P2R2C2

Study of Water Effects on Asphalt and Porous Asphalt

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Executive Summary

Should climate change follow prediction models, it is possible that some existing roads will face climatic conditions different from those they were designed for. Therefore, prudent planners and policymakers need to know what possibilities are available to them for rehabilitation and construction of new pavements. Specifically, what negative effects might events of this nature have, and what tools do we as engineers have at our disposal to mitigate such issues.

Moisture damage of asphalt pavements is a complex phenomenon which is not entirely understood; nevertheless a significant body of knowledge on the subject has been developed. It is known that significant increases in free water present in the asphalt-aggregate system have the potential to cause lasting damages to the existing roadway. Increased stripping is a possible outcome of increased rainfall if the appropriate conditions are present. The extent of the stripping will be dependent on traffic loading and quality of construction practices.

Stripping may be a particular problem in locations experiencing significant increases in precipitation coupled with significant increases in maximum temperature. Certain regions of France and central Europe appear especially at risk as increases in temperature will tend to be significantly higher within pavements at lower latitudes. Instances of intense rainfall may prove particularly damaging if such rainfall events result in poor drainage, and in a worst case scenario result in flooding.

Porous pavements have been proposed as potential solutions for areas with significant rainfall, and additionally for their noise reducing properties. These pavements are constructed using a larger percentage of coarse aggregate as well as higher binder contents. Issues have been raised in the past regarding the durability of porous pavements with regard to stripping and ravelling. Research has shown that properly designed and built porous pavements should not be susceptible to stripping.

It is believed that 80% of all asphalt/aggregate adhesion issues can be controllable during the production and construction phase. Generally speaking, drainage issues are known to be a significant source of moisture related damages within asphalt pavements. For this reason rapid removal of water from the pavement layers should be prioritized. In addition to this it is possible to use additives in the asphalt binder and aggregate to promote adhesion of the asphalt binder to the aggregate.

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1 Background

Asphalt pavements provide an excellent material for roadways; when designed properly these roads deliver a smooth, quiet, and durable solution. However, the success of any asphalt pavement is dependent on the paving material being designed for its environment. Pavement engineers are aware of the importance of climate on road design, and therefore the practice has become to design the road based on the extreme climatic conditions the road is likely to meet.

If climate change follows the scenarios that have been developed, it is possible that some existing roads today will face climatic scenarios somewhat different from those they were designed for. Therefore, prudent planners and policymakers need to know what possibilities are available to them for rehabilitation and new construction.

This literature review will focus on the effects of moisture on asphalt pavements; such a review will provide an introduction to what might happen to asphalt pavements in the event of climate change. Specifically, what negative effects might events of this nature have, and what tools do we as engineers have at our disposal to mitigate such issues. Moisture damage of asphalt pavements is a topic asphalt technologists have been aware of for a long time, as such a significant body of knowledge on the subject has been developed. Therefore, both laboratory and field studies will be discussed in an effort to better understand the impacts of moisture on asphalt pavements.

Porous pavements have been proposed as potential solutions for areas with significant rainfall and additionally for their noise reducing properties. These pavements allow runoff to filter through them rather than off the top of them, the benefits of doing so include reductions in hydroplaning, improved visibility, and increased tire-pavement friction. This paper will discuss the potential impacts of increased rain on porous pavements, as well as identifying common performance issues that these could exhibit.

Finally, conclusions will be presented based on the available knowledge using existing asphalt technology and climate change predictions. These conclusions will focus on the impacts of moisture on asphalt, and specifically how increased rainfall may promote failures of asphalt pavements.

2 Impact on Climate Change Predictions

Scenarios developed by Makkonen et al. (2010) were used when assessing the impacts of climate change on asphalt pavement performance. Conclusions reached through the development of multi model mean maps were referenced to identify anticipated climate changes. With regards to moisture damage in asphalt pavements, the following maps were selected for further analysis:

- Change in annual precipitation,
- Change in number of freeze-thaw cycles, and
- Change in annual maximum temperature.

2.1 Annual Precipitation

Makkonen et al. (2010) project that the most significantly affected area where precipitation is expected to increase is in northern European regions in contact with the Atlantic Ocean, as well as mountainous and elevated areas. An increase in annual precipitation in these areas is expected to come from a significant increase in heavy rain spells.

Additionally, as seen in Figure 1 it is expected that there will also be a significant increase in annual precipitation in western Norway. These increases, however, are not expected to cause considerable problems as this region already experiences significant rainfall, and therefore relatively speaking the impact of any increase will be felt less.

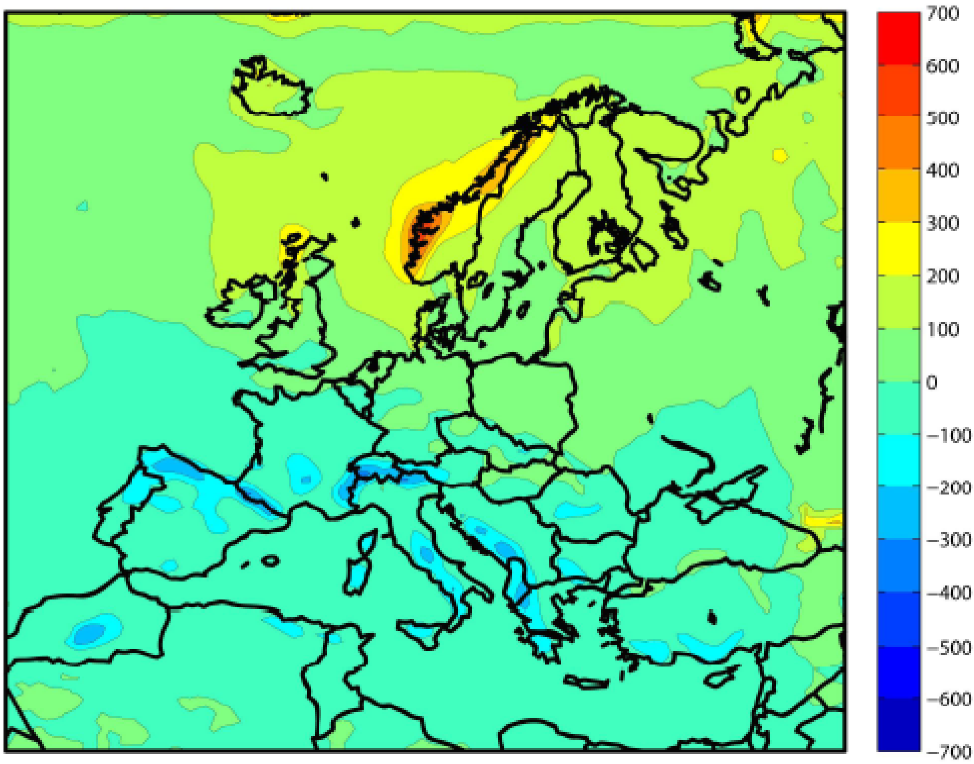

Figure 1: Change in the annual precipitation (Makkonen et al., 2010)

Makkonen et al. (2010) conclude that northern Europe (with increasing heavy rain spells) will experience significant effects, i.e. values of 3 to 4, with a possibility of reaching even extreme 5, on a scale from 1 to 5.

2.1.1 Effects on asphalt

From the available information, it can be concluded that significant increases in free water available in the asphalt-aggregate system have the potential to cause damages to the existing roadway. Increased stripping is a possible outcome of increased rainfall if the appropriate conditions are present. The extent of the stripping will be dependent on traffic loading and quality of construction practices.

Increased instances of intense rainfall may prove damaging if such rainfall events result in poor drainage, and in a worst case scenario result in flooding. In such events it is possible for asphalt pavements to experience saturation both within the pavement structure and the subbase. Saturated pavements are extremely susceptible to stripping mechanisms especially under traffic loading.

It is therefore necessary to identify increases in heavy rainfall occurrences, and design pavements that ensure no moisture is captured within the pavement structure. One method of doing so is by decreasing or increasing the interconnected air voids within the pavement structure. Therefore, designers often consider stone matrix asphalt (SMA) and porous pavements as valid alternatives to conventional dense graded asphalt.

2.1.2 Effects on porous asphalt

The impact of additional precipitation on porous asphalt will be dependent on the ability of the underlying mixtures of the pavement. In the event the underlying pavement is not well compacted and impermeable, there is the possibility that water will accumulate under the surface and ultimately lead to scouring of the lower layer mixture (D'Angelo & Anderson, 2003; Solaimanian et al., 2003).

Ravelling is known to occur within porous pavements when improper drainage is present, however, properly designed and constructed porous pavements have been shown to withstand moisture well (Roberts et al., 1996).

2.2 Freeze-Thaw

As seen in Figure 2, climate change predictions performed by Makkonen et al. (2010) anticipate:

"The amount of freeze-thaw cycles will decrease in both global model projections and scenarios except for the northernmost Europe, in particular Lapland."

Freeze-thaw cycles generate pore-pressures through cyclical thermal expansion and contractions of freezing and thawing water. This action tends to initiate cracking and result in cumulative damage of pavements and other porous materials.

Makkonen et al. (2010) anticipate a beneficial change in most European regions, it is further anticipated that this will decrease the pace of surface material degradation. With respect to infrastructure, Makkonen et al. do not anticipate significant changes and rate the threat as 1 on a 1 to 5 scale.

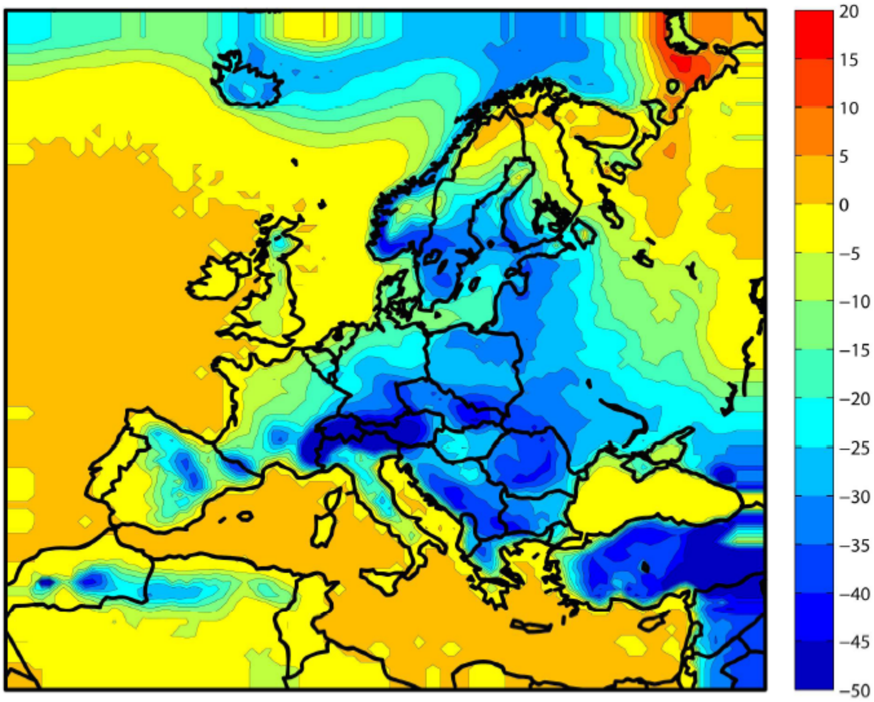

Figure 2: Absolute change in annual number of freeze thaw cycles (2071-2100)-(1961-1990) multi model mean(Makkonen et al., 2010)

2.2.1 Effects on asphalt

Freeze-thaw cycles have been known to cause pavement failures, however, as the Makkonen et al. (2010) report does not indicate significant increases in freeze-thaw events it is likely that properly designed and constructed asphalt pavements should not require any special attention as regards this issue.

2.2.2 Effects on porous asphalt

According to Makkonen et al. (2010), variations in the number of freeze thaw cycles will not require advanced measures, as "slippery" conditions are expected to decrease in most regions. Therefore, the use of porous pavements should not be contingent upon this aspect of predicted climate change.

2.3 Temperature

Figure 3 shows the anticipated scenario for climate change with respect to annual maximum temperature. These findings are interpreted by Makkonen et al. (2010) in the following manner:

"In all the models and scenarios the greatest change in the annual maximum temperature is observed in Central Europe; In France, in southern parts of Germany, northern Italy and in the Balkan region: 5 to 12 ^{o}C. In Western Europe the change is greater than in the Eastern Europe. In the Mediterranean region and Southern UK the change is not so extreme: 4 to 8 ^{o}C. In Northern Europe and Northern UK and Ireland the change is limited to 1 to 6 ^{o}C."

With regard to bitumen-coated roads, Makkonen et al. (2010) conclude:

"In the bitumen-coated roads rutting and deformation will significantly increase unless modifications are made to the surface materials in the future. One should most probably be

able to adapt to the increase in rutting in roads with a re-pavement cycle of less than 20 to 30 years. On thin paved roads the effect also applies to the unbound bearing layers and road base as the softened pavement redistributes the stress caused by traffic loading less effectively than planned. Changing of the pavement material to a more rigid one should be made by the middle of the century on thin paved roads to avoid unexpected deformations."

Makkonen et al. (2010) conclude the following with regards to the severity of temperature change:

"The graveness of financial and operational consequences as singular phenomena: Western Central Europe 3 and other regions 1 to 2 (scale of 1 – minor - to 5 - very severe)."

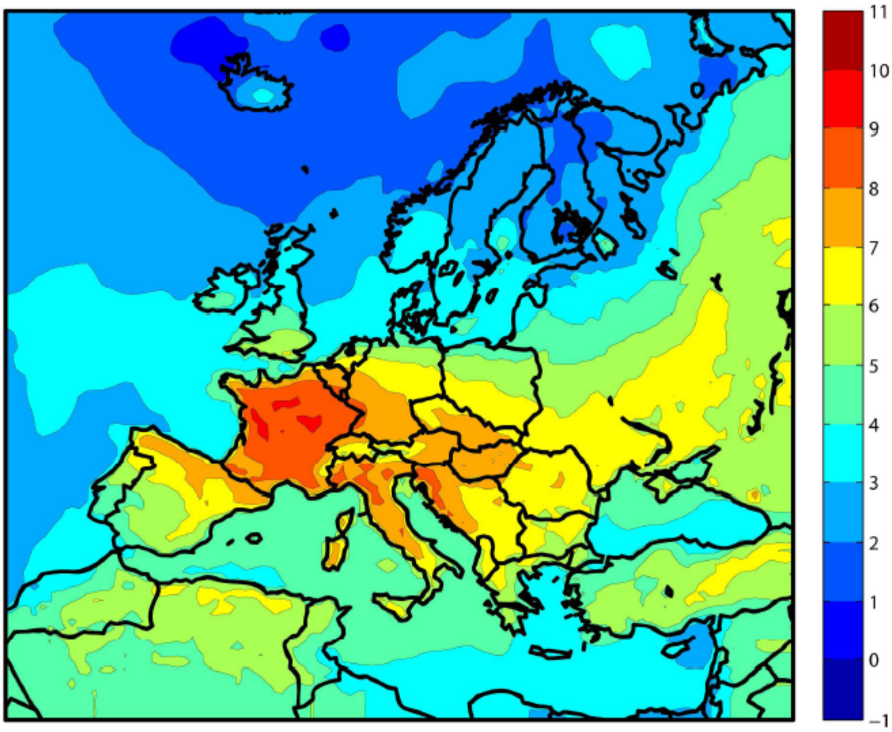

Figure 3: Change in the annual maximum air temperature (°C) (Makkonen et al., 2010)

2.3.1 Effects on asphalt

Asphalt binder is a visco-elastic material; as such its properties are temperature dependent. Additionally, as asphalt binders are today commonly graded based upon performance temperature, it is possible that variations in temperature may change the performance grade of the asphalt binder to be used in a particular location. Stripping may be a particular problem in locations experiencing significant increases in precipitation coupled with significant increases in maximum temperature. From Figures 1 and 3 it appears as if certain regions of France and central Europe fall into this category, especially because increases in temperature will tend to be significantly higher within the pavement at lower latitudes. Higher than anticipated pavement temperatures working in conjunction with excess moisture could lead to increased moisture damage.

Studies have shown that high pavement temperature is an important element of stripping; the adhesive strength of the asphalt binder at the aggregate interface is reduced with elevated temperatures. These factors render the pavement more prone to mechanical scouring (Kandhal & Rickards, 2001).

2.3.2 Effects on porous asphalt

The effects of heat are pronounced also on porous asphalt; in order for porous asphalt to maintain a high level of air voids, it is necessary to incorporate properly proportioned aggregates as well as the use of binders that exhibit the appropriate level of resistance to permanent deformation. Research has shown that modified binders tend to perform better than conventional binders with respect to permanent deformation for asphalt mixes with higher void contents (Kandhal & Mallick, 1999).

Therefore, in the event of increased temperatures it is possible that porous pavements will experience permanent deformation if the pavement temperatures exceed the design temperatures. This may in turn lead to uneven compaction of the road, and also to free water being captured within the air void structure. Continued temperature variation could lead to cyclic loading of the saturated pavement, thus leading to the development of increased pore-pressures and ultimately increased possibility of moisture damage.

3 Stripping

From the discussion on predicted climate change, it appears that moisture damage is a phenomenon that could significantly impact asphalt roads. In asphalt pavements stripping of the asphalt binder from the mineral aggregate is an indication of moisture damage within the asphalt-aggregate system. Kiggundu and Roberts (1988) define stripping as:

"The progressive functional deterioration of a pavement mixture by loss of the adhesive bond between the asphalt cement and the aggregate surface and/or loss of the cohesive resistance within the asphalt cement principally from the action of water."

Practically speaking, this equates to a removal of the glue that holds the stones together, and is also the starting point for numerous other pavement deterioration mechanisms. This method of deterioration manifests itself in a number of ways, but the following three steps of stripping can be used to identify a pavement experiencing moisture damage (Kandhal & Rickards, 2001):

- Deposition of water transported fine aggregate or dust from partially stripped aggregate on the road surface,
- Migration of asphalt binder to road surface or flushing, and
- Development of potholes in the flushed areas.

3.1 Mechanisms

There are a number of proposed mechanisms by which moisture removes the asphalt film from the aggregate, these include: Detachment, displacement, spontaneous emulsification, pore pressure, and hydraulic scouring (Shell Bitumen, 2003; Kiggundu & Roberts, 1988).

3.1.1 Detachment

Detachment is the process by which a microscopic separation of the asphalt film occurs from the aggregate by a thin layer of water without any obvious breaks in the film. This separation mode is thought to occur due to incomplete drying of the aggregate during production.

3.1.2 Displacement

Displacement involves the preferential removal of the asphalt film from the aggregate surface by water. Such failures occur when water is absorbed into the aggregate through an inconsistency in the asphalt binder film. As aggregate has a higher affinity for water than asphalt binder, the water tends to displace the asphalt film around the aggregate.

3.1.3 Spontaneous Emulsification

Spontaneous emulsification occurs when an inverted phase emulsion forms with the hot mix asphalt (HMA), this means that the water becomes suspended in the asphalt. This failure mode results in cohesive failures, however, the difficulty in assessing this failure lies in the fact that asphalt is not visibly removed from the aggregate.

3.1.4 Pore-Pressure

Pore-pressure occurs due to the presence of water in the interconnected voids of the HMA. As the HMA mat becomes denser following traffic loading, it is not uncommon for the air voids to become isolated and therefore no longer interconnected. This results in increasing and decreasing pore-pressure as traffic passes over the isolated air void sections. The effect of the variations of pore-pressure can lead to ruptures of the asphalt film, and ultimately lead to displacement or hydraulic scour.

3.1.5 Hydraulic Scour

Hydraulic scour occurs in surface layers when vehicle tires apply loads to saturated HMA. This leads to water being compressed into the pavement void structure, and subsequently released as the vehicle passes. The release of the water creates a vacuum in the void structure, which contributes to the compression-tension cycle, ultimately leading to moisture damage via displacement or spontaneous emulsification.

As seen in Table 1, stripping may occur singularly or through a combination of any of these mechanisms. In many instances one mechanism may act as a catalyst and lead to a combination of factors working in tandem to speed up the effects of moisture damage.

Table 1: Proposed relationships between theories of adhesive bond loss and stripping mechanisms (Kiggundu & Roberts, 1988)

		THEORY								
		Mechanical Interlock			Chemical Reaction			Interfacial Energy		
	Proposed Operating Mode	P	C	P-C	P	C	P-C	P	C	P-C
Stripping Mechanism	**Detachment**	S						S	W	
	Displacement					S		S		
	Spontaneous Emulsification				S	W				
	Film Rupture	S								
	Pore Pressure	S								
	Hydraulic Scouring	S								
	pH Instability					S				S

P = Physical
C = Chemical
P-C = Physical – Chemical
S = Primary Contributor
W = Secondary Contributor

3.2 Causes

Stripping is a complex phenomenon, and as such can be influenced by many of the variables present in an asphalt pavement. As seen in Table 2, research has narrowed the factors influencing moisture damage down to some principal contributing factors.

3.2.1 Pavement Design

While stripping is often related to the presence of moisture in the HMA, there is general agreement that many moisture related issues can be solved through the use of suitable paving materials and by designing the pavement with drainage as a priority.

Adequate pavement drainage must be employed to avoid stripping problems in asphalt pavements. Case studies have shown that stripping can be a localized phenomenon which occurs primarily in locations which are oversaturated with water/water vapour due to inadequate subsurface drainage conditions (D'Angelo & Anderson, 2003; Kiggundu & Roberts, 1988; St. Martin et al., 2003).

Table 2: Factors influencing moisture related distresses (Hicks et al., 2003)

MIX DESIGN	• Binder and aggregate chemistry • Binder content • Air voids • Additives
PRODUCTION	• Percent aggregate coating and quality of passing the No. 200 sieve • Temperature at plant • Excess aggregate moisture content • Presence of clay
CONSTRUCTION	• Compaction—high in-place air voids • Permeability—high values • Mix segregation • Changes from mix design to field production (field variability)
CLIMATE	• High-rainfall areas • Freeze–thaw cycles • Desert issues (steam stripping)
OTHER FACTORS	• Surface drainage • Subsurface drainage • Rehab strategies—chip seals over marginal HMA materials • High truck ADTs.

Water captured in the subgrade or the subbase may lead to vapour saturation of the air voids within the asphalt matrix in the event of temperature increases. Such events lead to significant increases in void pressure, which in turn are exacerbated by the pore pressure exerted by vehicle traffic on the pavement surface. These various stresses indicate that the internal water is in frequent motion and with time may contribute to a significant build up of pore-pressure (Roberts et al., 1996).

3.2.2 Material Selection

Material selection is known to heavily influence the moisture sensitivity of an asphalt pavement; of particular importance in such instances is the compatibility between the asphalt binder and mineral aggregate to form a cohesive bond (Shell Bitumen, 2003). As shown in Table 3, there are numerous physico-chemical properties of asphalt, aggregate, and the mixture itself which may influence the stripping potential of an HMA pavement.

Compatibility between the asphalt and aggregate is another important element to consider when evaluating the materials to be used in an HMA mix. Aggregates and asphalt are not all the same, and therefore, their mix properties are even more variable. As seen in Figure 4, the same binder using the same anti-strip additives, but different aggregates can exhibit varied responses with respect to tensile strength ratio (TSR) values (Putman & Amirkhanian, 2007; Tarrer & Wagh, 1991).

Table 3: Physico-Chemical Properties of asphalt, aggregate, and mixture influencing stripping (Yoon & Tarrer, 1988)

Materials	Physicochemical Properties
Asphalt	Viscosity Surface tension Volatility Relative fraction polar constituents Phenol group concentrations Carboxylic group concentrations Amine group concentrations
Aggregate	Size and shape Pore volume and size Surface area Chemical constituents at surface Acidity and alkalinity Adsorption site surface density Surface charge or polarity
Asphalt-Aggregate Mixture	Pore space fraction filled with asphalt Asphalt adsorption ratio Chemical constituents of adsorbed asphalt

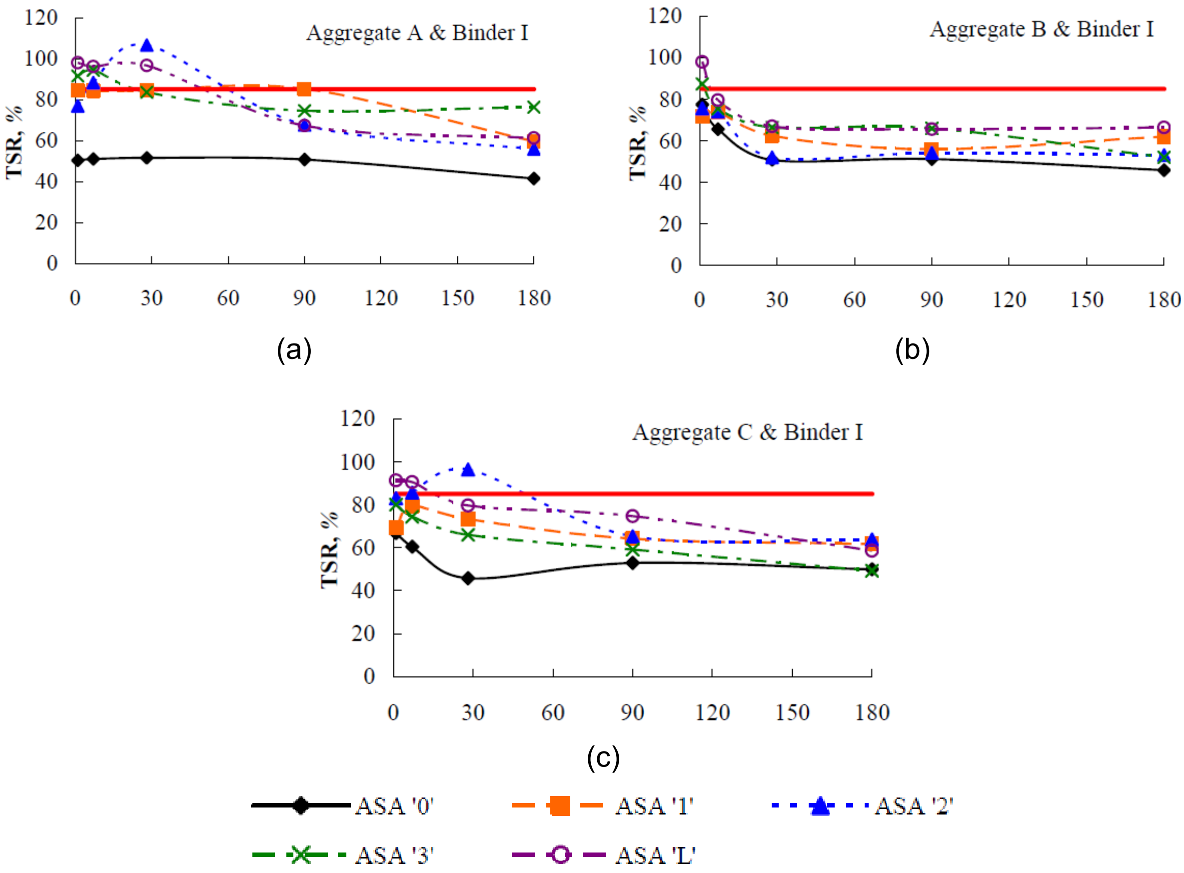

Figure 4: TSR % vs.conditioning duration (days)(ASA'0': no anti-strip agent, ASA'1-3': Liquid anti-strip agents, and ASA 'L': Hydrated lime) (Putman & Amirkhanian, 2007)

From Figure 4 it can be seen that the aggregate-binder combinations which used some form of anti-strip agent consistently yielded higher TSR values than the control samples prepared without anti- strip additives. As the conditioning time increased all the mixes showed lower TSR values, thus indicating a continued weakening of the samples. In this particular instance a minimum TSR acceptance value was set at 85% by the governing state agency, therefore it can clearly be seen that the ability of a binder-aggregate combination to meet acceptance criteria is dependent on the combined properties of the aggregate, binder, and anti-strip agent.

3.2.3 Production and Construction

During production and design, it is important to ensure that the aggregates used are of good quality and do not exhibit weak and friable properties. It is also necessary that the aggregate is sufficiently dry as moist aggregate provides an excellent starting point for later stripping problems (D'Angelo & Anderson, 2003).

Intimate contact between the asphalt cement and aggregate must be promoted in the mix, therefore, the openings in the asphalt-aggregate interface provided by dust coatings must be avoided as these cause the asphalt to stick to the dust coating rather than the aggregate (Roberts et al., 1996).

Dust coated aggregate should be avoided as there is the possibility that if the dust is a clay it might act as an emulsifier. As clay tends to expand in the presence of water, there is the possibility that the asphalt film might be lifted off the surface of the aggregate due to the expansion of the clay (D'Angelo & Anderson, 2003).

Construction practices play an important role in moisture sensitivity. According to Roberts et al. inadequate compaction of the HMA mat is probably the most common construction-related factor related to stripping. If the design air voids are not met during the compaction stage, excessive water may enter the pavement structure thus contributing to hydraulic pore-pressures build-up caused by traffic (Roberts et al., 1996).

3.2.4 Climate and Loading

The mechanisms through which stripping occurs are often dependent on the loading action of traffic as well as the presence of water. If the pavement is allowed to spend extended periods of time in water it is possible that increased pavement saturation will also occur. Heavy traffic loading in such instances can lead to high pressure build ups, which ultimately may exceed the adhesive strength of the asphalt film to the aggregate (Bagampadde & Kiggundu, 2006).

Additionally, as temperatures increase the viscosity of the asphalt will decrease. If this occurs in conjunction with a recent rainfall, it is possible that the asphalt binder will creep up the edges of the water droplets to form blisters. As temperatures continue to increase, the blister will continue to expand thus leaving a pit through which the water can access the aggregate (Shell Bitumen, 2003).

Saturation followed by stripping can be equally harmful in cold temperatures where the development of ice crystals within the asphalt matrix can lead to the development of high pore pressures which can lead to stripping as well (Kiggundu & Roberts, 1988).

3.3 Solutions

According to the Shell Bitumen Handbook, 80% of all asphalt/aggregate adhesion issues can be controllable during the production and construction phase (Shell Bitumen, 2003). Generally speaking, drainage issues are known to be a significant source of moisture related damages within asphalt pavements. For this reason rapid removal of water from the pavement layers should be prioritized. Additionally, good construction practices are needed if moisture damage is to be avoided, such practices include:

- Ensuring that target compaction levels are met.
- Use of clean aggregate that does not have excessive dust coatings.
- Ensuring that all aggregates used in the mix exhibit dry surfaces.
- Avoiding the use of weak and friable aggregate.

Caution must also be used when overlaying HMA pavements over deteriorated concrete pavements. Such deteriorated pavements often contain significant quantities of water and are conducive to moisture vapour build up in the system. Similarly, caution must also be used in the application of water proofing membranes and seals. If used wrongly, these seals may act as vapour seals, thus effectively capturing the moisture within the system (Roberts et al., 1996).

Numerous additives have been shown to promote adhesion between asphalt binder and aggregate, these include:

- Liquid anti-stripping additives: These additives are added in liquid form to the asphalt cement, they act as surface activation agents which promote increased adhesion of the asphalt binder to the mineral aggregate (Tarrer & Wagh, 1991).
- Lime additives: These additives are added to the aggregate, and have been proven to be very effective at mitigating moisture damage through improved adhesion of asphalt binder and aggregate (Putman & Amirkhanian, 2007).
- Modified asphalt binders: Polymer modifiers such as SBS are typically used to modify the asphalt binder; such modifiers tend to improve the performance of the binder by increasing its elasticity and decreasing its susceptibility to permanent deformation. These binders typically yield greater film thicknesses, which have been shown to protect against moisture damage (Gorkem & Sengoz, 2009).

4 Unravelling of Porous Asphalt

Porous asphalt, also known as an Open Graded Friction Course (OGFC) (CalAPA, 2010), has developed into an attractive solution for planners and engineers alike. This pavement type is typically characterized by a higher void content than conventional pavements. The purpose of the increased void content is to permit the drainage of water through the pavement layer. Such pavements are constructed using a larger percentage of coarse aggregate. Advantages associated with these pavements include reductions in hydroplaning, improved skid resistance, improved visibility, improved surface reflectivity, and reduced road noise (Kandhal & Mallick, 1999).

In addition to using a larger amount of coarse aggregate, it is not uncommon for porous pavements to exhibit slightly higher binder contents as well. It is also common practice to use modified binders when constructing porous pavements, in fact many agencies specify that modified binders must be used when building porous pavements (CalAPA, 2010).

While there are numerous advantages associated with porous asphalt, research and field experience has shown that these pavements are prone to distresses as well. In the past many US states suspended the use of porous pavements due to stripping related issues that affected their porous pavements. In many instances, ravelling was noted as one of the failure methods of porous pavements.

Ravelling is typically a symptom of top down stripping; it is characterized by a progressive disintegration of the asphalt layer as a result of the dislodgement of the aggregate particles. Stripping is not the only cause of ravelling; rather it is one of a number of factors that promote ravelling.

In some cases porous pavements retain moisture longer than conventional pavements. Additionally, studies have shown that when using porous pavements stripping occurs in the layers underlying the porous section of the pavement. Therefore, in the event that a porous pavement solution is used it is of utmost importance for the underlying pavement section to be tested for moisture susceptibility (Roberts et al., 1996).

Properly designed and constructed porous pavements are extremely durable with respect to moisture damage. As seen in Figure 5, the air voids of the HMA mix are extremely important in dictating its moisture sensitivity. Permeable pavements lie on the free draining side of this chart; therefore, when they work properly they are not subjected to the harmful effects of still standing water within the mix. Of specific importance when using porous pavements are the properties of the underlying mixture. This mixture must be well compacted and impermeable, if not the water may accumulate in the semi-permeable mixture and result in scouring following traffic loading (D'Angelo & Anderson, 2003).

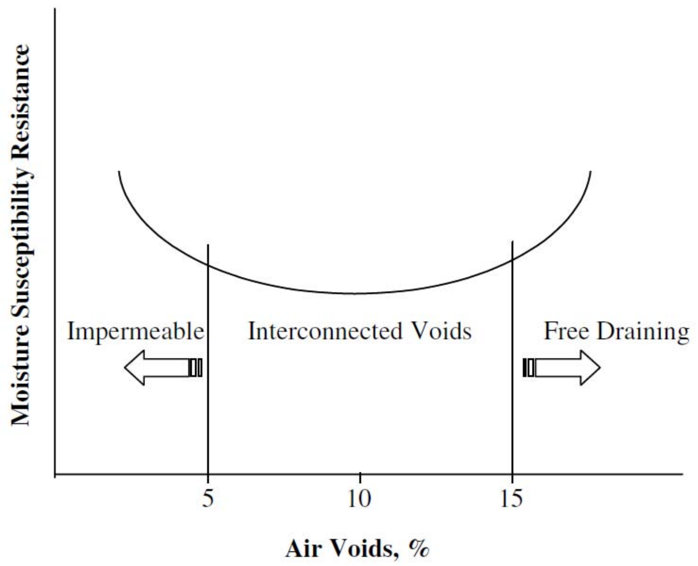

Figure 5: Research concept of pessimum voids(Terrel & Shute, 1989)

5 Resistance to Permanent Deformation

Moisture damage may also lead to permanent deformation, in fact many tests use permanent deformation as a criterion in evaluating the extent of moisture damage. When rutting occurs in conjunction with moisture damage it typically happens due to a loss of strength in the asphalt due to the presence of moisture (Epps Martin et al., 2003).

Permanent deformation may be a specific concern relating to stripping problems when the stripping occurs due to progressive blistering. If low viscosity binders are used during construction, there is the possibility that blistering may lead to water entrainment of the binder, and that these might lead to increased susceptibility to permanent deformation (Shell Bitumen, 2003). Rutting may also occur if water saturation decreases cohesion within the aggregate matrix, thus resulting in uneven compaction along the wheel path due to traffic loading.

The occurrence of permanent deformation of this nature generally decreases with time, as the binder ages it tends to oxidize and harden, thus becoming less susceptible to permanent deformation and water infiltration (D'Angelo & Anderson, 2003).

6 Relevant Laboratory Test Methods

The tests used to evaluate moisture sensitivity are dependent on the agency responsible for assuring the quality of the mix. However, ASTM and AASHTO standards have been developed for evaluating moisture sensitivity of asphalt mixes. Laboratory tests for evaluating properties relevant to stripping and coating of asphalt mixes generally fall into two categories: Those conducted on loose mixes (Table 5) and those conducted on compacted mixes (Table 6). Tests conducted on loose samples provide an estimate of asphalt-aggregate compatibility and stripping potential. Tests conducted on compacted mixes attempt to take into consideration mix properties (compaction, air voids, gradation, etc.), water action, and effect of traffic.

The importance of asphalt-aggregate compatibility cannot be understated; therefore, such tests provide an excellent method of quickly and inexpensively evaluating asphalt-aggregate combinations.

While the use of particular tests is agency dependent, statistics are available as to which methods are more commonly used. As seen in Table 4, the Modified Lottman test is commonly used in the US. It and has also proven to show varying degrees of correlation with field performance (Hicks et al., 2003; Epps et al., 2003). While the test methods referred to in Tables 4-6 mention ASTM standards, these are similar in nature to test methods used throughout Europe.

Table 4: Most commonly used moisture sensitivity tests (Hicks et al., 2003)

Test Method	No. of Agencies Using
Boiling water (ASTM D3625)	0
Static immersion (AASHTO T182)	0
Lottman (NCHRP 246)	3
Tunnicliff and Root (ASTM D4867)	6
Modified Lottman (AASHTO T283)	30
Immersion–compression (AASHTO T165)	5
Wheel tracking	2

Table 5: Moisture sensitivity tests on loose samples (Solaimanian et al., 2003)

Test	ASTM	AASHTO	Other
Methylene blue			Technical Bulletin 145, International Slurry Seal Association
Film stripping			(California Test 302)
Static immersion	D1664*	T182	
Dynamic immersion			
Chemical immersion			Standard Method TMH1 (Road Research Laboratory 1986, England)
Surface reaction			Ford et al. (1974)
Quick bottle			Virginia Highway and Transportation Research Council (Maupin 1980)
Boiling	D3625		Tex 530-C Kennedy et al. 1984
Rolling bottle			Isacsson and Jorgensen, Sweden, 1987
Net adsorption			SHRP A-341 (Curtis et al. 1993)
Surface energy			Thelen 1958, HRB Bulletin 192 Cheng et al., AAPT 2002
Pneumatic pull-off			Youtcheff and Aurilio (1997)

* No longer available as ASTM standard.

Table 6: Moisture sensitivity tests on compacted samples (Solaimanian et al., 2003)

Test	ASTM	AASHTO	Other
Moisture vapor susceptibility			California Test 307 Developed in late 1940s
Immersion–compression	D1075	T165	ASTM STP 252 (Goode 1959)
Marshal immersion			Stuart 1986
Freeze–thaw pedestal test			Kennedy et al. 1982
Original Lottman indirect tension			NCHRP Report 246 (Lottman 1982); Transportation Research Record 515 (1974)
Modified Lottman indirect tension		T 283	NCHRP Report 274 (Tunnicliff and Root 1984), Tex 531-C
Tunnicliff–Root	D 4867		NCHRP Report 274 (Tunnicliff and Root 1984)
ECS with resilient modulus			SHRP-A-403 (Al-Swailmi and Terrel 1994)
Hamburg wheel tracking			1993 Tex-242-F
Asphalt pavement analyzer			
ECS/SPT			NCHRP 9-34 2002-03
Multiple freeze–thaw			

Loose sample testing varies from country to country; however, the principles behind the test are generally similar to the ones used in AASHTO T 182. The procedure for this test involves coating coarse aggregate (9,5-6,3 mm) with asphalt and any required anti-strip agents. The resulting loose mixture is then immersed in distilled water for 24 hours and subsequent degree of stripping noted under water to estimate the degree of bitumen coating still present on the aggregate.

Other versions of loose sample testing involve exposing the mix to elevated temperatures as well as moisture. The Texas boiling test (ASTM D 3625) involves adding the asphalt-aggregate mixture to boiling water and then re-boiling the water after the addition of the mixture. The mix is then visually inspected and asphalt coating noted. This test procedure is a quick method for evaluating the moisture sensitivity of an asphalt-aggregate mixture, however, it does not account for mechanical properties of the mix nor does it take into account effects of traffic action.

Compacted sample testing generally involves the preparation of asphalt samples (with all additives), exposure to water, and evaluation of physical properties. AASHTO T 283, commonly known as the Modified Lottman test, was developed to compare the indirect tensile strength test results of a dry sample and corresponding sample exposed to water as well as freeze/thaw cycles. The TSR value is obtained through testing the dry and wet samples and calculating the corresponding ratio:

$$TSR = \frac{S_2}{S_1}$$

Where,

TSR = Tensile Strength Ratio

S_1 = Average dry sample strength

S_2 = Average conditioned sample strength

Typically field produced samples are expected to achieve a minimum TSR value of 0.70, however, according to AASHTO laboratory produced samples should achieve a minimum TSR value of 0.80 to meet moisture susceptibility requirements.

Another variation of compacted sample testing is the Hamburg Wheel-Tracking Device (HWTD): Originally invented in Hamburg, Germany, this device is today used to measure the combined effects of rutting and moisture damage by rolling a steel wheel across a compacted asphalt specimen immersed in hot water. The test is complete when a rut depth of 20 mm or 20,000 wheel passes are achieved. As seen in Figure 6, an additional advantage of this test lies in its ability to quantify the various responses of the pavement to loading.

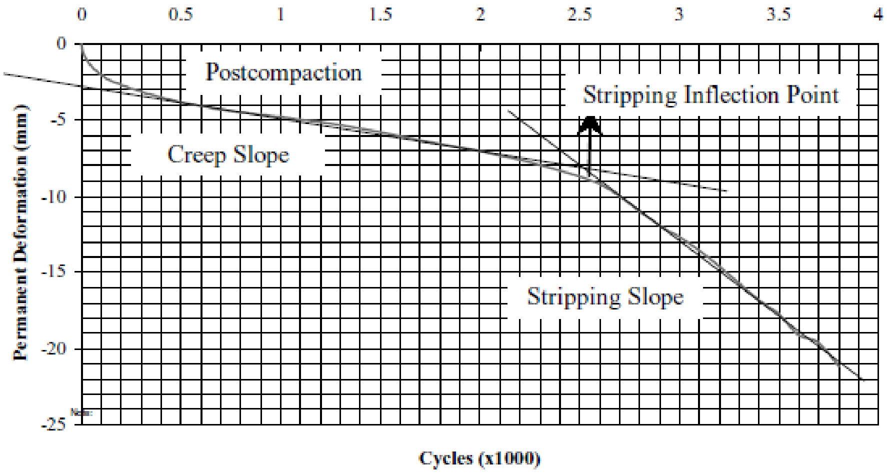

Figure 6: Sample results of HWTD

7 Laboratory Studies

The following section provides some information on recent laboratory studies conducted on the effects of moisture on asphalt mixes. Emphasis has been placed on identifying studies that provide information on how the presence of moisture damages asphalt, and subsequent remediation and design methods that have been shown to mitigate the damaging effects of moisture.

7.1 *Effect of Moisture on Strength*

Copeland's research on the effects of moisture on strength of asphalt-aggregate mixtures provides information on the variation of strength of the asphalt mixture with respect to moisture content. As seen in Figure 7, as moisture content in the asphalt mix increases, the percent strength decreases. These findings indicate that strength of the mix is dependent on the moisture content, and that moisture tends to weaken the mix.

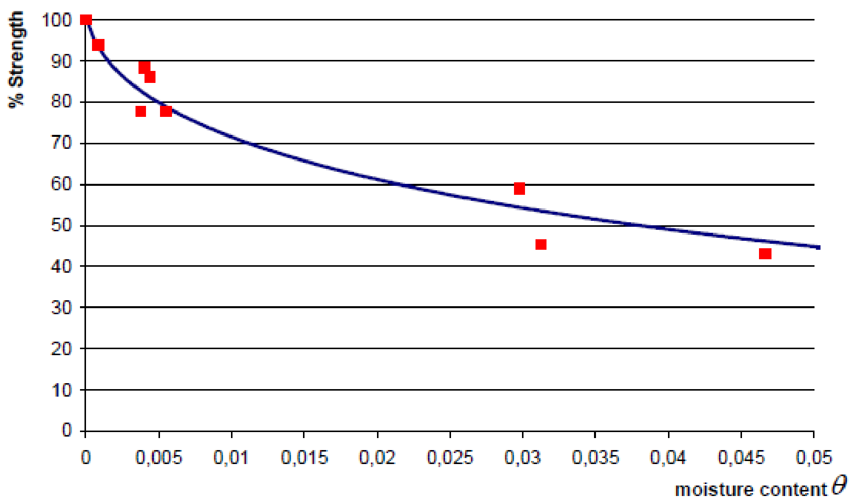

Figure 7: Effect of moisture content on strength(Copeland, 2007)

7.2 *Use of Modified Asphalt and Hydrated Lime*

Numerous additives such as hydrated lime and polymer modifiers have been used successfully to decrease the detrimental effects of moisture damage. Details of research conducted by Gorkem and Sengoz provide quantification of the effects of these additives.

Research conducted by Gorkem and Sengoz confirmed that mixtures produced with SBS and EVA polymer produced HMA mixtures with reduced stripping potential and moisture susceptibility compared with HMA mixtures prepared with conventional asphalt binder (Gorkem & Sengoz, 2009). The increases in TSR values following the use of polymer modifiers ranged between 4 and 8% depending on polymer type and concentration. They concluded from these findings that polymer modified binders provide increased adhesion to the aggregate, thus creating a network structure within the bitumen. These results are clearly illustrated in Figures 8 and 9, whereby it is apparent that as modifier concentration increases so too does the ITS and the TSR.

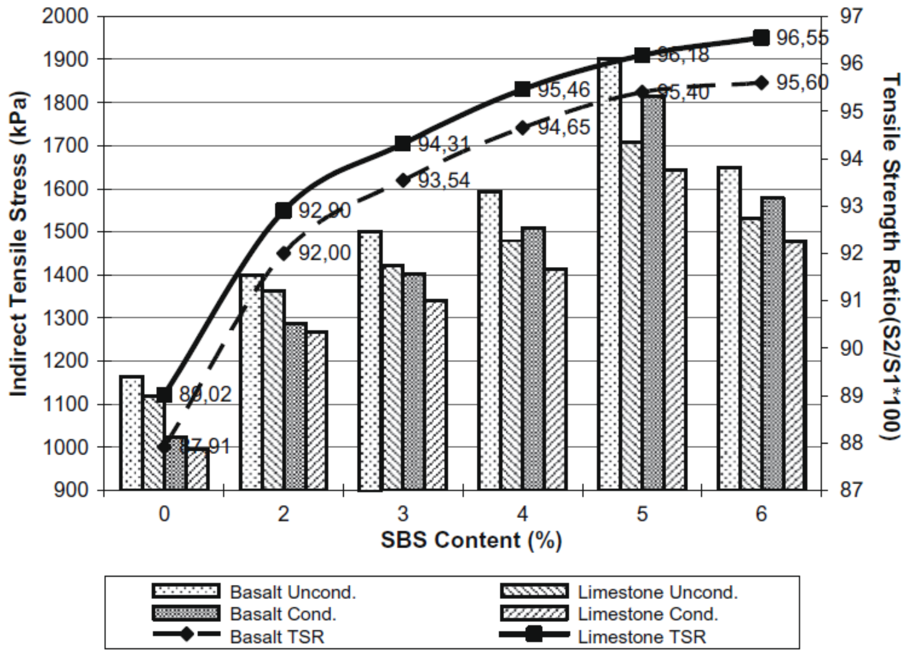

Figure 8: ITS and TSR results for each type of aggregate with SBS PMB(Gorkem & Sengoz, 2009).

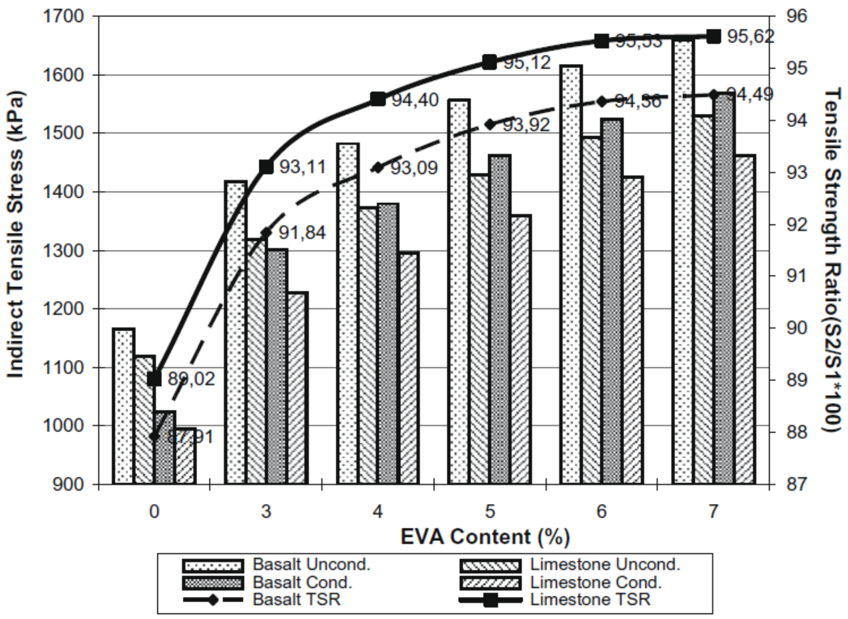

Figure 9: ITS and TSR for each type of aggregate with EVA PMB (Gorkem & Sengoz, 2009).

As seen in Figure 10, the addition of hydrated lime increased TSR values. The ability of hydrated lime to protect against moisture damage is dependent on the type of aggregate used; however, it has proved successful enough that many specifying agencies routinely require hydrated lime to be used in all mixes.

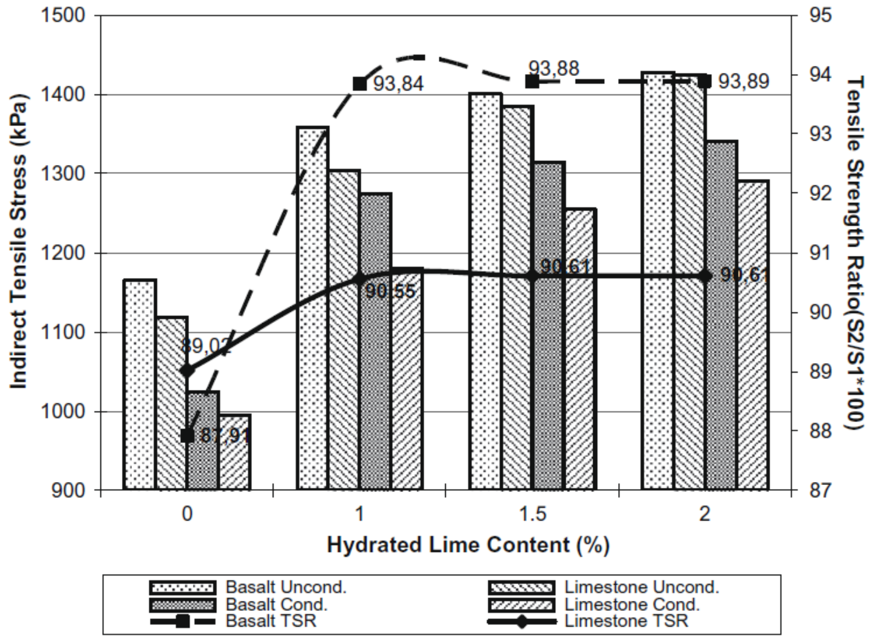

Figure 10: ITS and TSR results for each types of aggregate with hydrated lime additive (Gorkem & Sengoz, 2009)

7.3 Film Thickness

In other research presented by Sengoz and Agar, it was shown that there is a strong correlation between TSR values and the asphalt binder film thickness. From Figure 11 it can be seen that there is a linear relationship between TSR value and film thickness for film thicknesses between 5 and 11.5 micrometers. Sengoz and Agar conclude that the optimum range of asphalt film thickness lies between 9,5 and 10,5 µm.

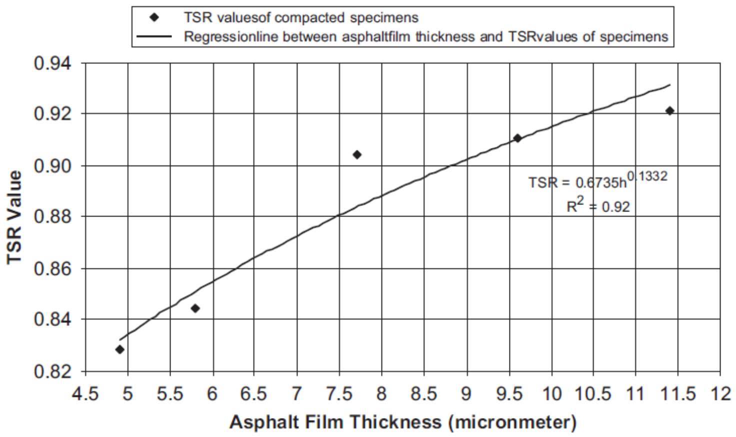

Figure 11: Relationship between asphalt film thickness and the tensile strength ratio (TSR)(Sengoz & Agar, 2006)

7.4 Freeze-Thaw Cycles

Research has shown that freeze-thaw cycles have an effect on the strength of the mix. As seen in Figure 12, when specimens were subjected to increasing freeze-thaw cycles the TSR values consistently decreased. However, samples prepared using lime and anti-strip additives tended to lose less strength than samples with no anti-strip treatment. These findings correlate with the visual stripping identified in Figure 13, whereby it was noted that visual stripping of the samples increases with increasing freeze-thaw cycles. These findings suggest that freeze-thaw cycles promote stripping of the asphalt, which in turn results in a weakening of the mix.

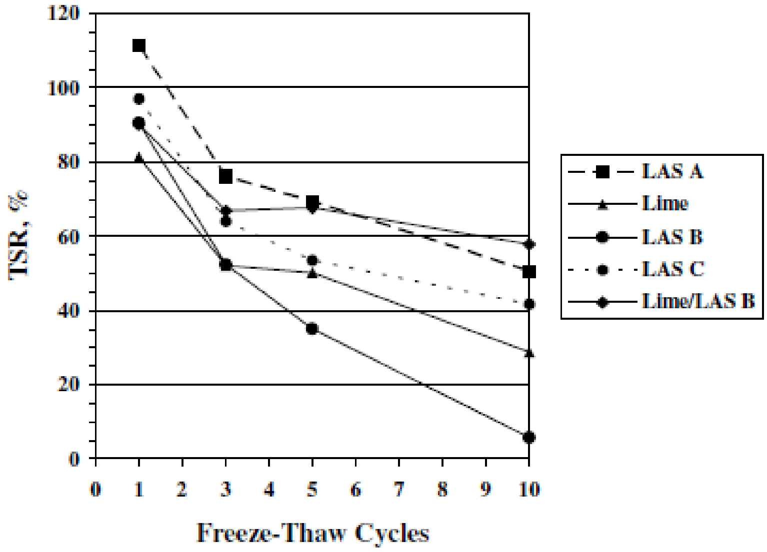

Figure 12: TSR test results as a function of freeze-thaw cycles for various antistrip agents in mixtures in Louisiana (Epps et al., 2003)

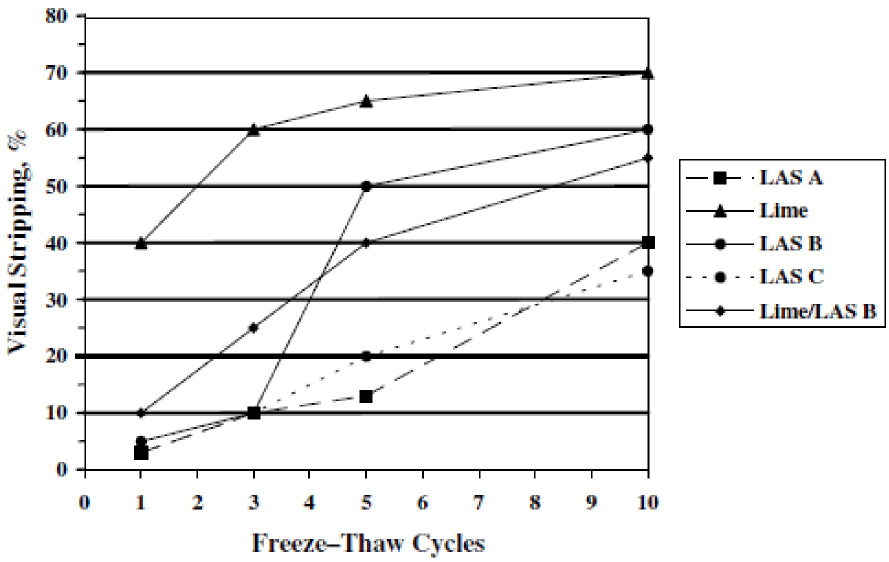

Figure 13: Visual stripping results as a function of freeze-thaw cycles for various antistrip agents in mixtures in Louisiana (Epps et al., 2003)

8 Experience from Field Trials

8.1 Kandhal and Rickards, 2001

In a field study from the US, the detrimental effects of poor drainage and construction were evident. The Pennsylvania Turnpike project was a 37 mm thick dense graded wearing course laid in 1994. The project started to exhibit premature distress in 1996, following onsite observations of the pavement the following signs of moisture damage were noted: fines brought to the surface by water (mud stains), flushing of the surface, and potholing (Figure 14). Potholes had formed in both lanes, however, there were more potholes in the inside wheel track than the outside wheel track. Rutting had also started to develop in a number of locations.

Figure 14:Potholes and rutting in Pennsylvania Turnpike (Kandhal & Rickards, 2001)

The pavement consisted of five HMA courses laid over an existing Portland cement concrete pavement (PCCP). Holes were cut in the pavement to get a better idea of the mechanisms driving the pavement failure. From the holes the investigators discovered that the underlying PCCP surface was very wet. It was thought that the moisture was being pulled from the subbase under the paved median in the asphalt overlays. Subsequent testing of asphalt cores removed from the site revealed that the top layer of the pavement (especially under the wheel tracks) had been significantly compacted, thus rendering the top layer impermeable. These conditions meant that the water was captured within the pavement system and did not have a way of draining out. As pore water pressures built up from a combination of thermal expansion and cyclic stresses, the bond between the aggregate and asphalt became strained and ultimately failed thus resulting in stripping.

The investigators believed that some of the underlying layers were already stripped prior to the 1994 overlay. It was thought that earlier stripping had caused the moisture to migrate upward, causing surface flushing. Flushed areas developed into potholes due to the fact that there was only bare aggregate underneath. This in turn allowed more water to enter the system, thus promoting additional stripping of the pavement to occur.

Ultimately the investigators recommended milling off all the asphalt overlays (approximately 200 mm) right down to the PCCP. They suggested rubblizing the existing PCCP and the installation of a 100 mm thick layer of asphalt treated permeable material (ATPM) over the rubblized PCCP. Additionally, they suggested that ATPM be connected on both sides to longitudinal edge drains.

With regards to construction materials, the investigators suggested the use of 1-1.5% of hydrated lime (by weight of aggregate). The report mentions that hydrated lime is not a substitute for drainage, rather a method of increasing the resistance of the HMA to stripping. The investigators recommended the use of AASHTO T283 (modified Lottman test) to determine the mix's resistance to moisture damage.

8.2 Bagampadde and Kiggundu, 2006

In research conducted by Bagampadde and Kiggundu (2006), an evaluation of a 65,6 km stretch of highway in Uganda was undertaken. The road was rehabilitated in 2002 with a 150 mm lime stabilised gravel sub-base, 125 mm crushed stone base, and a 100 mm dense asphalt mixture. Within two years of service the road was showing moisture damage related failures.

The evaluation of the pavement was done using two randomly selected sections of the roadway. Sieve analysis of the recovered aggregate confirmed that the aggregate gradation was still within the required specifications. Core samples were removed from three locations within the roadway: The inner wheel track (IWT), outer wheel track (OWT), and between wheel tracks (BWT). Analysis of these cores revealed that the inner and outer wheel tracks yielded saturation levels that were statistically similar, but that were twice as high as the saturation levels in the BWT cores. When visual stripping levels were compared for the various sections it was seen that the IWT and the OWT sections were statistically similar, but the BWT sections revealed less stripping.

The amount of water these pavement sections were exposed to was also dependent on the depth of the water table. Analysis of the core results indicated that water table depth had a statistically significant effect on the percent of in situ moisture, percent saturation, and the stripping rate. In situ moistures were found to be significantly higher in shallow water tables than deep water tables.

The researchers concluded that the degree of saturation influenced the pore water pressures induced by truck tire loading. This in turn caused increases in pressure due to cyclic loading caused by traffic, ultimately resulting in the pressurized water breaking the seal between the asphalt and the aggregate.

Conclusions from the report identify the importance of water table depth on stripping levels and compaction of air voids. These findings indicate that as saturation increases in air voids that are not interconnected, so too does the rate of stripping noted (Bagampadde & Kiggundu, 2006).

9 Conclusions

Asphalt pavements are climate sensitive, as a result of this they are designed to satisfy conditions historically present in a given area. When these conditions deviate significantly, it is not uncommon for the asphalt pavements to experience distresses. In the event of increased precipitation it is anticipated that incidences of stripping and stripping related failures may increase. Excess water in the HMA generally leads to stripping; however, the nature of the stripping is dependent on how and when the asphalt and water are introduced to one another as well as a series of design, construction, and loading related issues.

With respect to moisture damage in asphalt pavements, the following conclusions can be made:

- Causes: Factors promoting stripping include: inadequate pavement drainage, inadequate compaction of the HMA pavement, excessive dust coating on the aggregate, inadequate drying of the aggregates, use of weak and friable aggregates, overlays on deteriorated concrete pavements, use of waterproofing layers and seal coats when there is moisture beneath the pavement, and the inappropriate use of open graded friction courses.
- Pavement design: Adequate pavement design principles must be used during the design stage. Specifically, testing must be done to assess the compatibility of the asphalt-aggregate mix to be used as well as to evaluate the performance of a given pavement to climatic and traffic effects. The effect of traffic and loading on stripping cannot be understated as the pore water pressure that is built up from traffic loading is often one of the principal actors involved in the stripping mechanism.
- Additives: Liquid anti-strip agents, hydrated lime, and the use of modified asphalt have been shown to significantly increase the moisture resistance of pavements. The use of such additives can be used to increase the moisture resistance of a binder-aggregate blend; however, they are not a substitute for good drainage.
- Testing: Laboratory procedures are available to evaluate both asphalt-aggregate compatibility as well as the effects of loading and climate on the mix. Required values have been set for these parameters to ensure that moisture resistant pavements are produced. For the best pavement design it is important that all pavement variables (including anti-strip additives) be tested together.
- Porous pavements: As with all other pavement types, the success of these pavements is dependent upon proper design and construction of the pavement. When properly designed and built, these pavements should be a possible option.

Climate change models indicate that there is a possibility that some aspects of the climate will experience changes in the coming years. These changes are variable across the European continent; therefore, their effects will also be varied with regard to effect on infrastructure. With respect to the effects of climate change scenarios on asphalt pavements in Europe, the following conclusions can be made:

- Increases in moisture damage of asphalt pavements are a possible outcome of increased rainfall. The extent of the stripping will be dependent on traffic loading and quality of construction practices. Specifically, instances of intense rainfall may prove damaging if such rainfall events result in poor drainage, and in a worst case scenario result in flooding. The extent of damages will also depend on the proportional increase of pavement temperature to air temperature; generally pavement temperatures tend to decrease as one goes north in Europe.

- Stripping may be a particular problem in locations experiencing significant increases in precipitation coupled with significant increases in maximum temperature. Certain regions of France and central Europe appear especially at risk as increases in temperature will tend to be significantly higher within the pavement at lower latitudes. These damages may be particularly severe if low viscosity asphalt binders were used during production.
- Freeze-thaw cycles are not projected to increase; therefore, it is likely that properly designed and constructed asphalt pavements should not require any special attention due to this issue.
- Good design and construction practices should ensure that increased rainfall does not contribute to additional moisture damage. With regards to designing and constructing pavements that are less susceptible to external moisture damage, there is a significant body of knowledge that can be drawn upon to provide guidance on the topic.

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