected by the polymer. The percentage of lime mixed with the DPP depends on the plasticity of the material treated; it is almost nil if the soil is non-plastic, and increases up to 50% of the DPP if the soil is very plastic. The amount of product needed to ensure effective treatment of the clayey particles, and thus to create the waterproofing effect, is about 1.5 - 2% of the total weight of the material.

Laboratory soaked CBR tests on poor quality aggregates treated with DPP (Lacy, 2004) showed a rather large increase of strength, and also the observed performance in the field over a period of 10 years has been very satisfactory. In particular, in the nineties some roads were treated with DPP; according to the Austroads Guide to the Structural Design of Road Pavements, they should have failed by now, nonetheless they still maintain their shape and do not need maintenance. There has also been successful use in Finnish (freeze-thaw) conditions (Kalliainen, 2008)

Rodway (2001) describes laboratory tests to confirm the waterproofing effect. Both untreated and treated gravel cylindrical samples 100 mm high were placed in a tray containing 30 mm of water; after 24 hours, the untreated samples disintegrated below the waterline, and water rise due to capillarity reached the surface of the samples. DPP treated samples, instead, suffered a capillary rise of only about 25 mm and were still intact.

Also triaxial tests were conducted on both untreated and treated materials (Rodway, 2001), and the results, presented in Table 2, demonstrate a well performing material when treated.

Test specimen	Moisture content (%)	Apparent cohesion (kPa)	Friction angle (°)
Dry untreated gravel	1.6	450	39
Wet untreated gravel	8.2	0	22
Wet DPP-treated gravel	8.9	125	37

Table 2: test results from triaxial tests on untreated and DPP treated gravel (Rodway, 2001).

Dry Powdered Polymers are used, in particular, in regions of high groundwater table and in those subjected to periodic flooding (Rodway, 2001). As a matter of fact, as their price appears to be relatively high when compared with other techniques, the use of such additive will be probably considered, in this research, only in particular conditions of necessity, such as in coastal zones and zones with a high risk of flooding.

3.6 Open graded aggregates

In order to try to remove water as soon as possible from the pavement structure, the concept of an open graded drainage layer (OGDL) as subbase layer has been taken into consideration in the past. In particular, the US state of Illinois experimented with its use for a period of time starting in the late 1980's and continuing until the early 1990's.

An OGDL is obtained by selecting a uniform size graded aggregate and removing all the finer material. The resulting structure is a very porous aggregate, where the interconnection between pores allows water to freely flow through the material and thus easily reach under-drainage pipes in a rather short time. The aggregate may be bound with small amounts of cement and bitumen in order to increase its resistance.

Winkelman (2004) evaluated the use of OGDLs in Illinois. Sections of roads were built using cement treated and asphalt treated OGDLs; the thickness was between 8 and 16 cm, the grain size as that shown in Table 3 (Winkelman, 2004) and in Fig.7 (Christopher & Zhao, 2001).

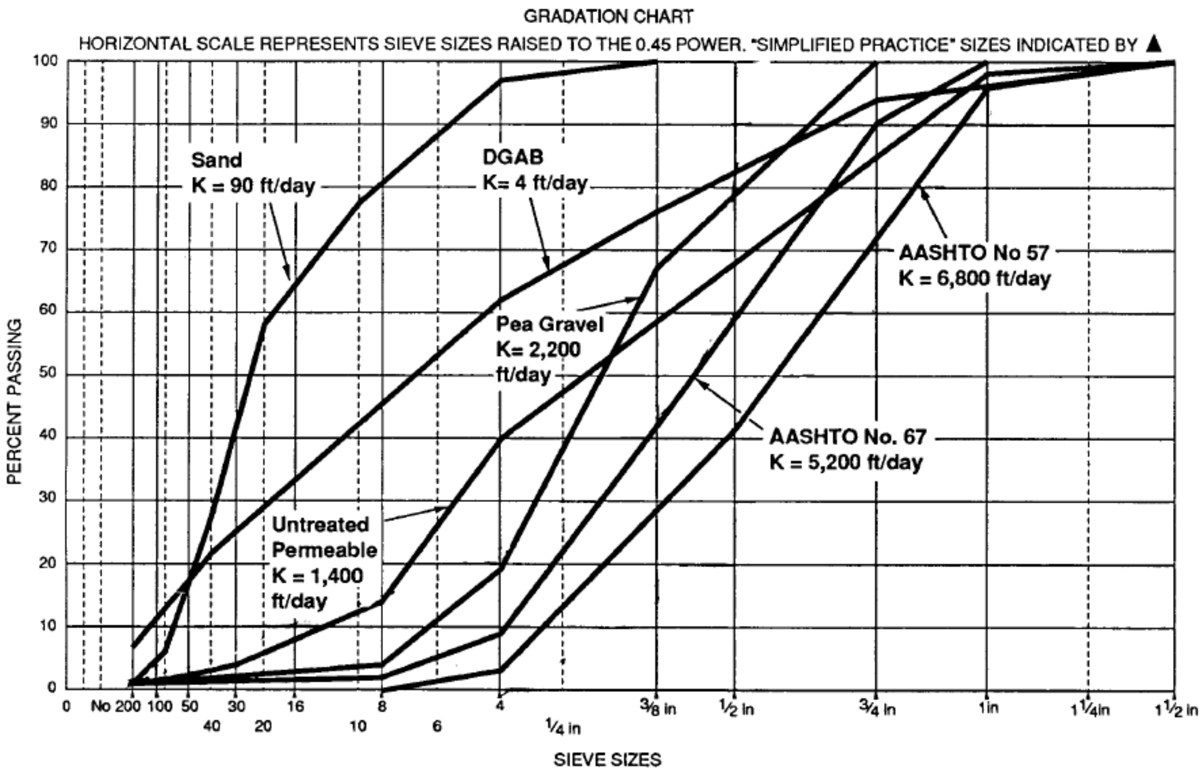

Fig. 7: grading curves of two different OGDL (AASHTO 57 and 67) compared to those of denser graded bases (Christopher & Zhao, 2001). NB, 1ft/day ≈ 3.5 x 10^{-6} m/s

Performance monitoring, over time, was made through Falling Weight Deflectometer (FWD) measurements, International Roughness Index (IRI) values and Condition Rating Survey (CRS) values based on visual pavement distress surveys.

Sieve Size	37.6mm	25.4mm	12.2mm	4.75mm
Percent Passing	100	95 ± 5	45 ± 5	5 ± 5

Table 3: example of gradation used (Winkelman, 2004).

Unfortunately, the results showed a tendency to quickly deteriorate. The problems encountered were early superficial pavement distress, severe lane to shoulder settlement and high pavement deflections with both longitudinal and transverse cracks on the road surface that formed blocks. The main reasons for such poor performance were attributed to high stresses concentrated on the contact points between the aggregates, the infiltration of fines into the OGDL, or the settlement of the OGDL into the subgrade. Also, it was believed that the voids of the OGDL hold large quantities of water within the pavement substructure for longer amounts of time, if compared to a more common dense graded or stabilised subbase. Per se, this is not negative: in case of floods, water can be “stored” in the subbase for the time necessary for the drainage pipes to empty. However, the presence of still water in the subbase acts as a means for migration of the subgrade fines, thus filling the voids, and for the softening of the underlying subgrade.

Other results worth of note were the fact that no significant difference was observed in the FWD measurements between the cement treated OGDLs and the asphalt treated OGDLs, and also the thickness did not influence the stiffness values measured. These results might mean that the two treatment methods cause similar benefits, and that the layer thickness does not have a major role on the behaviour of the pavement. However, it might be that the poor quality of an aggregate characterised by single grading dominates the deterioration, despite the treatment.

As the resulting costs were even higher than for a stabilised subbase, and because the results were not satisfactory, the OGDL was deemed an unsuitable choice, and was therefore discarded as a future construction technique.

This is not to say that drainage is undesirable. Quite the contrary. As discussed below in Section 3.10, drainage is important and likely to become more so as aspects of climate change. However, the specific use of OGDLs in thick pavements has not been found to be particularly successful, so this particular drainage strategy is not further recommended.

3.7 Geosynthetics

Geosynthetics have found wide usage in civil engineering projects; in particular, they are often used for erosion control, drainage, soil reinforcement and stabilization. Geosynthetics' performance in pavements have been the subject of relatively few studies when compared to other road improvement methods (Bohuslav, 2008). Nevertheless research generally indicates satisfactory results.

There are several types of geosynthetic available for pavements, the most common of which are geogrids and geotextiles. In pavement engineering, they are used for three main applications (Bohuslav, 2008):

- pavement surface layer reinforcement (for HMA)
- geotechnical reinforcement
- drainage and moisture control.

In surface layer reinforcement, the aim of the use of geosynthetics is to reduce the reflective cracking, rutting and to resist moisture intrusion into lower pavement layers. Wasage et al. (2004) analysed the rutting resistance of geosynthetic-reinforced-asphalt pavement through full-scale track tests and laboratory-simulated wheel tracking models. The tests were performed in a saturated condition in order to simulate the high frequency of rainfall in Singapore. The tests results demonstrated that geogrid reinforcement placed at the surface course/base course interface increased the rutting resistance of an asphalt pavement and provided a more uniform load distribution. These results agreed with earlier work undertaken by Brown and co-workers (e.g. Sanders et al, 1999) who also reported much reduced rates of asphalt fatigue cracking.

In geotechnical reinforcement, geosynthetics can have a passive role that consists in separating the different layers of material and thus avoiding their mixing. When fine-grained soil particles move into the overlying base, it can create a significantly finer gradation over time, causing a decrease in strength and non-recoverable deformation. Geotextiles are the most suitable type of geosynthetic for this purpose, as they are permeable, i.e. they do not block the movement of water through the media, but they allow separation of the subgrade fines from the coarser aggregate (Kercher) and vice-versa (Fig. 8).

Geosynthetics can also have an active role in geotechnical reinforcement, and in particular in the road subgrade strengthening, by supporting part of the load applied to the structure. For this purpose, geogrids (Fig. 9) are geosynthetic materials shaped in an open, grid-like pattern, that allows interlocking of the aggregate.

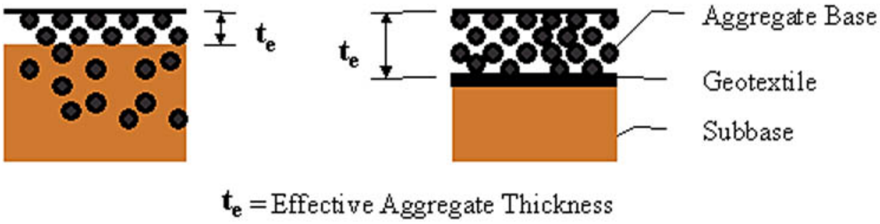

Fig. 8: Geosynthetic Separator preventing aggregate loss (Kercher).

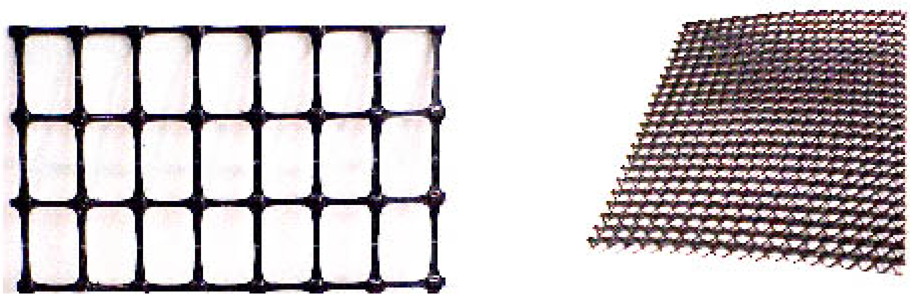

Fig. 9: a) Geogrid (left) b) Geonet (right)
(http://www.kercherei.com/pw_institute/geosynthetics/geo.html)

The increasing resistance linked to the presence of geogrids in the base course has been widely demonstrated (Tsai, 1997, Perkins and Ismeik, 1997 among the others). Geogrid behaviour does not depend on water content, thus a loss in strength due to an increase of moisture content in the soil/aggregate is somewhat compensated by load take-up in the geogrid.

The application of geosynthetic material to help drainage is shown in the Table 4 (Bohuslav, 2008). It can be seen that different types of geosynthetics can help achieve the aim of having a fast removal of water from the subbase and subgrade.

The geosynthetic can act as filter by preventing the finer material from being transported with water and removed from the structure, in the meanwhile allowing the water to flow through. In the drainage processes, the water flows along the plane of the geosynthetics (in-plane drainage), while, in filtering applications, the water flows across the plane of the material (as shown in Fig. 10.

Material	Application
Geotextile	• Transmission of moisture to pavement edge. • Wrapping drainage pipe to prevent siltation of the drain. • Wrapping aggregate to provide confinement and prevent fine soil intrusion.
Geomembrane (A geosynthetic material waterproof when used as a fluid barrier)	• Moisture barrier for pavement edges. • Encapsulation provision for confining and waterproofing material in the roadbed.
Geoweb (A composite material of other materials listed here)	• Provision of both a drainage structure and separation with a geotextile.
Geonet (A geosynthetic material consisting of parallel sets of intersecting ribs that form a three-dimensional net-like material – see Fig. 9b)	• Delivers improved drainage by creating a "thin" plane for water to travel through, especially when used as part of a composite between two geosynthetic layers.
Vertical Drain (A composite material of other materials listed here – often a geonet arrangement)	• Transmits water from the roadway, through a geotextile (e.g. geoweb or geonet) and down to a drainage structure.

Table 4: Geosynthetics for drainage (modified from Bahuslav, 2008).

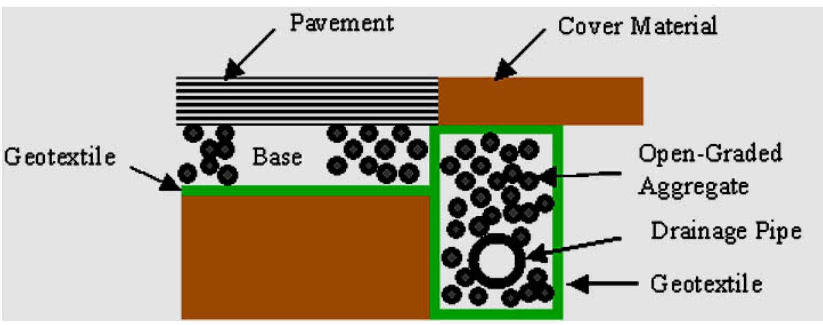

Fig. 10: Example of how the geosynthetics help filtration (Kercher).

3.8 Bitumen emulsion

Bitumen may be emulsified with water using an emulsifying agent (Asphalt Academy, 2009) thereby forming a binder that may be used cold as a stabilizer. One difference from foam bitumen as far as application is concerned, is that bitumen emulsion can last for months before it is used. So it doesn't need to be made at the point of use, either, but can be made under factory conditions and then applied on-site to the sub-base or soil that is to be treated. A schematic of the production is shown in Figure 11.

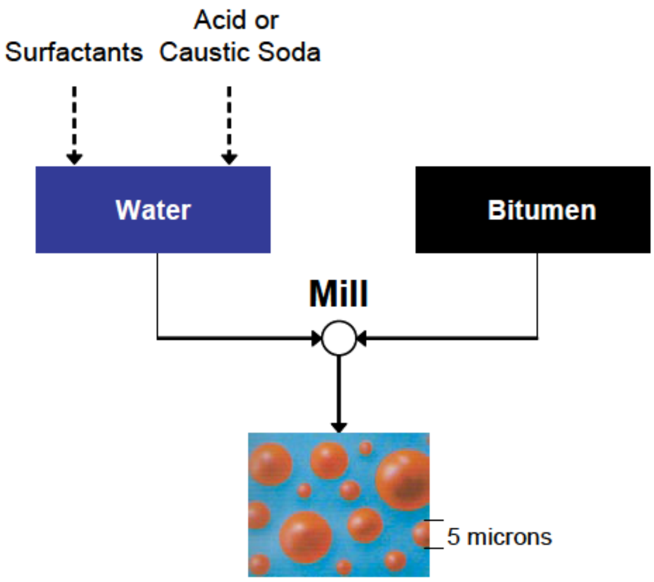

Fig. 11: Production of bitumen emulsion (from Asphalt Academy, 2009).

Hodgkinson & Visser (2004) found that emulsion-treated materials have a retained strength after soaking that is very good, with retained strength values around 100%, thus much higher than that of the materials treated with foam bitumen. The decrease of moisture content sensitivity is mainly due to the fact that bitumen disperses amongst the finer particles, which are, therefore, coated and immobilised, creating a strong binding matrix. Small amounts of active filler such as cement or hydrated lime are commonly added to the mix, at the point of treatment, in conjunction with the bitumen emulsion to improve the retained strength under saturated conditions and also to assist in dispersing the bitumen (Asphalt Academy, 2009).

Some concern, especially for northern countries, can be the fact that bitumen emulsion cannot be used at temperatures lower than 5ºC, as it would tend to break prematurely (Asphalt Academy, 2009). However with appropriate, seasonal application its use in colder countries such as Sweden is possible and may even be widespread (Jacobson, 2002). Furthermore, as the climate changes, the probability of having temperatures below 5 ºC will decrease and thus bitumen emulsion might be usable, in the future, also in those countries that do not envisage its use at present.

3.9 Other products

Many different products, especially by-products derived from industrial activities, have been tested and used, usually in addition to cement or lime, to improve the binding, or to reduce the prices without influencing the quality of the binder, thanks to the pozzolanic properties that often characterise such materials. For the purposes of this report, the characteristic that a product must have, is not much the ability to increase the strength of the material, but the ability to increase the resistance to water and tolerance to higher temperatures, i.e. the retained strength in presence of water and warmth. In general this suggests a move towards hydraulically bound materials with moderate (but not high) strength so that they retain a non-brittle, yet stabilized, behaviour in both wetter and warmer conditions. An example of such an approach is to be found in the results of Wild et al. (1998) who substituted part of the lime in a lime-stabilised kaolinite with Granulated Blast Furnace Slag (GGBS).

A variety of soil stabilisers is available on the market. Their sellers are keen to report successful use, often quoting significant improvements in the mechanical properties of soils which previously had inadequate soil strength or were particularly sensitive to water. Usually, these additives act by changing the chemistry of the soil in some manner that is not clearly stated (and may not be fully understood). Rarely have such commercialised products undergone a proper research study involving a large variety of soils with different gradings and properties, and often they work well only for a specific type of soils (Kalliainen, 2008). Furthermore, the higher cost of these products compared to other stabilisation methods, and the fact that they are usually not effective with different types of soil, make these chemical binders not suitable for common practise.

One specialist use of stabilizers is as a dust palliative on unsealed gravel roads. For a recent study, readers are referred to Edvardsson (2010). There are a wide range of such stabilizers available, but the costs and/or environmental impacts make many of then rather undesirable. Climate change can be expected to make their use more problematic. Dryer summers (or, at least, longer and dryer periods between rain in the summer months) will mean that dust is likely to become more of a problem, so that the demand for dust reduction will rise. But heavier rainfall will be likely to wash the palliative out of the pavement more rapidly reducing its efficiency.

3.10 Alternative drainage systems

It was shown by Fwa (1987) that permeability requirements should be introduced, making not only the entire road bed permeable but also each underlying layer more permeable than the one above to promote free-drainage. Therefore, despite the poor performance of OGDLs on thick pavements (see Section 3.6 above) drainage systems that effectively remove water from the pavement in a timely manner are to be encouraged and are expected to become more important in areas of increased rainfall or places where rainfall occurs in shorter, more intense rainfall events. In the light of the OGDL experience, and Fwa's recommendations for increasing permeability with depth, it seems that drainage at the lowest level in the pavement is to be preferred.

An advantage of having drainage layers as such a low level is that they do not allow capillary rise of water, e.g. they work as "capillary breaks", thus avoiding water to migrate from the subgrade into the road structure (Watmove, 2008). This is particularly beneficial in frost affected areas as frost heave requires water to be available for freezing, so an efficient cut-off will reduce heave potential. For low level drains to work, they must slope down to a marginal drain that still falls towards a drainage outlet point. The implication is that deeper drainage must be considered during pavement reconstruction. In cases where the outlet level is fixed due to hydrologic conditions, this will necessitate the road levels being raised or pumping to empty drainage systems – both very expensive options. In such cases water-resistant, stabilised materials (see Section 3.9 and earlier) will probably be a more sensible and economic option.

The addition of a good *sealing barrier* in conjunction with good drainage will help water in the subgrade to move away. This sealing needs to be an almost impermeable material; it can be natural, such as clay, or it can be a geosynthetic barrier. If this sealing layer is placed just below the draining pipe (Fig. 12), this will prevent water from accumulating at deeper levels. The drainage conditions and possible modifications are dealt with further in Report No. 9.

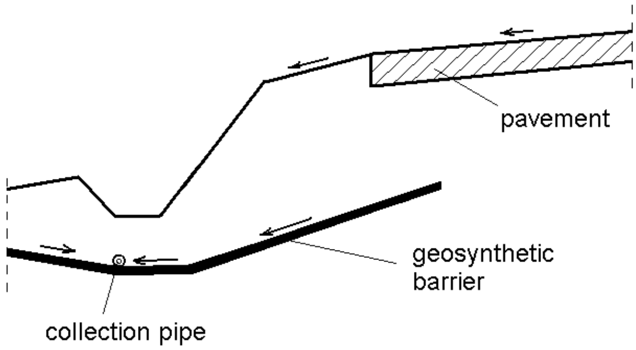

Fig. 12: Correct application of a sealing barrier (Watmove, 2008).

4 Brief description of other possible solutions to climate related problems

In addition to pavement layer sequences and materials, good road design geometry (crown slope and elevation above water tables) are suggested to prevent stationary water from collecting on the road prism and, thereby, soaking in (Fwa, 1987). Fwa also mentioned the importance of ensuring that longitudinal and transverse joints as well as interfaces between various lifts of asphalt are sealed or water-tight.

Thawing used to be a problem related to spring periods, when temperatures would have increased and ice and frozen ground started to melt. Unfortunately, this problem seems to be more and more diffused throughout the whole winter, often lasting for just a day or two or a week or two, but for a duration that is enough to create problems in the case of heavy trucks passing. Eigenbrod and Kennepohl (1996) suggest that load restrictions usually applied by those countries whose roads are subjected to spring thaw problems should, instead, be related to real-time deflection measurements, for example by means of a FWD. A similar recommendation, but for lower volume roads, has been made by the Roadex project (Saarenketo & Aho, 2005). Eigenbrod and Kennepohl (1996) also give indications regarding future road construction: according to them, subgrades containing less than 2% silt do not develop excess pore water pressure during thaw. Also, a clean, open graded granular aggregate layer placed between the pavement and a silty subgrade would prevent the accumulation of water beneath the pavement base (see Section 3.10).

Salt can have a destructive effect on aggregates and can promote stripping of aggregates from an asphalt mix as well as the well-known corrosion effects on metallic elements in a road's construction. Problems with salinity are harder to control through construction techniques, however, wherever possible, good drainage should be ensured in order for any deleterious effects to be minimized. In the event of heightened winter precipitation in the form of snow, de-icing salts should be used cautiously for the same reasons. De-icing chemicals such as acetates and formats should be probably be avoided altogether, as they seem to increase damage (Alatyppö et al., 2008).

5 Conclusions and implications

From the analysis of the evidence of the results obtained in the past using different treatment methods to improve the performance of the pavement in presence of water, some conclusions can be drawn.

Bitumen and polymer stabilizing treatments, as contrasted with cement treatments, are not subject to much fatigue cracking and are less susceptible to overloading or to deficiencies in thickness (Wilmot & Rodway, 1999). Polymers are more suited for very poor quality gravels and soil, especially given their higher costs of the product. Foamed bitumen gives good results regarding a reduction in water susceptibility especially for well-graded crushed rock of low plasticity. Both foamed bitumen and polymer treatments work well with the finer material in the aggregate or granular soil allowing the creation of a matrix that is waterproof, and which also improves the plastic deformation of the aggregate. However, differently from polymer treatment, foamed bitumen use also increases the strength and stiffness of the material, therefore it is more suited for those subbases and bases that not only are significantly affected by moisture, but that also, when dry, do not have much strength.

In Australia, the different stabilisation methods are chosen according to the aggregate grading characteristics as illustrated in Table 5. However, such a table does not take into account the effects of water infiltration, that are usually evaluated, if needed, as a separate phase following the choice of the binder. The future increase in probability of having higher water contents in the subgrade and subbase, if not even their complete saturation, makes the evaluation of the treated soil's resistance after water ingress very important.

	MORE THAN 25% PASSING 75µm			LESS THAN 25% PASSING 75µm		
Plasticity Index	PI ≤ 10	10 < PI <20	PI ≥ 20	PI ≤ 6 PI x % passing 75µm ≤ 60	PI ≤ 10	PI > 10
Form of Stabilisation						
Cement and Cementitious Blends	Usually suitable	Usually suitable	Doubtful	Usually suitable	Usually suitable	Usually suitable
Lime	Doubtful	Usually suitable	Usually suitable	Usually not suitable	Doubtful	Usually suitable
Bitumen	Doubtful	Doubtful	Usually not suitable	Usually suitable	Usually suitable	Usually not suitable
Bitumen/ Cement Blends	Usually suitable	Doubtful	Usually not suitable	Usually suitable	Usually suitable	Doubtful
Granular	Usually suitable	Usually not suitable	Usually not suitable	Usually suitable	Usually suitable	Doubtful
Dry powdered polymers	Usually not suitable	Usually suitable	Usually suitable	Usually not suitable	Doubtful	Usually suitable
Key	Usually suitable	(black)	Doubtful	(grey)	Usually not Suitable	(white)

Table 5: guide to selecting a binder for stabilisation in Australian roads (Austroads, 1998).

Thus, when choosing the most suitable treatment method, it should be also taken into account the reduction in water susceptibility that the treatment brings. In particular, according to Wilmot & Rodway (1999), the mechanistic pavement design procedures usually employed to estimate pavement life are only based on the stiffness increase that the addition of bonding additives would bring. However, such methods are not able to take into consideration, and thus correctly evaluate, the direct and indirect improvements that other types of products (such as polymer treatments) bring: in these cases, past experience and current field evidence are the only way to evaluate them.

While there are considerable attractions associated with foamed bitumen stabilization (especially with a lime or cement additive included) – especially compared with cement or polymer competitive approaches – yet there are drawbacks (Vorobieff and Wilmot, 2001). So, while increased durability and waterproofness are anticipated, the need for a suitable grading, see Section 3.3, prevents it being the panacea that might be desired. Bitumen emulsion, also with a lime or cement additive included, is another attractive possibility for stabilisation but it has not been possible to determine the relative benefits of foam and emulsion stabilization as a response to climate change.

Other stabilizers are available, particularly those with a lower strength hydraulic binding action (e.g. some slags) that allow the stabilized layer to maintain flexibility and not to crack. In some cases fibre-based stabilization may be desirable – again giving a stronger yet flexible non-cracking resultant material. The relative desirability of hydraulic and fibre treatment will, eventually, probably turn out to be a question of cost. Neither use expensive raw materials at typical dosage rates, but obtaining the material at a particular site far from the source and then addressing the issues, and costs, of practical installation may make one much more preferable.

In order to avoid the presence of water in the road structure, drainage layers are an essential element of a pavement engineer's toolbox. Often, geosynthetic separators and filter layers will need to be used with such layers to keep the aggregate clean and to help water to escape efficiently. Drainage layers typically provide valuable improvements in performance, particularly after wet weather or in frost heave situations, and are, therefore, becoming more and more frequent. However, because such aggregates are necessarily open-graded, they tend to have not a very good mechanical performance under trafficking. One solution is to mix the aggregate with small amounts of bitumen or cement (Christopher & Zhao, Contech, 2001) as a layer stabilizer – though this must be done with caution if the permeability is not to be lost. Another approach is to place the layer low, well below the direct effect of trafficking. The problem in that case is ensuring positive falls to drainage outlets.

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