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Review

A review on moisture damages of hot and warm mix asphalt and related investigations

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ABSTRACT

Moisture damage has been reported as one of the main forms of distress in asphalt mixtures since the 1900s. The bond between asphalt aggregate constituents fails in the presence of water interacting at the interface, resulting in the stripping of binder from the aggregate surface and cohesive failure within the asphalt binder. This paper reviews various techniques and investigations for assessing the moisture damage and aims to optimize the standard testing protocols. The introduction of new in-situ testing techniques and material selection criteria is required to address the moisture susceptibility of asphalt mixtures. These efforts can improve the field assessment of moisture damage that appears during the design life of an asphalt pavement and bridge the gap between field and laboratory investigations.

1. Introduction

Moisture damage in asphalt mixtures has remained a topic of debate among investigators for many years. Moisture shortens the service life of asphalt mixtures, resulting in failures such as alligator cracking, ravelling, potholing and rutting (Liddle and Choi, 2007). There are three major areas of research in asphalt moisture damage: field investigations, laboratory experiments and analytical studies. Initially, most research was limited to field observations. Later, laboratory-based testing methods combined with field investigations were developed (Mehrara and Khodaii, 2013). The laboratory approach was based mostly on the development of techniques for simulating the field conditions accurately rather than conducting a fundamental assessment of asphalt moisture damage. In contrast, analytical methods based on surface free energy (SFE) evaluation are used to characterize the fundamental properties of aggregate and binder as related to moisture damage resistance (Howson et al., 2009). This fundamental evaluation can yield input criteria for material selection and design for preventing moisture damage in the field. New in-situ testing techniques can assess the expected failures in asphalt mixtures more practically and correlate well with the material selection criteria. Therefore, these techniques can minimize the need for laboratory-based simulations of field conditions such as air void interconnectivity in field samples.

This article reviews the approaches used to address moisture damage in asphalt mixtures. The primary goal when preparing asphalt mixtures is to remove the root cause of moisture damage. Here, one key consideration is the proper identification and assessment of distress. There are two common ways to reduce pavement distresses: preventive measures based on experiences and the cautionary measures based on fundamental understanding. However, a third and more profound way of addressing moisture-related problems is currently under investigation. It is suggested that a combination of in-situ testing, material selection criteria and proper mix design can be used to effectively prevent moisture damage in asphalt mixtures.

2. Background

First observed in the early 1900s, moisture damage was identified as one of the major causes of distress in asphalt pavements (Huang et al., 2010). Traffic-generated stresses reduce the internal strength of hot mix asphalt (HMA) pavement and can result in early rutting, fatigue cracking and ravelling of the HMA layer (Kok and Yilmaz, 2009). In asphalt mixtures, the adhesive and cohesive forces within the aggregate and binder are primarily responsible for holding the latter together. Moisture can infiltrate into an asphalt

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pavement layer via the permeation of rainwater, a rising of the ground water table, the absorption and adsorption of water vapor or a combination thereof (Arambula et al., 2007). Such an ingress of moisture shortens the design life performance (durability) of asphalt pavement, resulting in high maintenance costs. Every pavement requires maintenance at some point in its service life. Maintenance is the art of ensuring that a pavement is in an operational condition, while minimizing expenditures and inconvenience for road commuters. Although inappropriate maintenance can often be worse than doing nothing, preventive maintenance is a prudent addition to the other basic forms of maintenance (Hunter and Ksaibati, 2001).

The presence of water in asphalt pavement adversely affects the durability of the pavement and as a result can lead to very complicated modes of distress, stiffness and structural loss of strength. Although the presence of water does not initiate distresses such as cracking, permanent deformation and ravelling, it exacerbates their severity and extent. Local road maintenance authorities in the United Kingdom and Wales alone spend £2.5 bn annually to prevent these distresses (ALARM, 2006). Attention has shifted from making repairs to taking preventive measures because the former imposes high costs on the road authorities involved and poses an inconvenience to road commuters. The current practice among mix designers is to purchase the binder and aggregate based on individual specifications. However, because there is a lack of knowledge about these mix ingredients, it is still not clear whether they can interact favorably (Kringos, 2007).

In 1984, to develop techniques for the assessment of highway performance, Ensley et al. (1984) developed a method to measure the bond energy of asphalt and aggregate. Gharaybeh (1987) investigated the available testing methods for assessing the stripping potential of asphalt mixtures. There were no comparable developments for assessing moisture susceptibility until the Strategic Highway Research Program (SHRP) funded research for the development of new testing procedures aiming to prevent asphalt moisture ingress. Al-Swailmi and Terrel (1992) developed the environmental conditioning system (ECS), while Aschenbrener and Currier (1993) introduced the concept of the Hamburg wheel-tracking device (HWTD). Comprehensive work on asphalt chemistry and its significance related to moisture damage was conducted by the Western Research Institute (WRI). The asphalt source plays an important role in the separation of asphalt polar constituents from the aggregate. Presently, WRI is working on a rapid centrifugation method to evaluate the displacement of polar constituents by moisture in asphalt binder. The concept is based on the observation that insoluble calcium salts in asphalt components form in asphalt-aggregate mixtures that are less prone to moisture damage. In addition, surface energy parameters are possible tools for the assessment of asphalt-aggregate adhesion. However, although recent research has greatly aided the selection of asphalt-aggregate mixtures, it has not considered the effect of traffic-generated stresses combined with moisture damage (WRI, 2002). To this end, the National Cooperative Highway Research Program (NCHRP) Project 9–34 has focused on the environment-traffic factors for properly simulating moisture damage in asphalt mixtures (Solaimanian et al., 2003).

3. Moisture damage mechanism

According to Caro et al. (2008a, b) moisture damage mechanism is based on the following steps:

1. Moisture transport: processes by which moisture in either a liquid or vapour state infiltrates the asphalt mixture as well as the asphalt binder or mastic and reaches the asphalt binder–aggregate interface, and
2. Response of the system: changes in the internal structure leading to a loss of load carrying capacity of the material.

There are historically, six contributing mechanisms of moisture damage identified: detachment, spontaneous emulsification, displacement, pore pressure–induced damage, hydraulic scour, and the environment effect on the aggregate–asphalt system. It is evident that moisture damage is normally not limited to only one mechanism but is the result of a combination of processes. It is important to develop a more fundamental understanding of the moisture damage process, by taking into consideration the micro mechanisms that affect the asphalt aggregate adhesive interface and the cohesive strength and mastic durability (Little and Jones, 2003).

The micro and macro mechanisms are considered to be the two mainstreams studies in the stripping evaluation of asphalt mixtures. There are some theories in asphalt and aggregate that explains the adhesion and cohesion failure on a molecular scale. Some other theories explain the adhesive and cohesive failure using macro-scale mechanical theories. However, both approaches can be seen in most of the recent researches (Mehrara and Khodaii, 2013). The micro mechanisms are further classified into mechanical theory, chemical reaction theory, molecular orientation theory, surface energy theory, weak boundary theory, and micro-theories include the six traditional mechanisms. Whereas, macro mechanisms encompass formation of excess pore pressure in saturated pavement, hydraulic scouring, physical erosion of asphalt due to high velocity hydraulic flows (Mehrara and Khodaii, 2013).

3.1. Stripping

Early efforts to classify and describe asphalt stripping date from the 1960s and 1970s (Field and Phang, 1967). Lottman (1978) described that moisture damage could result from excess pore pressures that developed in the HMA pavement from traffic and thermal expansion. However, in the 1980s, this subject attracted the interest of highway agencies and the pavement industry nationwide (Taylor and Khosla, 1983). In a report submitted to the National Center for Asphalt Technology (NCAT), Kiggundu and Roberts (1988) assembled several definitions of stripping in asphalt mixtures from the point of view of a number of researchers (Petersen, 1982; Tunnicliff and Root, 1984):

"Deterioration or loss of the adhesive bond between the asphalt and the aggregate from the action of water; The physical separation of the asphalt cement from the aggregate produced by the loss of adhesion primarily due to the action of water or water vapour; The displacement of asphalt cement films from aggregate surfaces by water caused by conditions under which the aggregate surface is more easily wetted by water than by asphalt; The breaking of the adhesive bond between the aggregate surface and the asphalt cement; The loss of the bond between the asphalt binder and the mineral aggregate due to separation of asphalt cement coating in presence of water; 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".

From the above definitions, stripping is the separation of asphalt from aggregate or the rupture of asphalt texture in asphalt mixtures under the combined, simultaneous action of cyclic traffic load and water or water vapor. According to Kiggundu and Roberts (1988), a more complete definition of stripping includes the cohesive and adhesive failures that are considered the main causes of moisture damage. Moisture infiltration is normally considered a primary cause of stripping in asphalt mixtures; it therefore causes the

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removal of asphalt binder from the aggregate surface. The stripping phenomenon leads to a pre-mature rehabilitation and higher maintenance cost (Haghshenas et al., 2015). The progressive dislodgement of aggregate can occur because of the continuous and combined action of moisture and traffic load (Kringos, 2007). Studies that have evaluated several aspects of stripping are classified based on fundamental studies, qualitative studies and quantitative or engineering-based studies (Kiggundu and Roberts, 1988).

3.2. Mechanisms of the stripping process

There are a number of mechanisms that can account for stripping in asphalt mixtures (McGennis et al., 1984). According to theses mechanisms, there must be a stripping initiation point and its subsequent expansion (Tarrer and Wagh, 1991). Stripping usually begins at the bottom of the bituminous layer where it is thought that the moisture content is high and moves upward (Graf, 1986). The mechanisms of stripping in asphalt mixtures are formulated and compiled by Bagampadde et al. (2004) and are presented in Table 1.

3.3. Adhesion failure as a major contributing factor

The failure mechanism of the asphalt and aggregate adhesion bond has remained a topic of debate among researchers. It is thought to be related to one or both of the following phenomena. First, moisture may interact with the binder, causing a reduction in cohesive strength and subsequently a reduction in mixture stiffness. Second, water can gain access to the spaces between the asphalt film and aggregate, breaking the adhesive bond and finally stripping the asphalt binder from the aggregate. In both failure mechanisms, the moisture may diffuse through the asphalt binder to the interface, or it may already exist in the aggregate micropores due to the low-temperature production of asphalt mixture in accordance with warm mix asphalt (WMA) (Zaniewski and Viswanathan, 2006). According to Hicks (Hicks, 1991), adhesion is defined as "the physical property or molecular force by which one body sticks to a body of another nature". The asphalt-aggregate adhesion is influenced by many factors including the interfacial tension between the asphalt binder and the aggregate, the aggregate temperature, the chemical composition of the asphalt binder and the interfacial moisture content present at the time of mixing.

Adhesion is a fundamental property of the asphalt-aggregate interfaces (Al-Qadi et al., 2006). Research has established the importance of adhesion to asphalt moisture susceptibility and its relation to pavement durability and quality (Kringos, 2007). The molecular forces between adhesive and substrate play a large role in every adhesive and adherent system. The physical and chemical behaviors of wetting and interlocking are strongly affected by the molecular forces. Therefore, the adhesion strength of road materials strongly depends on the interaction, affinity and attraction between the asphalt and aggregate. Hence it is believed that the chemical nature of asphalt and aggregate governs adhesion (Merusi et al., 2010). There are basically four general theories of adhesion that attempt to explain the asphalt-aggregate adhesion. These include the Mechanical Interlocking Theory, the Chemical Reaction Theory, the Surface Energy Theory and the Molecular Orientation Theory. However, these theories can only partially explain the nature of adhesion (Hicks, 1991; Johnson, 2002).

3.4. Asphalt-aggregate interface

Moisture can accelerate the damage due to different types of distress in asphalt mixtures (Cho and Kim, 2010). The response of asphalt mixtures to different distresses is influenced by the mechanics of aggregate-binder interface bonding, which is affected by moisture damage conditions. Moisture at the asphalt-aggregate interface is a major contributing factor to the debonding of asphalt and aggregate (Moraes et al., 2011).

There are many possible mechanisms by which the water can access the asphalt-aggregate interface. These include migration through pinholes and diffusion through the asphalt matrix, local inhomogeneities, defects and pores in asphalt films. It is evident that during situations where the interface is exposed to a high water concentration for a short time or there is a thin water layer at the interface of thick asphalt films, water transport to the interface from the outside occurs through the hydrophilic or water-soluble regions of the asphalt film. The areas covered by the highly polar groups of asphalt molecules or water-soluble impurities (e.g., ions and salts) in the asphalt film are considered hydrophilic regions (Lu and John, 2005). Each water-soluble impurity is probably linked to a polar site in the asphalt. Therefore, it is possible that water-soluble impurities and polar groups of asphalt molecules are present in hydrophilic regions of an asphalt film (Nguyen et al., 1996, 2003). In summary, water-soluble materials, which can be transferred from the environment, transferred from the asphalt film or present at the interface (i.e., transferred from both asphalt and aggregate), form a water-sensitive layer at the asphalt-aggregate interface. This results in the formation of a water layer, many thick monolayers at the interface and finally in the stripping of asphalt or loss of adhesion of asphalt at the siliceous aggregate interface (Nguyen et al., 2005). The polar constituents at the asphalt-aggregate interface form a bond between the asphalt and aggregate surface. The bonding force between asphalt and aggregates decreases because of the loss of these polar constitutes in asphalt; this weakening could ultimately accelerate the adhesion

Table 1
Mechanisms of stripping in asphalt mixtures.

Process	Theory	Mechanism
Displacement	Thermodynamic and chemical reaction	Water with lower surface energy and higher dipole moment than bitumen displaces it from aggregate surfaces.
Detachment	Thermodynamic and chemical reaction	Water with lower surface energy and higher dipole moment than bitumen detaches it from the aggregate surface.
Spontaneous emulsification	Electrostatic	Emulsion formation, due to presence of agents like clay coatings, weakens the bonding at the interface.
Pore Pressure	Mechanical break	High pore water pressure in undrained conditions causes a break in bitumen film allowing water to enter the interface.
Chemical disbonding	Chemical reaction and electrostatic	Chemical and electrostatic interaction between water and some aggregates favour removal of bitumen from them.
Microbial activity	Bacterial metabolism	Microbial metabolic processes at the interface give by-products that break adhesion at the interface.
Osmosis	Diffusion	Concentration gradient across the bitumen film causes water to be transported to the interface.

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failure in asphalt pavements. Early adhesion failure at the asphalt-aggregate interface may also be caused by preferential binding of the aggregate to acetate anions, which are more polar than the asphalt molecules. Furthermore, acetate anions can weaken the bond between asphalt and aggregate, leading to different forms of distress such as ravelling and stripping, which normally occurs in moisture-damaged asphalt pavements (Pan et al., 2008).

4. Laboratory testing methods

Since the 1920s, efforts have been made to develop laboratory-based testing methods to assess the performance of mixtures with respect to stripping (Solaimanian et al., 2003).

4.1. Standard and nonstandard laboratory test techniques

The laboratory-based testing methods are categorized according to the viewpoints of different investigators and are presented in Table 2 (Mehrara and Khodaii, 2013).

1. Test on loose mixtures and mixture components.
   a) Qualitative measures of stripping
   b) Indirect quantitative measures
   c) Energy based methods
      i. Mechanical tests, measure of adhesion and cohesion
      ii. Energy based indexes
      iii. Non-mechanical test
   d) Advance techniques
2. Test on compacted mixtures
   a) Destructive mechanical test on compacted mixtures
   b) Non-destructive mechanical test on asphalt concrete
   c) Non-destructive non-mechanical tests.

4.2. Recently developed testing techniques

The investigations based on the moisture susceptibility of aggregate-binder constituent materials are summarized and tabulated in Table 3. Studies of the asphalt-binder ingredients were initiated to assess the susceptibility with respect to individual characteristics of the mixtures. The physical interactions of these ingredients were measured using different techniques. The pull-off tension test is the most popular test for understanding the fundamental properties such as adhesion and cohesion. For the consistency and validation, the results obtained from the pull-off tension test were further correlated with other techniques using dynamic shear rheometer (DSR) and HWTD; however, no appropriate correlation was determined with the HWTD results. A Fourier transform infrared spectroscopy (FTIR) analysis was conducted to determine more precisely the mechanism of moisture diffusion through asphalt-binder film. Furthermore, SFE evaluations were conducted to analytically determine the moisture damage properties (adhesion, cohesion and wettability). The details and outcomes of these investigations are summarized in Table 3.

4.3. Issues related to laboratory moisture damage assessment

There are various issues involved in assessing moisture damage as a standardize laboratory testing procedure. Fig. 1 shows the process of evaluating the performance of the asphalt pavement life cycle and moisture damage. This process involves the identification of material that is most responsible for the resistance against moisture damage. Severity analyses are executed to evaluate the extent of the reported damage. Furthermore, an independent investigation is conducted and correlations are developed with other experiences. A technique development phase is initiated to address the regional issues. Furthermore, a standardized procedure is developed to address the process of using material selection criteria to identify the most appropriate material that is resistant to moisture damage.

4.4. Technical approaches

The development of techniques to address the issues related to asphalt moisture damage is of prime concern to the pavement technologist. The flow chart in Fig. 2 describes the stages of a pavement's life cycle including the process of pavement production and moisture damage during the pavement design life. It is emphasized that the introduction of in-situ field testing techniques should be incorporated as a design parameter to address the moisture-related problems in a more practical manner. In addition to the analytical correlations, the laboratory assessment of field-reported moisture damage is required to incorporate the in-situ field testing procedures for further necessary recommendations. Fig. 2 highlights the importance of incorporating in-situ field tests along with laboratory assessment techniques during the material selection process and pavement design life. The in-situ field testing procedures may also include mechanical strength tests that can contribute to the prediction of moisture-resistant material. Therefore, the gap between the simulation of field conditions and laboratory predictions can be minimized.

Hammons et al. (2006) attempted to develop a nondestructive procedure to identify in-situ stripped sections of a road or pavement. A combination of advanced technologies (air-coupled ground penetration radar GPR, infrared thermography, surface distress survey, transverse and longitudinal profilometry, non-destructive falling weight deflectmeter FWD, seismic measurements) are being used. It was hypothesized that the damage mechanism which can lead to HMA stripping is associated with the change in the physical properties of the pavement. Increased porosity and high moisture content can be detected as increased GPR reflections. It was suggested that electromagnetic GPR can be used to detect and identify the layer thickness and the change in physical properties due to stripping. Thermal anomalies were not a reliable indicator of stripping in thick HMA pavements. The asphalt pavement experiences moisture damage after the continuous action of environmental and traffic loading. It is important to conduct the in-situ test on the damaged section to quantify the material behavior. Furthermore, based on laboratory assessments, a correlation between in-situ and laboratory test results can be developed. Finally, actual field simulations can help identify a suitable material that can perform better in the field and is more resistant against moisture damage (Saarenketo and Scullion, 2000).

5. Research investigations to evaluate moisture damage

5.1. Binder-aggregate constituent studies

Many studies have been conducted worldwide on moisture damage in asphalt aggregate constituents. Bhasin et al. (2007) proposed four energy ratios based on the surface free energy of asphalt binder and aggregate with and without the presence of water. The energy ratios are based on the adhesive energy and the debonding energy, which is the energy required to degrade the adhesive bond in the presence of water. The wettability factor and specific surface area of the aggregate are also included in these four energy ratios. The ratio comprises the work of adhesion in the presence of water to the work of adhesion under dry conditions. Mechanical strength tests were conducted on asphalt mixtures in a direct-tension mode to assess the dynamic modulus and dynamic

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Table 2
Details of standard and nonstandard laboratory test techniques.

Category		Test method	Test description
Tests on loose mixtures and mixture components			
Qualitative measures of stripping		Static immersion	Percent of aggregates surface that have maintained their asphalt coatings after static immersion in water
		Dynamic immersion	Percent of aggregates surface that have maintained their asphalt coatings after being agitated in water
		Boiling water	Percent of stripped aggregates after immersion in boiling water
		Methylene Blue	The amount of harmful clays of the smectite (montmorillinite) group, organic matter and iron hydroxides present in fine aggregates
		Quick and Rolling Bottle test	Measuring the adhesion capability of asphalt to Ottawa sand
Indirect quantitative measures		Net adsorption	A quantitative index based on the difference of the adsorbed asphalt to aggregate surface in presence and in absence of moisture
		Chemical immersion	A quantitative index based on the concentration of a chemical material for the initiation of moisture damage
		Surface reaction	A quantitative index based on the pressure of produced gas due to reaction of a chemical with the stripped surface of aggregates
		Tack Test System (TTS)	Measuring the required force to cause cohesion failure in asphalt
Energy based methods	Mechanical tests, measure of adhesion and cohesion	Pneumatic Adhesion Tensile Testing Instrument (PATTI)	Measuring the required force to cause adhesion failure between asphalt and aggregate in presence and absence of moisture
		Peel Test	Measuring the adhesive fracture energy of asphalt and aggregate
	Energy based indexes	Dynamic Mechanical Analyzer	Controlled-strain; cyclic torsional experiment on asphalt matrix
	Non-mechanical Test	Wilhelmy plate	Measuring the surface energy of asphalt
		Universal Sorption Device (USD)	Measuring the surface energy of aggregate
		Contact Angle Sessile Drop Test	Measuring the surface energy of binder and aggregate
	Advance Techniques	Inverse Gas Chromatography (IGC)	Similar to previous test
		Ultrasonic	Measuring the ratio of the stripped surface, determined visually
		Fourier Transform Infra-red (FTIR)	Measuring the adsorption/desorption of water in thin asphalt films
		Nuclear Magnetic Resonance (NMR)	Measuring the changes in chemical composition/molecular mobility of asphalt due to moisture
		Ellipsometry	Optical surface sensitive technique to measure the refractive index of aggregates and bitumen binders
		Micro calorimeter	Measuring the energy adhesion components of aggregate and binder
Test on compacted mixtures			
Destructive mechanical tests on compacted mixtures		Hveem stability	Measuring the ratio of Heveem stability after moisture conditioning to that before conditioning
		Immersion compression	Measuring the ratio of compressive strength after moisture conditioning to that before moisture conditioning
		Marshall immersion	Measuring the ratio of Marshall strength after moisture conditioning to that before moisture conditioning
		Freeze–thaw pedestal	The number of freeze–thaw cycles to crack initiation in sample before and after moisture conditioning
		Lottman/Tensile Strength Ratio (TSR)	Measuring the ratio of diametric strength after moisture conditioning to that before moisture conditioning (with freeze and thaw cycles)
		Root–Tunicliff	Measuring the ratio of diametric strength after moisture conditioning to that before moisture conditioning (without freeze and thaw cycles)
		Double punch	Measuring the ratio of punch shear strength after moisture conditioning to that before moisture conditioning
		Dissipated Creep Strain Energy (DSCE)	Fracture mechanics/energy
		Wheel tracking	Number of cycles corresponding to the intersection point of the slop of second and third part of creep curve (known as stripping turning point)
		Direct Tensile Test	Measuring the ratio of direct tensile strength after moisture conditioning to unconditioned
		Beam fatigue	Fatigue life before and after moisture conditioning
		Cantabro Test	Measuring the ratio of Abrasive Strength loss after moisture conditioning to unconditioned
Non-destructive mechanical tests on asphalt concrete		Environmental Conditioning System (ECS)	Measuring the permeability of compacted asphalt mixtures and changes of their resilient modulus during application of thermal cycles and cyclic loading
		Resilient Modulus	Retained resilient modulus, ratio of conditioned to unconditioned resilient modulus of asphalt mixtures
		Dynamic Modulus	Use of Simple Performance test to measure the dynamic shear factor of asphalt mixtures
		SATS	Measuring the ratio of resilient modulus after moisture conditioning to that before moisture conditioning
Non-destructive non-mechanical tests		Permeability, CT Scan, Diffusion, Capillary rise	Indirect measure of moisture sensitivity of asphalt mixtures based on interconnectivity of air voids

creep properties as a function of fatigue life under dry and wet conditions. Furthermore, a linear correlation model and logarithmic transformation were used for these energy ratio parameters; this technique is an application of surface energy parameters that is useful for selecting material combinations that are more resistant to moisture damage. The methodology is a promising first step in determining the selection criteria for material design; however, it does not consider mixture properties such as air void distribution and mechanical strength. The moisture damage is dependent on the combined action of asphalt and aggregate and cannot be

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evaluated based on either individually (Masad et al., 2006). Nevertheless, some of the energy parameters correlated well with the mixtures' mechanical test results; further work should be conducted using these energy parameters. Mladenovič et al. (2015) used different alternative materials in road construction in order to replace natural aggregates. The bottom ash in the sub-base layers of road was used to replace gravel. Coal waste and its ash were utilized to improve the mechanical properties by increasing the Marshall

Table 3
Methods and techniques developed for the aggregate-binder constituent moisture susceptibility.

Technical approach	Reference	Contributing parameters	Outcomes/observations
Pull Off tension test			
Quick measure of bond strength degradation to provide a relationship of strength loss over time after moisture conditioning.	(Copeland et al., 2007)	Long Term Aging (LTA) effect, polymer modified binder	LTA increases the cohesive strength and the moisture conditioning with Aging decreases the adhesive strength
Integrated experimental-numerical approach	(Ban et al., 2011)	Cohesive zone model was included in finite element technique to simulate the adhesive fracture at asphalt aggregate interface	Moisture damage mechanisms and binder-aggregate with varies antistripping additive can be estimated by the proposed degradation function used in the approach
Study of Bond Strength	(Kanitpong and Bahia, 2005)	Polymer and anti stripping effect	Polymer improves the adhesive and cohesive properties while the anti stripping additive only improves the adhesion
Study of Bond Strength	(Wasiuddin et al., 2011)	Novel conditioning method of asphalt binders is used and determined the adhesive strength	1. Cylindrical holes within a reasonable time appears and water infiltrates up to the interface (binder and glass) later removing the asphalt film from the interface, 2. Adhesive strength compared with adhesion strength calculated from surface free energy does not show a good correlation
Bitumen Bond Strength and Strain Sweep test were conducted by using modified Dynamic Shear Rheometer (DSR) test in which the binder is sandwiched in aggregate substrates	(Moraes et al., 2011)	Different asphalt aggregate combinations are used to assess the repeatability/reproducibility	The ranking order for both bond strength and modified DSR Strain Sweep test results are similar
Bitumen Bond Strength and HWTD	(Mogawer et al., 2011)	WMA technologies on the adhesion characteristics, effect of antistripping agent, Aging time and temperature	1. High temperature and more Aging time improved the resistance to moisture damage when assessed with HWTD. 2. Anti-stripping agent (limestone) has no effect on the bases of HWTD data. 3. Only Sasobit improved adhesion strength of Pull Off test significantly. 4. No correlations are found between Bitumen Bond Strength (BBS) and HWTD results.
TSR/Conventional tests combined with other parameters			
Stripping resistance evaluation with digital image analysis and axial tensile stress and strain measurement using DSR	(Merusi et al., 2010)	Evaluated the Wax potential	1. Asphalt binders modified by Wax reduces stripping due to the presence of binder surface layer provided by wax with enhanced impermeability and different water affinity 2. Axial tensile stress and strain supports the findings of stripping test
Fourier Transform Infra-red (FTIR)			
Water diffusion of asphalt binder thin film	(Vasconcelos et al., 2010)	Diffusion model is used to fit the data obtained	1. Water diffuses through binder and its presence causes the mechanical loss of asphalt binder 2. Further research is required on the rate of diffusion at binder–substrate interface, diffusion of polymer modified binder including the concern with casting/preparing thin homogenous films
To measure in-situ water film thickness on asphalt coated with SiO_2 covered Si prism. The Model is verified by using other epoxy Silone treated substrates when the water enters into the interface	(Nguyen et al., 2005)	The stripping of asphalt from aggregate surfaces due to water by using two layer model derived from internal reflection spectroscopy theory	Water ingress along the interface is responsible for the formation of monolayer. To form stronger bonds with acidic asphalt a base-modified siliceous surface is desirable to resist the water damage process.
FTIR Spectroscopy	(Pan et al., 2008)	Acetate based deicing effect on asphalt emulsification	Asphalt emulsification is due to acetate anion. Based on the results, a proposal of emulsification mechanism is suggested. The recommendations to use PMB/binders with high viscosity when acetate-based deicers are used. Though, the FTIR spectrum was not able to detect any chemical change. The analytical methods like Mass Spectroscopy (MS), Nuclear Magnetic Resonance (NMR) Spectroscopy are suggested to be used for further investigations

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Table 3 (*continued*)

Technical approach	Reference	Contributing parameters	Outcomes/observations
A versatile reflection Spectroscopy technique, when an infra-red light is directed through an ATR prism, it undergoes multiple total internal reflections owing to the reflection angle being greater than some critical value. Some radiations are commonly called an evanescent wave, when water is interacted with bitumen film therefore water enters the interface via the film and interacts with the evanescent wave and thus is detected.	(Bagampadde and Karlsson, 2007)	Evaluated the effect of substrate type, film thickness, bitumen type, temperature and amines modification on water damage	At least one of the process could occur which are water diffusion, bitumen displacement and film fracture. Diffusion of water does not obey Fick's Law when Silicon and germanium substrate are used, the stripping is influenced by the binder type. Also when the thickness of film increases the amount of water passing through film increases to get into interface.
FTIR- Attenuated total reflectance (ATE)	(Karlsson and Isacsson, 2003)	Rejuvenator diffusion in asphalt binders type, film thickness, temperature and chemical change	Fick's Law can be used to describe diffusion process. The importance of studying the diffusion process attributes the mixing of new and old binders, where if the process is incomplete then the properties of recycled asphalt will be negatively influenced. The film thickness has no influence on diffusion however the temperature had major influence on diffusion rate.
Surface Free Energy (SFE)			
Used SFE method to investigate the wettability and adhesion properties	(Wasiuddin et al., 2008)	Adhesion and wettability the dynamic receding (dewetting) and advancing (coating) angles were measured, Spreading coefficient was determined as a quantitative measure of wettability through numerical calculations of SFE that is work of adhesion and cohesion.	Wettability increased with the increase in Sasobit Percent amount for different binders due to the decrease in surface energy, increases the hydrophilic characteristics thereby increasing wettability, and Aspha Min had not considerable effects of improving wettability. Also Sasobit increased the moisture susceptibility due to reduce adhesion values as compared to Aspha Min.

stability, tensile strength and resilient modulus particularly in the long-term. These improvements were more obvious for coal waste ash because of its higher pozzolanic features (Modarres and Ayar, 2014). Moghadas et al. (2013) evaluated the effect of hydrated lime (HL) on moisture susceptibility using characteristics related to surface free energy. The Wilhelmy Plate and universal sorption device (USD) methods were used; the results were compared with conventional mechanical strength and showed that the low polar molecules of asphalt binder with the aggregate were responsible for the adhesion characteristics. The acid-base components of the asphalt binder were weak acids. The decrease in total SFE improved the water resistance of asphalt binder with an aggregate composition that was primarily made of granite instead of limestone. The result shows that HL is effective in reducing moisture sensitivity. Furthermore, when stripping occurs, the amount of energy released by the asphalt binder and aggregate is equal to the difference between the free energies of adhesion under dry and wet conditions.

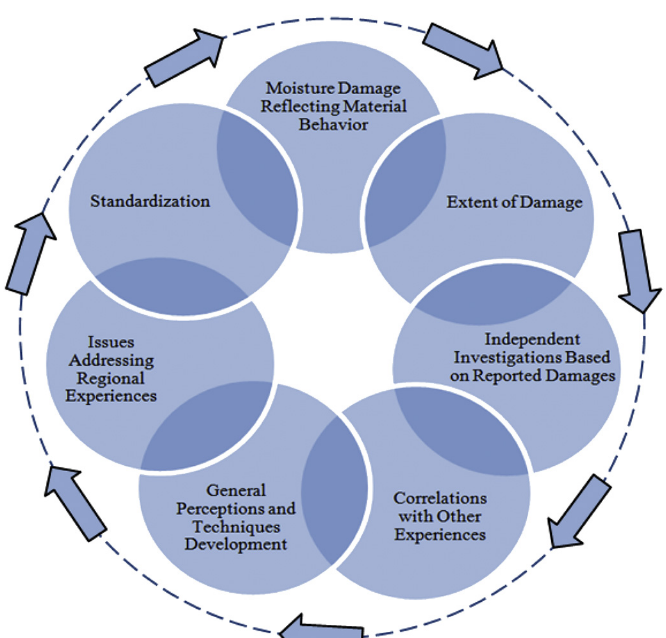

Fig. 1. Different aspects of moisture damage standardization.

Using SFE based on the WP and USD testing methods, Arabani and Hamedi (2010) evaluated the effect of high- and low-density semicrystalline polyethylene (PE) material on moisture damage when used as an aggregate coating. The results were further validated with a controlled-strain repeated unconfined compressive load dynamic modulus test on the asphalt mixtures. The aggregate SFE components were modified with PE, and the total SFE of PE-treated aggregate decreased. The acidic polar component decreased with an increase in the basic component; this behavior improved the adhesion conditions. The amount of nonpolar component increased; as a result, the wettability was improved. The addition of PE improved the free energy of adhesion and decreased the water-aggregate SFE, which shows better moisture resistance for granite and quartz-treated aggregate. However, the PE's effect on limestone aggregate was not promising. The results were further validated with a dynamic modulus test. To address moisture damage in a more fundamental way, Wasiuddin et al. (2007) carried out the warm-mix additive effect on surface free energy. They found that the wettability and an adhesion base energy parameter were more important for explaining the asphalt-aggregate interface mechanism. The spreadability of the asphalt binder over the aggregate was calculated from SFE and correlated with the adhesion of the asphalt aggregate. A major conclusion was that styrene butadiene styrene (SBS) modification changes a hydrophilic binder to a hydrophobic one and therefore increases the water repulsion, spreading coefficient and interfacial energy; hence

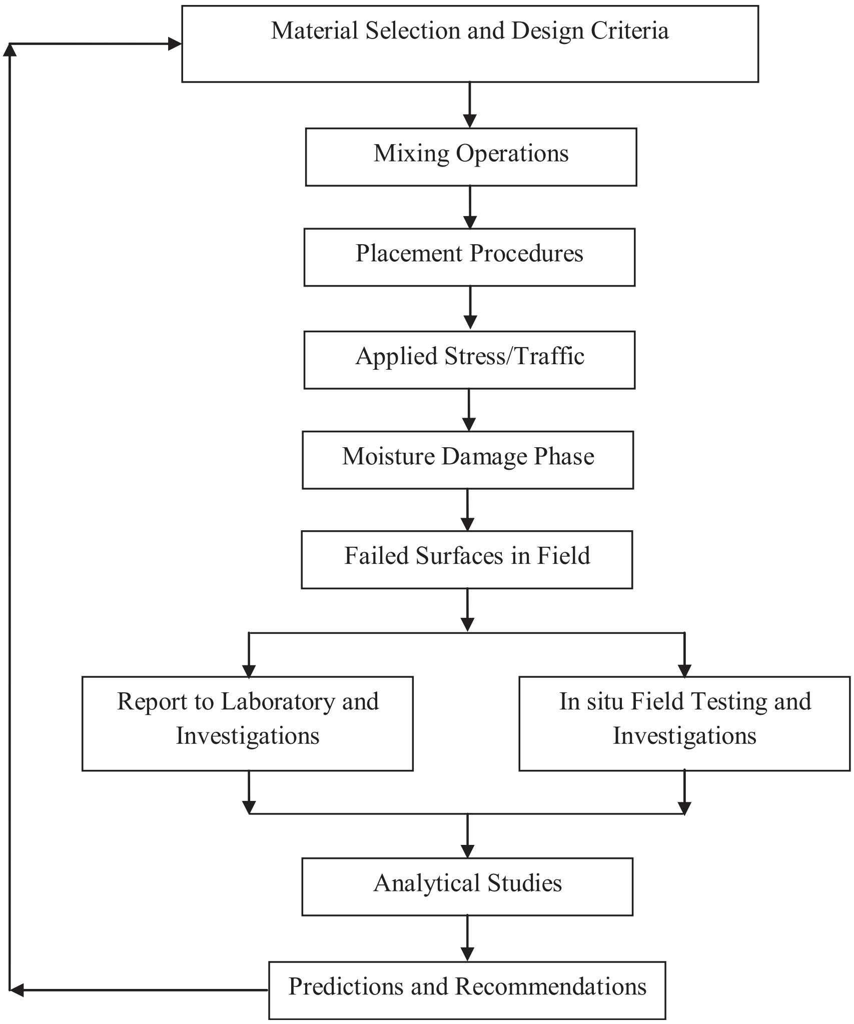

Fig. 2. Asphalt pavement moisture damage process incorporating in-situ field test.

the wettability was increased irrespective of the aggregate type used. Sasobit reduced the SFE and increased the wettability of the asphalt binder over aggregate significantly. The reduction in moisture susceptibility was more significant for SBS-modified binder than for non-modified binder; however, the moisture susceptibility was reduced for Asphamin.

In recent years nanotechnology has become a promising and creative technique in the material industry, and nano-materials have been widely applied to various fields across the world. The nanotechnology is used as a form of new materials, such as nanclay, nano-silica, nano-hydrated lime, nano-sized plastic powders, or polymerized powders, nano-fibers, and nano-tubes, to name a few, are recently been used to modify the asphalt (Yusoff et al., 2014). Arabani et al. (2012) used SFE and a dynamic modulus testing method to assess the effect on moisture damage of Zycosoil (Z_y), a new nanotechnological material used as an anti-stripping additive in WMA mixtures. A moisture sensitivity index based on SFE and dynamic modulus results was developed and adopted. To evaluate moisture damage, the wet-to-dry ratio of compression stiffness was expressed in terms of the SFE of adhesion with or without the presence of water. The evaluations were based on moisture damage in terms of the percentage (P) of the area of aggregate replaced by the water in asphalt mixtures. The addition of Z_y material to a WMA prepared with acidic aggregates reduces the adhesion failure due to increase in the surface energy of the acidic component of the binder. Therefore, a weak bond between the binder and the aggregate may be strengthened with the addition of Z_y, which causes an increase in surface free energy of adhesion. Thus this additive increases the moisture resistance of WMA mixtures. The dynamic modulus ratio of WMA, which is lower compared with HMA, was improved with the addition of Z_y. The Z_y decreases the percentage of the area wetted by water owing to the formation of a hydrophobic zone when it reacts with aggregate surface, forming Si–O–Si siloxane bonds. Water sensitivity of asphalt mixtures is directly related to the performance and durability of these materials during the road pavement life (Oliveira et al., 2013). Estakhri et al. (2010) evaluated the WMA performance in the laboratory and conducted field trials for implementing its construction and material design. The work of cohesion and the work of adhesion were evaluated using surface free energy characteristics. The results were compared using a dynamic mechanical analyzer (DMA). The authors found that there was a positive effect of certain WMA additives (Sasobit, Advera, Rediset and Asphamin) on the cohesive fracture energy under both dry and wet conditions. The adhesive fracture resistance was poor compared with that of the unmodified control mixture under both dry and wet conditions. These findings were based on the assumption that different asphalts may have similar total SFE values but that the SFE of their components may differ depending on their particular chemical compositions. The SFE method is a fundamental tool for optimizing

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the selection of different combinations of materials by evaluating the cohesive and adhesive properties of the constituents. The results of DMA revealed that the fatigue behavior of WMA significantly improves under dry conditions and decreases under wet conditions, indicating that the material is moisture susceptible; therefore, these results support the findings drawn from SFE calculations.

Bhasin and Little (2009) worked on the surface free energies of asphalt and aggregates by using microcalorimetry, which is a fast and cost-effective method. This method is based on the equilibrium of heat flow due to the immersion in known physical probe liquids. The work of adhesion between two materials is related by the individual surface free energy components according to an acid-base theory (Van Oss model). The results were compared with that of the aggregates obtained from USD, which were similar for the samples used in the study. There were several disadvantages of this method. The micro calorimeter procedure assumed a work of entropy based on the heat of immersion and adsorption for several pure minerals whereas the aggregate was considered to be a composition of those minerals. The procedure required knowledge of the specific surface area of the aggregates under observation. The method was based on the total energy of adhesion whereas the models used for the calculations were based on the free energy or work of adhesion only. The surface free energy values of asphalt aggregate were based on values measured at 25 °C for the computation of work of adhesion whereas the method can evaluate the asphalt aggregate adhesion at a higher temperature (up to 150 °C). The authors believed that these differences had no significant effect on the results. Moreover, the microcalorimeter had some advantages when considering the effect of moisture content on the surface free energy components. Future work should take into consideration the contribution of entropy and an assessment of the adhesion of polar organic compounds with various aggregate types. Wasiuddin et al. (2005) evaluated the cohesive strength of the binder as function of moisture damage by using surface free energy calculations. Because laboratory-retained strength tests still do not properly address the moisture damage mechanisms, dynamic contact angles were measured using the dynamic Wilhelmy plate method (DWPM) to assess the SFE of different binders. A modification was made to the method by using cylindrical tube samples instead of Wilhelmy plates. In addition, the effects of anti-stripping additives on different binders were evaluated. The results showed that higher grade binder was more resistant with respect to fracture and healing behaviors based on the receding and advancing free energies of cohesion, respectively. The use of glass tubes provided better binder coating uniformity of thickness which therefore minimizes the effects due to non-uniformity on the results. Use of an image analyzer also improved the precision of the results while monitoring the specimen geometry. Furthermore, the anti-stripping agents reduced the SFE, improving the asphalt-aggregate adhesion.

Alvarez and Ovalles (2012) worked out on the effects of mineral filler on the SFE properties at different proportions. To evaluate the energy parameters, the work of adhesion under dry and wet conditions, indexes, energy ratios and spreading coefficient were used. The addition of mineral filler to unmodified binder had positive effects on the SFE components and total SFE values. The indexes, based on the work of adhesion under dry and wet conditions, characterized modified mineral relative to neat asphalt binder. The effects of mineral filler varied depending on specific asphalt filler and aggregate combinations. This approach could be used to characterize the microscope response of HMA. Via measurement of the SFE, the energy parameters can be used as a fundamental material property and as a threshold to rank the material for mixture design purposes. Taking surface free energy as a first phase, Howson et al. (2009) evaluated energy ratios of asphalt aggregate constituents in second and third phases. Based on the effect of fine aggregate mixture using DMA, the mechanical damage of the full mixture asphalt was calculated. The development of a database for selecting the desired asphalt aggregate combination as a first screening criterion is useful. Furthermore, remedial precautions were taken with respect to the use of anti-stripping agents, polymers, lime and other additives. Observations of the same source of aggregate over time showed that surface properties changed over time. However, the polar component, which is the most significant factor in the assessment of moisture damage, did not change significantly. On the other hand, significant changes in the asphalt surface energy of the same batch and source were observed over time. Therefore, it was recommended that the SFE should be measured more frequently for asphalt than for aggregates. In addition, a database that is more user-friendly and has more inputs can potentially measure the SFE components and the adhesion characteristics of different combinations of asphalt-aggregates by using the properties of asphalt and aggregate.

Blackman et al. (2013) used a novel adhesion peel testing method to assess the adhesive fracture energy of asphalt aggregate. This method, which has advantages over the conventional method, addressed failure due to moisture damage by considering fundamental properties and fracture characteristics. The crack resistance at the interface represented by peel force was used as measure of adhesive fracture energy. The result showed that the asphalt-aggregate interface adhesive fracture energy decreased due to the effects of conditioning. Visual inspection revealed that the mode of fracture changed from cohesive to adhesion when the samples were exposed to water. The fracture remained cohesive under both dry and wet conditions when aluminum substrates were used instead of limestone aggregates. The authors concluded that the cohesive strength was not affected by moisture; however, the interfacial adhesion was main the dominating factor. Hefer et al. (2007) evaluated the surface free energy of asphalt binders at different temperatures using Inverse Gas Chromatography (IGC). Their results showed that the total surface free energy value γ^{LW} was the main contributor. The surface energy values of different binders tested were similar to each other, supporting previous research. A positive feature of IGC is that it can measure the surface energy of a binder at higher temperatures. Furthermore, their results showed that the SFE reduces with an increase in temperature. This finding is consistent with the definition of SFE, which is the work is required to increase the surface by a unit area. An increase in temperature increases the mobility of molecules so that less work is required to increase the area.

5.1.1. *Chemical and physical behavior*

In the adhesive and adherent systems, adhesion directly depends on the molecular forces between the adhesive and the substrate (Petrie, 2000). Adhesion is strongly influenced by the physical and chemical properties that determine wetting and interlocking (Al-Qadi et al., 2006). Thus adhesion strength in road materials strongly depends on the interaction, affinity and attraction between aggregates and bitumen; likewise, adhesion in asphalts depends on the chemical origin of aggregates and bitumen (Merusi et al., 2010).

Using chemical reaction theory, Scott (1978) explained how polar groups absorption are modified by variations in the pH of the water at the aggregate surface, thus building up opposing, negatively charged electrical double layers on the surfaces. The buildup attracts more water and enhances the physical separations (Zollinger, 2005). From these insights into the asphalt-aggregate chemical and physical properties, a microscale design for improving the performance of asphalt mixtures is desirable (Mo, 2010).

5.1.2. Wettability and viscosity

The development of a good bond between asphalt and aggregate is primarily dependent on the ability of the asphalt to wet the aggregate. The wettability of aggregate increases when the surface tension or surface free energy of adhesion decreases (Majidzadeh and Brovold, 1968). It is believed that asphalt binders are generally hydrophobic and aggregates are mostly hydrophilic; it is not easy to wet hydrophilic aggregates with a hydrophobic asphalt binder (Tarrer and Wagh, 1991). The spreading coefficient is a quantitative measure of wettability. During the advancing-wetting process, the spreading coefficient ($S_{L/S}$) of a liquid over a solid is simply the reduction of SFE upon the loss of baer solid surface and formation of new solid/liquid and liquid/vapor interfaces (Zettlemoyer, 1968). When wettability and adhesion are evaluated from the wetting-advancing contact angle, it is assumed that an increase in wettability is related to an increase in adhesion (Wasiuddin et al., 2008).

Loosely speaking, surface free energy may be expressed as the comparative wettability of aggregate surfaces by water or asphalt. Due to its lower surface tension and lower viscosity, water is considered a better wetting agent than asphalt. However, the evaluation of the cohesive strength of asphalt binder-mastic and adhesive bond energy at the interface between the mastic or asphalt cement and aggregate surface using surface energy is still considered a complex topic (Solaimanian et al., 2003). In different coating processes, the wettability is expressed in numerous forms. In many industrial processes, the substrate is immersed in a liquid coating material and then withdrawn to leave a liquid film on the substrate. The film (coating) thickness depends on the surface tension, withdrawal speed, substrate geometry, roughness and melting viscosity (Asthana and Sobczak, 2000). High viscosity is associated with poor bitumen wettability over the aggregate. The viscosity measures the molecular mobility and the magnitude of intermolecular attractive forces in bitumen. During mixing, the intermolecular forces are weakened and the polar constituents in bitumen easily diffuse toward the interface (Bagampadde et al., 2004).

5.2. Binder-aggregate interaction

The two main constituents of an asphalt mixture are binder and aggregate. More sustainable production of bituminous mixes can be obtained without significantly affecting their level of mechanical performance (Rodríguez-Alloza et al., 2014). The interaction of the asphalt binder with the aggregate is a phenomenon that involves the surface chemistry of the individual components (binder and aggregate), molecular structure, chemical composition, physical interaction, mechanical interlock and the exchange and balance of heat energy. The following subsections explain these factors.

5.2.1. Surface chemistry

The stripping potential depends on the chemical and rheological properties of the binder, morphology, aggregate surface chemistry, pH conditions at interface, traffic, construction methods and the nature of anti-stripping agents. Fig. 3 shows the surface chemistry as evaluated by chemical composition and the morphology of aggregates. Aggregates offer electrostatic and Lewis acid-base sites for interaction with bitumen polar constituents (Jeon, 1990; Curtis et al., 1992). The chemical nature of different types of aggregates is shown in Fig. 3. Research on asphalt bonding showed that the bitumen-adsorbing groups are mainly naphthenic acids. Therefore, the basic aggregates can form stronger bonds with bitumen (Bagampadde et al., 2004).

5.2.2. Molecular structure and chemical composition

The molecular structure and chemical composition of the asphalt binder are strongly influenced by its rheological properties (Hagos and Molenaar, 2008). Asphalt is a complex molecular system with extensive molecular interactions, and the molecular motions of the asphalt constituents at different temperature are controlled by these interactions (Netzel, 2006). Research has shown that, depending on chemical composition, materials such as asphalt and aggregate may form covalent bonds when they interact with each other (Plancher et al., 1977).

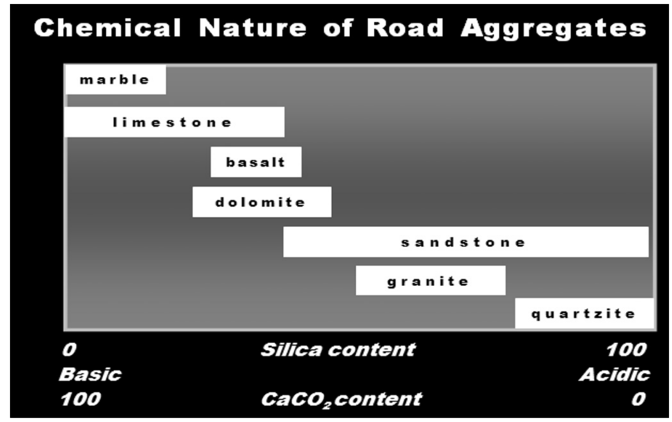

Fig. 3. Chemical nature of road aggregates (Courtesy of Akzo Nobel Surface, chemistry LLC).

According to the theory of molecular orientation, asphalt molecules, depending on the amount of polarity, align themselves in the direction of the aggregate surface when these molecules are adjacent to it. Hence they can satisfy the energy demand of the aggregate (realignment) (Mehrara and Khodaii, 2013). However, when water comes in contact with the aggregate surfaces, a series of hydrolytic processes and slow decomposition begins. It therefore changes the pH of the neighboring water layer by several units (Nguyen et al., 2005). This change in pH alters the state of ionization and type of polar groups adsorbed by the aggregates, leading to the buildup of opposing, negatively charged electrical double layers on the aggregate asphalt surfaces and eventually to the separation of the asphalt and aggregate (Tarrer, 1986; Lu and Harvey, 2008).

5.2.3. Mechanical interlock

Several studies including Rice (1958), Thelen (1958) proposed that the aggregate surface texture is the main factor affecting the adhesion property of asphalt aggregate. Here the chemical interaction of asphalt and aggregate was ignored when the mechanical interlocking property was considered. The cohesion in the binder and the interlocking properties of aggregate particles, including individual crystal faces, absorption, surface coating, angularity and aggregate porosity, were assumed to be responsible for the bond strength. If these properties were not significant enough to produce the interlocking network, the system could lead to adverse effects due to action of water (Kiggundu and Roberts, 1988). A high amount of surface pores and a rough aggregate surface texture give rise to resistance to the moisture damage (D'angelo and Anderson, 2003). To produce better mechanical interlocking, aggregates with high angularity were assumed to be favorable (Stuart, 1990). Analytical approaches have also been developed by Caro et al. (2008a, b) to characterize the adhesive bond with respect to the mechanical framework.

5.2.4. Heat energy transfer rate and balance

The energy that a system must acquire before any process can occur is called the activation energy for that process (Vasconcelos, 2010). Phenomena in asphaltic materials such as viscosity (Salomon and Zhai, 2002), oxidation (aging) (Ait-Kadi et al., 1996;

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Liu et al., 1996), and crack growth processes (Jacobs et al., 1996), have activation energies. This concept was used to rank the relative compaction effort of asphalt mixtures in the field (Salomon and Zhai, 2002). Ensley et al. (1984) used microcalorimetry to evaluate the heat released due to the interaction between the asphalt and aggregate. Their observations suggested that bond strength measurements were related to the stripping potential. Plancher et al. (1977) used a range of temperatures while studying the interaction of nitrogen compounds with various aggregate surfaces. Their results showed that those aggregates which interacted strongly with nitrogen compounds may have low stripping potentials. Further studies are needed in these fundamental areas.

5.3. Mixture based performance studies

Kim et al. (2004) used dynamic mechanical analysis to assess the effects of moisture susceptibility on fatigue damage and viscoelastic nature of sand mastic asphalt. The microscopic evaluation of moisture damage was performed using DMA. The relationship, based on viscoelastic surface energies, suggested that moisture accelerated the fatigue damage and reduced the fatigue life. The moisture infiltrated into the mastic (binder + sand particle) and reduced the stiffness. This DMA-based work should be extended to different binders, fine aggregates, the aging effect and binder additives to evaluate moisture damage. The results showed that the moisture damage strongly depended on the characteristics of mixture constituents; therefore, DMA testing combined with surface energy principles could address issues of moisture damage resistance. Dong et al. (2008) developed a laboratory test method based on 3D finite element model (FEM) to analyze the mechanical response of saturated asphalt pavement due to the action of pore water pressure in asphalt mixtures. The test included repeated indirect tension tests and repeated uniaxial compression tests at varying stress levels on samples in a conditioned chamber. Stripping and scouring phenomena may be induced by the reversal of pore pressure in a saturated pavement due to dynamic vehicle loading. It can be seen in Fig. 4 that the pore pressure changes with depth. Dong et al. (2008) further recommended that because the pore pressure highly influenced the permeability, a relationship between the two should be established.

Collop et al. (2007) used saturated aging tensile stiffness (SATS) to evaluate the moisture damage of asphalt mixtures in terms of aging and pressure. Their results showed that the basic aggregate is more sensitive to the pressure than the acidic aggregates, even though the moisture damage factor as a measure of moisture sensitivity was lower for the acidic aggregates. This means that the mixture prepared with acidic aggregates was more sensitive to moisture damage. The aging factor decreased as the retained saturation increased because there was less air available for aging the bitumen. It was observed that there was a significant reduction in stiffness during depressurization; this reduction was later minimized by reducing the aging temperature during depressurization. Airey et al. (2008) evaluated the moisture damage in asphalt mixtures using the SATS testing method. The change in volumetric and binder content had a negligible effect on the stiffness values measured on specimens conditioned in SATS. The filler may have affected the moisture damage performance of acidic aggregate mixtures. Although the AASHTO T283 and SATS ranks mixtures in the same order with respect to moisture damage, SATS provides a more aggressive conditioning protocol compared with AASHTO T283. Kavussi and Hashemian (2012) assessed the water-based warm mix asphalt for rutting and moisture susceptibility. Their result revealed that WMA was more susceptible to both moisture damage and rutting compared with HMA. The moisture sensitivity and rutting could be improved by the addition of 2% hydrated lime.

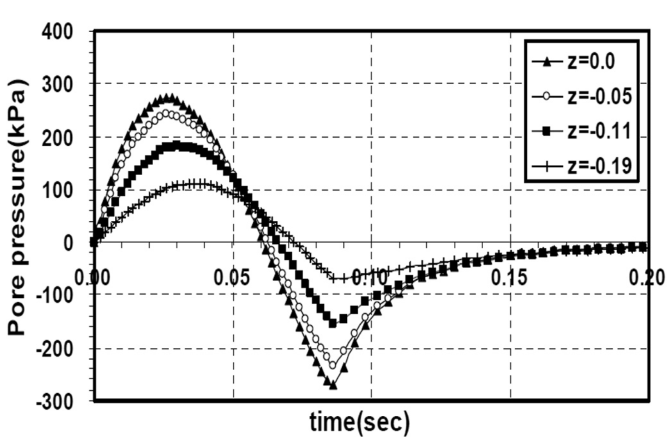

Fig. 4. Pore pressure histories at different depths (Dong et al., 2008).

Solaimanian et al. (2007) used a simple approach to reduce the testing time and simplified the conditioning procedure shown in Fig. 5. Submerged cylindrical specimens were tested under the indirect tension and uniaxial compression modes inside the conditioning chamber. The loading response was continuously monitored during testing. The modulus or deformation of the specimen was measured during conditioning and a decision factor was developed rather than conducting measurements before and after completion of conditioning. In this approach, the modulus (or strain) of the specimen was monitored while conditioning was in progress, and once the value of the modulus dropped below a threshold (or once the deformation exceeded a certain level), excessive damage was indicated and the test was stopped. However, further investigations are essential to distinguish the damage induced by load and water.

Mehrara and Khodaii (2010) evaluated the moisture resistance of two asphalt mixtures (dense and coarse graded) using a dynamic creep test. The dynamic creep test was performed on both dry and saturated samples to detect the amount of permanent deformation due to the simultaneous effects of traffic and water pressure. Their results showed that the dense graded mixtures were more prone to moisture damage than course graded mixtures. This finding is due to the interconnected air void structure in coarse graded mixtures from which the water can easily escape. On the other hand, the dense mixture's air voids were not well-connected, such that when a load was applied, a sharp increase in water pressure appeared. The authors further described that when temperature was high the asphalt mixture became more sensitive to temperature than to moisture. Aksoy et al. (2005) used different additives to check the behavior of asphalt mixtures with a conventional mechanical test. Two approaches were used to overcome the stripping potential in asphalt mixtures. First, the aggregates could be treated to reduce its surface energy and achieve an enhanced adhesion of the asphalt aggregate. Second, the surface energy of the asphalt binder could be lowered with a surfactant that provided an electrical charge opposite to that present on the aggregate to achieve better coating and adhesion. The strength results indicated that the tensile strength ratio (TSR) remains lower than the Marshall stability (MS) ratio owing to the higher dry tensile strength relative to the wet tensile strength. Depending on their nature, the additives could improve the stripping resistance. Kok and Yilmaz (2009) investigated the effects of SBS and lime filler on moisture resistance of asphalt mixtures. The combined effect of lime and SBS on moisture damage was evaluated with a conventional mechanical strength test. The strength properties studied included the Marshall

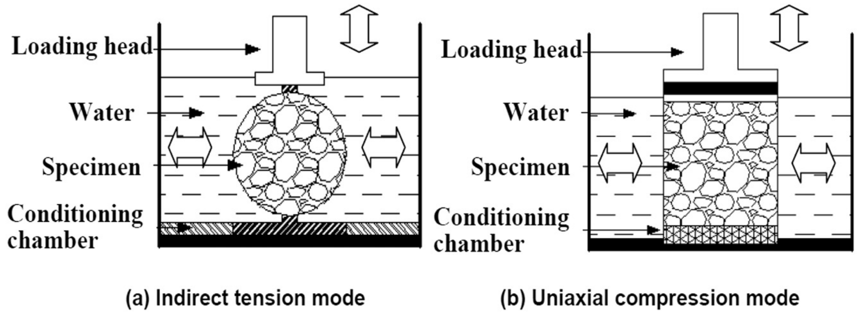

Fig. 5. Sketch map of specimens subject to the coupled water/loading action (Solaimanian et al., 2007).

stability, stiffness measured as the MS/flow ratio, indirect tensile strength (ITS) and TSR. These properties improved with the addition of lime or SBS, and improvements were maximized when higher amounts of SBS with lime were used.

Huang et al. (2010) evaluated the moisture susceptibility of asphalt mixture by using different mineral fillers as anti-stripping agents. The assessments were based on the Superpave indirect tensile test (IDT), TSR and dynamic modulus tests. The authors described that finer proportions of lime should be used when added as mineral filler in asphalt mixture. The finer the filler, the more surface area it has to react with asphalt and aggregate therefore, eventually improves the moisture resistance. In the fracture mechanics criterion Birgisson et al. (2004) used energy ratio (ER) to identify the effects of moisture on the fracture resistance of asphalt mixture. It was revealed that the ER decreases with the effects of moisture conditioning. Therefore, with the decrease in fracture resistance the moisture damage increased. The results also described that anti-stripping agents improves the resistance of fracture energy against moisture damage. The idea of using single parameter such as energy ratio in fracture mechanics can be implied to quantify the moisture damage in asphalt mixtures. To produce a moisture resistant material, Hajj et al. (2011) used a number of additives including amines, diamines, polymers, Portland cement, fine dust and hydrated lime being common. The assessment of lime treatment and its impact on ravelling and moisture sensitivity of local HMA pavements was conducted. Resilient Modulus (M_r) properties were used to assess the moisture resistance of asphalt mixture by using different methods of lime addition. The marinating process used, was moist lime when added into aggregate and cured for 48 h prior to drying and mixing process of the mixture. The lime treated mixture showed higher resistance against M_r stiffness and remained above 2070 MPa, whereas the untreated mixture remained around 700 MPa at an extent of 18 Freeze Thaw (F-T) cycles.

Arambula et al. (2007) used X-ray computed tomography system to relate the internal air voids structural distribution and connectivity with moisture susceptibility. The mechanical strength evaluations were used and correlations were developed with surface energy and fracture energy modelling. Dynamic tensile force was applied until it fractures the specimens in direct tension, which showed more stripped surfaces when the specimens were moisture conditioned. The mixtures with lower air void radius showed more susceptibility towards moisture damage as compared to larger air void radii. This brings the attention of researchers towards the importance of mix design and compaction methods that can be used to optimize the moisture resistance. Cui et al. (2009) analyzed the dynamic response of saturated asphalt pavement by using Finite Difference Method (FDM). When the pore water pressure under wheel gap is positive it showed the pumping action in contrast the negative designated the suction. Therefore it proves that in pavements surface course the water is sucked repetitively under traffic loads. The dynamic pore pressure increases when velocity of vehicle increased. The Moisture Induction Simulation Test (MIST) used by Twagira and Jenkins (2010) evaluates the cyclic water pressure in bituminous stabilized materials. The moisture ingress in asphalt mixtures was evaluated by using Shear parameter and mixture stiffness M_r. The cyclic water pressure as a measure of moisture damage acceleration differentiated between high moisture resistant and moisture susceptible mixtures.

Iskender and Aksoy (2012) evaluated the moisture susceptibility of asphalt mixtures with respect to different laboratory testing protocols using field cores and Marshall laboratory samples. The different moisture evaluation methods adopted in the laboratory revealed that the indirect tensile strength and creep deformation values remained higher for the specimens collected from field than for the laboratory samples; however, the M_r values for the field specimens remained lower because the laboratory samples were thought to have higher load spreading capacities and higher resistance to rutting. Xiao et al. (2010) assessed the effect of different anti stripping agent (ASA) on the moisture susceptibility of WMA by using standard laboratory testing procedures. Correlations between ITS and toughness values were developed. It was found that the hydrated lime provided better moisture resistance in WMA mixtures than liquid ASA could provide. Xiao et al. (2011) conducted conventional ITS tests to assess the effect of anti-stripping additives in WMA with respect to long-term soaked duration. The anti-stripping resistance of WMA mixtures decreased with conditioning duration; in addition, the strength of the mixtures improved when anti-stripping additives were added. However, Xiao et al. (2010) reported that hydrated lime improved the moisture resistance compared with liquid ASA regardless of WMA additive and aggregate type. The saturation duration did not play a key role in finding the ITS values.

Bausano and Williams (2009) used a simple performance test method to evaluate the moisture damage in asphalt mixtures. It is believed that the dynamic modulus test parameter is sensitive to the pore pressure only in wet specimens. Therefore, the study suggested that a transition of the standard AASHTO T283 test procedures from the Marshall mix design to the current Superpave mix design could be considered. The evaluation criteria is based on the ratio of condition to unconditioned dynamic modulus values. The dynamic modulus used in Superpave mix design method and as an input in mechanistic-empirical pavement design guide (MEPDG), do not consider the moisture damage, hence, benefits can be found in terms of already existing test values. When pavement is under wet conditions, it remains under repeated hydraulic loading. Based on the moisture damage evaluation of field samples, results show that AASHTO T283 and the proposed retained dynamic modulus criteria rank the sample differently. Cheng et al. (2011) evaluated the effects of Sub Nano Sized Hydrated lime

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(SNHL) on the moisture damage properties of WMA. The micro structure of SNHL and regular hydrated lime (RHL) are assessed by using scanning electron microscopy (SEM) which gives rough, irregular and fractured surface with sharp angle. The result reveals that the aggregate type and WMA additive used have predominant effects on the use of SNHL as anti-stripping in WMA. Kanitpong and Bahia (2008) assessed the TSR relationship using field data. The pavement field performance is evaluated based on the data obtained from pavement distress index. Further, pneumatic adhesion tensile testing instrument (PATTI) is used to validate the test results, as adhesion is a direct measure of moisture resistance of asphalt binders. From the correlation analysis it is found that the distresses that are expected to be affected by moisture in the field do not show a good relation with TSR values that are produced from original laboratory mixtures. The anti-stripping additives can reduce the surface tension of asphalt binder when added and improves adhesion to aggregate which reduces the bond loss due to moisture. The approach to measure moisture damage using TSR method is not practical for obtaining fundamental bonding properties of asphalt binders and aggregates. Therefore, further investigations based on interfacial properties of asphalt and aggregate should be conducted.

Kanitpong et al. (2012) studied the effect of aggregate gradation on the aggregate physical properties to assess the moisture damage mechanism of WMA. Based on the dynamic creep test results, it was found that the WMA could resist permanent deformation better than the HMA, while the WMA was more prone to moisture damage. Zhou et al. (2009) used an index called Retained Marshall Stability Ratio in Immersion Saturated State (RRISS) to evaluate the influence of saturation state of HMA mixture in laboratory. The saturation results obtained after the samples of different air voids are left in water, the absorption increases with temperature and air voids up to certain days and then become constant. However, the saturation duration could not be fixed and RRISS results are not sensitive to the air voids. Mohammad et al. (2008) evaluated moisture damage of WMA by conducting mechanical performance tests such as ITS, HWTD, Dynamic Modulus and Semi Circular bending test. Lower values are obtained for WMA compared with HMA in terms of ITS strain evaluation. The rut depth is slightly lower for WMA than HMA in the limited studied data.

Medeiros et al. (2012) used the third-scale model mobile load simulator (MMLS3), which is a laboratory accelerated loading device with four pneumatic tires (each having a diameter of 300 mm). The tires can be driven using a variable speed motor to assess moisture damage. Both WMA and HMA mixtures were tested; it was concluded that WMA samples prepared with Sasobit were susceptible to moisture damage, while the Asphamin specimen did not indicate moisture susceptibility. Low temperature thermal cracking are also evaluated which shows negative impact of WMA compared with HMA. McCann and Sebaaly (2003) evaluated the significance of different mechanical moisture test methods which includes resilient modulus, tensile strength and simple shear test. The method of lime addition is also assessed. Though, the method of lime addition (Dry, Wet slurry, Marination 0 and 48 h) does not affect the HMA mechanical properties. However, the addition of lime additive reduces moisture damage. From statistical data evaluations, the resilient modulus method is more sensitive when there are very slight changes in the strength due to moisture damage. Whereas, when the strength reduction exceeded 20% of the tensile strength it provides a better statistical correlation. Lu and Harvey (2008) and his co-workers developed a fatigue based test procedure to evaluate moisture damage in asphalt mixture. The conditioning temperature significantly influences the moisture sensitivity and the high temperature accelerates the moisture damage especially in untreated materials. While the moisture content and duration has no such effect during fatigue test. The fatigue beam test procedure can distinguish different moisture damage mixes. It ranks the material and can reflect the material behavior prior to the field experiences. The procedure can be included in pavement design to consider moisture damage but before applying such procedures the conditioning test parameters and field performance data needs to be correlated.

Medeiros et al. (2012) used three different laboratory accelerated moisture damage procedures: the MMLS3, MIST and F-T Cycles testing methods. The MMLS3 procedure showed that the rut depths for mixtures containing lime as an anti-stripping agent were not significant. The differences are observed in the visual stripping of samples. Variations are found in TSR values using different mixtures. The results obtained from F-T cycles of AASHTO T-283 are not in agreement with MMLS3 results, as the MMLS3 results show a type of aggregate with good resistance to moisture damage, but the results obtained from AASHTO-T283 show the opposite trend. The main reason behind this was thought to be that the distress mechanism in AASHTO-T283 is due to volumetric expansion and contraction stress, whereas in MMLS3, it is due to traffic and moisture at high temperature. The results obtained from MIST test was somehow consistent with MMLS3, which ranks material in a same manner, as is in the case of MMLS3 and with field performance data. Medeiros et al. (2012) recommends that when F-T cycle method is used, consider at least six F-T cycles and use resilient modulus instead of tensile strength. To increase the level of certainty consider semicircular bending or fatigue test to evaluate moisture sensitivity. Attia and Abdelrahman (2010) investigated the base-course reclaimed asphalt pavement (RAP) material to evaluate moisture damage by conducting an M_r test. From the results obtained, it was found that with the increase in moisture content, the M_r values decreased. The F-T conditioning does not show a negative impact on the stiffness of RAP, which is elaborated by the fact that RAP has a low ability to hold extra moisture after optimum moisture content. Xiaojun et al. (2008) evaluated the effects of sulfur extended asphalt modified (SEAM) on moisture susceptibility. The use of conventional laboratory test procedures includes TSR and boiling water test. The different anti-stripping agent when added to SEAM modified mixtures can rank against moisture susceptibility differently. Additionally, it is observed that course graded mixtures can perform well and lower air void can increase the resistance against moisture damage with increasing binder content which enables thick coating of aggregates. Amelian et al. (2014) used the boiling water test and applied image analysis to convert it from subjective evaluation to a more objective estimation, so that it does not depend on visual rating and operator's judgments.

Breakah et al. (2009) utilized dynamic modulus testing methodology to include a moisture damage assessment parameter of asphalt mixtures in the MEPDG. The dynamic modulus test was already used as an input design parameter. The methodology is applied on two projects and results are compared with the dynamic modulus values and standard testing procedure AASHTO T-283. The dynamic modulus ratio conditioned to unconditioned increases with the increase in frequency which can be attributed as the pore water pressure build-up at higher frequency. The results show E^* ratio is higher than AASHTO T283 TSR values. One of the interesting fact that is highlighted, after an understanding the TSR and E^* ratios show only whether the mixtures are moisture susceptible or not, but using dynamic modulus test results in MEPDG reveals that how the moisture damage affect the pavement performance. This is a good approach in determining whether the increase in distresses due to moisture damage will be in design limits or it will exceed. Chen and Huang (2008) used dynamic modulus Superpave IDT creep resilient modulus and strength tests to evaluate moisture susceptibility. Different conditioning methods and the extent of different course angular aggregates (CAAs) are used to evaluate the mixtures. The CAA has no significant effects on moisture susceptibility. The result reveals that there is an effect of the extent of conditioning including both conditioning methods (MIST and F-T). The authors have not made correlation of different testing procedures on the extent of moisture damaging in asphalt mixtures. Kim et al. (2008) evaluated the fundamental property to measure the behavior of asphalt mixtures containing anti-stripping additives and correlated mixture component behavior to produce a more fundamental in-depth analysis related to moisture damage properties. The TSR AASHTO T 283 results showed a greater influence of hydrated lime when subjected to six F-T cycles. Additionally, the stripping inflation point from the HWTD test shifted toward higher number of cycles, and the rut depth from asphalt pavement analyzer (APA) improved when HL was added. The DSR results revealed that the stiffness of mastic increases with the addition of HL. Hydrated lime can improve the bonding between mastic and aggregates. The result of fundamental strength properties measured from HWTD, APA and TSR are consistent with striping performance based on ranking, which is also verified by energy based measurements of asphalt aggregate.

Oliveira et al. (2011) assessed the effects of surfactant and wax at different production temperatures and at different proportions. The assessments are based on mixtures that showed improved surfactant moisture resistance. The evaluation based on standard conventional test methods reveals that WMA composed of both wax and surfactant can improve rutting and fatigue. The recommendations are based on the economic assessment that should be made to assess the overall significance of future WMA mixtures. Kringos et al. (2008a, b) developed a testing protocol for the measurement of adhesion and cohesion strength of asphalt mastic. To evaluate the effect of moisture infiltration on aggregate mastic bond strength, the numerical moisture infiltration simulation was performed using finite element analysis tool RoAM (Ravelling of Asphaltic Mixtures). The conclusion drawn, recommends that the influence of aggregate micro structure, climatic conditions of field and the erosion of mastic film due to moisture concentration and water pressure should be included in moisture conditioning process.

Tarefder and Yousefi (2012) evaluated asphalt mastics and matrix using different types of fillers and combinations thereof. The assessment was based on the DSR, pull-off and direct shear strength tests. The mastic and matrix material based on moisture damage can provide a useful understanding of the factors involved. Small sizes of rectangular beam matrix are prepared to test in DSR. Result shows that at high temperature both wet and dry shear modulus values are almost equal. This shows the possibility of damage that occurs due to high temperature and may exceed during the wet conditioning damage. Low frequency modulus of wet and dry is not clear and hence, recommendations based on the observation direct, to test samples at low temperature and high frequency for consistency (Mastic). The TSR results cannot predict well moisture damage on the basis of field experience, which may provide false positive and negative results. DSR can provide a better identification of moisture damage on the basis of mastic and matrix material used. It is found that course matrix and mastic are more susceptible to moisture damage compared with fine matrix and mastic. The stress values decreased during matrix tension and pull-off tests when samples are conditioned however, the direct shear test shows an increase in maximum stress when samples are conditioned. Vuorinen and Hartikainen (2001) used ultrasonic cleaner to assess the moisture resistance of asphalt mixtures. The phenomenon of stripping is associated with adhesion failure in asphalt mixtures. The stripped bitumen from aggregate substrates is evaluated both visually and by weight loss and correlation of the result is significant. The soaking duration increases the binder stripping over aggregate substrate and also it affect the stripping rate, with the increase in spreading temperature the stripping decreases. In this work the testing conditioned defined only for selected viscosity binders. The result shows some correlations with Wheel Track Device data but has no good correlations with TSR. The conclusions justifies that the test method is very quick and easy, does not require much instrument involvement. Further research is needed to generalize the findings.

McCann et al. (2006) conditioned the loose asphalt mixture in the laboratory by introducing ultrasonic accelerated moisture conditioning. The loss of smaller particles of aggregate is monitored by weight measurement for 5 h. Linear Regression function is applied on the data and the slope representing the rate at which the smaller aggregate particle dislodges is measured. The recommendations specifies that ultrasonic accelerated moisture conditioning procedure may be used as a one day test method to assess moisture damage. A correlation study shows a reasonable agreement of test result with TSR after one F-T cycle and even slightly better relationship is found when specimens conditioned at multiple F-T cycles. This further encourages that the method can be used to assess moisture sensitivity in asphalt mixtures. Besamusca et al. (2012) conducted simple test methods to evaluate the adhesion and its durability. The methods included the vandskak test, Munich Shake, Indirect Tensile; Duriez wet attrition in Deval, Cantabro, water stripping, PATTI and visualization test (MoD stripping test). The observation explains that during the tensile strength test the strength is the function of both cohesion and adhesion. The hypothesis shows that bitumen adhesion is affected by the stiffness or viscosity during testing and the temperature and conditioning are affected by the water stripping test. The conclusion based on the work states that there is no simple and easy test method to be used, which provide stickiness indicator. Further, due to too many factor involved other than adhesion test methods that measure the mechanical strength based on ratio of conditioned and unconditioned. Al-Barrak (1982) investigated the effect of Ordinary Portland Cement on the performance of HMA using dosage of 0, 2, 4 and 6%. The result indicates that cement is effective in improving the 24 h stability of bituminous mixes due to hardening resulting from hydration of cement. Isacsson (1993) investigated mixtures using cement at dosage of 1 and 2%. The results do not show a significant difference in reducing moisture sensitivity.

The concept of reversible moisture-induced stiffness degradation was introduced by Apeagyei et al. (2014). Moisture-induced stiffness degradation indicates a plasticization process and suggests cohesive rather than adhesive failure dominates the durability of asphalt mixtures under long-term moisture exposure. Khan et al. (2013) developed an improved technique in the laboratory to simulate the aging and moisture damage of asphalt material. Furthermore, a non-destructive technique is used to study the internal permeability that changes as a result of moisture damage in asphalt mixtures. The conditioning of asphalt mixture is performed using the modified Saturation Aging Tensile Stiffness (SATS) test along with image analysis. X-ray CT scan is used under dry and saturated condition to determine the volume of air voids and its interconnectivity. The lower values of stiffness are obtained for specimens with higher void connectivity irrespective of the aggregates type (limestone and granite) used. However, higher retained stiffness is observed for the specimens prepared with basic aggregates. This shows that limestone is better resistant against moisture damage compared with granite aggregates. Fig. 6 (a) and (b) shows typical 3D image of extracted air voids before and after saturation, respectively. Khan et al. (2013) concludes that the design air void content and chemistry of aggregates are the

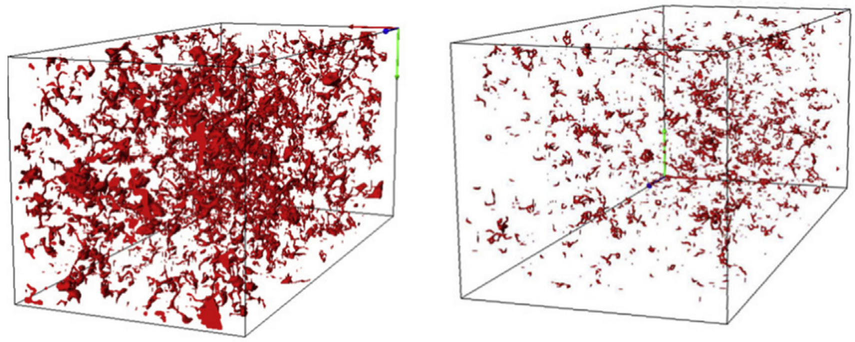

Fig. 6. Typical 3D image of extracted air voids a) before saturation b)after saturation (Khan et al., 2013).

important parameters to study the asphalt moisture damage. Hamzah et al. (2014) investigated moisture susceptibility of warm mix asphalt using direct tensile test and applied image analysis technique to assess the percent adhesion failure susceptibility due to moisture damage as shown in Fig. 7. The results show that with the increase in number of freeze thaw cycles, the adhesion failure increases, and its percent varies with different binder types in use. The use of response surface method is also encouraged to evaluate the moisture damage of asphalt mixtures, to minimize the time and efforts during laboratory testing (Hamzah et al., 2013b).

5.4. Moisture damage micro mechanical modelling

Cheng et al. (2003) proposed two models of adhesion fracture and moisture diffusion based on moisture failure mechanisms. These models are based on the surface free energy and USD methods. The results are evaluated by conducting experiments based on mechanics of asphalt mixtures. It is observed that the surface free energy, surface texture of aggregate and the presence of water affect the adhesion strength. Analytical models developed for adhesion and diffusion are validated by the laboratory based mechanical tests on asphalt mixtures. The adhesion model is developed based on surface energy theories while the model of diffusion is evaluated based on USD. The absorption is the process in which moisture is absorbed into asphalt film, whereas water on the surface of asphalt film is considered as adsorption factor. When comparing moisture damage of asphalt mixtures prepared with different aggregates, the Gib's free energy per unit mass of aggregate concept is employed, which considers both the surface energy and surface texture characteristics of the aggregate. The idea is valid based on mechanical testing of asphalt mixtures. The results of surface energies in terms of moisture resistance agreed well with mixtures tested by mechanical methods. The higher diffusion rate of a binder resisted moisture damage more than lower diffused binder because the amount of moisture a binder holds is more important than rate of diffusion, which is observed during the permanent deformation mechanical testing.

Kutay and Aydilek (2007) developed a three-dimensional fluid flow model based on Lattice Boltzmann to investigate the unsteady dynamic fluid flow in asphalt pavements. It is observed that specimens with replicates having the same compaction energies and NMAS have different hydraulic conductivities because of different aggregate orientations, angularities and distributions of fines, even with same compaction levels. Therefore, different internal pore structures can result. The 3D numerical model is developed, which provides important findings on how the dynamic fluid pressure affects the moisture transport through asphalt mixture. Further recommendations states that more investigation should be accomplished on other types of mixtures. Caro et al. (2009) developed a coupled micro mechanical model to study the asphalt mastic aggregate interface fracture along with moisture diffusion. The main objective of the work is to formulate micro mechanical model application, which evaluates the combined deleterious effect of moisture diffusion and mechanical loading on the asphalt mixture micro structure. The model is based on the input data of material physical and mechanical properties including shape geometry of mixture constituent, moisture concentration, diffusion process and simulating mechanical loading and finally the result analysis. The suggestions are made, that material of same properties with different air voids contents can significantly offer

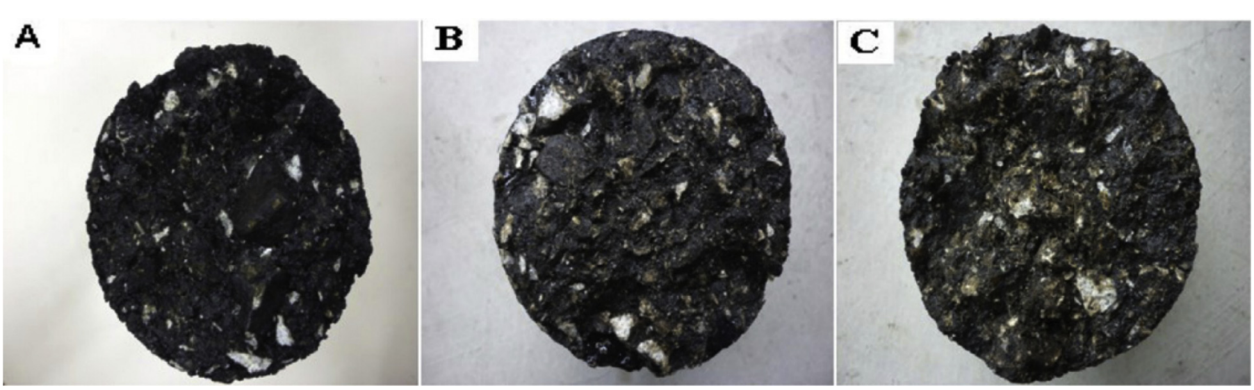

Fig. 7. Original images of warm mix asphalt fractured surfaces A) Dry B) 1 freeze–thaw cycle C) 3 freeze–thaw cycles (Hamzah et al., 2014).

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different moisture resistance, as the mixture air voids structure affects the moisture diffusion of mastic. Also the result of simulation shows that time required to initiate the crack at aggregate mastic interface has a relationship with the amount of moisture content. Therefore, the time required for the crack initiation in the model for lower moisture concentration profile is less than the higher moisture concentration. The authors suggest that there is a need to conduct experimental measurements to assess the material properties for the proper calibrations of the micro mechanical model presented. The inclusion of realistic distribution of air voids structure in the model is also recommended.

Kringos et al. (2009) evaluated the actual moisture concentration inside the asphalt mixture and during the time over which moisture damage may occur in the field. The microscale finite element analysis is used to assess the pore-space distribution inside the mixture. The issues mainly related to conventional standard test AASHTO T283, as many of the shortcomings are reported in the past related to field and laboratory variations. By using such standard laboratory test methods, one of the main drawbacks is that during indirect tensile test the fracture area lies in the center, but during moisture conditioning process in the laboratory, it may be possible due to clustering of the pore space outside specimen. Most of the moisture damage occurs away from the tensile area and is therefore not detected. Further, the vacuum suction is inducing the micro cracking, which could be another variable that is not taken into consideration. Additionally, the field mechanism from mechanical point of view is different in nature, as the long-term effect of cyclic loading in asphalt pavements occur combined with aging and erosion of mastic due to pumping action.

6. Moisture damage in porous asphalt mixtures

Porous asphalt concrete is an open, bitumen-bonded material and it has been applied primarily to mitigate pavement traffic noise (Hamzah et al., 2013a). The binding is generated at the stone–stone contact regions where a limited amount of mortar acts as binding agent (Mo, 2010). Porous asphalt is characterized by high amount of air voids and percentage of coarse aggregates. Compressive, tensile and shear forces are believed to be subjected on the bituminous mortar binding these aggregates together. The damage in material during the process of stress development finally leads to the loss of aggregate (ravelling). Taking into account the open structure of porous asphalt, the ravelling may occur in cohesive or adhesive failure modes. The sudden progressive failure in mortar show cohesive failure and the stone-mortar interface failure results in adhesive failure.

Porous asphalt mixtures easily allow the access of water; these mixtures are highly permeable such that water can quickly pass water through them. From the fact that ravelling typically occurs on porous asphalt surfaces and is seen as a defect type, one can assume that environmental and thermal-induced stresses, traffic loading and aging (bitumen hardening) are the main reasons for ravelling. The deterioration process is certainly affected by moisture damage, but is not believed to be the main reason for the raveling of porous asphalt (Hagos and Molenaar, 2008). The oxidation effect and increased interfacial moisture content due to the open structure of porous asphalt offers large surface area to rapid aging of binder, as a result binder aggregate interfacial failure occur which reflect the moisture damage. The presence of water in the form of liquid, solid or gas is a very important aspect to be considered in porous asphalt. Therefore, it is evident from previous research work that the deterioration of mechanical properties of porous asphalt is mainly due to the water exposure (Poulikakos and Partl, 2012). To simulate the aging of porous asphalt in the field, a Weatherometer is used that combines the effects of temperature, humidity/moisture, and ultraviolet (UV) light during aging seems a practical aging protocol (Hagos and Molenaar, 2008). As shown in Fig. 8, Kringos (2007) explains the mode of failures (adhesive and cohesive) in porous asphalt mixtures.

Switzerland has been practicing porous asphalt concrete since 1979 with different outcomes. Several types of Swiss porous asphalt mixtures have been investigated by federal research projects (Swiss-Standard, 2008). It has been found that in porous asphalt mixtures polymer modified bitumen performed better than the non-modified polymer. Therefore, the current Swiss standard for porous asphalt need polymer modified binder to be incorporated in porous asphalt mixtures. However, this is not the requirement in all over Europe (Poulikakos et al., 2006). The combined action of loading and mortar hardness due to aging of porous asphalt leads to the development of micro cracks and its effect is more pronounced at low temperatures. Water gets inside the micro cracks during the frost–thaw cycles and the water expands in these cracks when it starts freezing. Due to the brittle behavior of stone–stone contact region to relax this expansion, the micro cracks start to progress. The failure finally occurs in the stone–stone contact region after the increase in number of frost–thaw cycles (Mohan, 2010). Hamzah et al. (2012) developed a Dynamic Asphalt Stripping Machine (DASM) to realistically simulate stripping of porous asphalt mixtures subjected to the dynamic action of flowing water. The resistance to stripping was evaluated from the ratio of ITS when tested wet and dry. The results show that both Indirect Tensile Strength Ratio (ITSR) and permeability reduces with conditioning time. Huurman et al. (2010) presented the simplified schematic of Life Time Optimization Tool (LOT) design strategy as shown in Fig. 9. The porous asphalt mixture, when subjected to traffic tire loads, has been studied by a meso-mechanical tool. Parameters such as tire-pavement contact load, mortar response in terms of stress-strain at various locations within the mixture and mixture geometry are fitted to a finite element model. In mixture stress-strain signals are used to estimate the life expectancy of porous asphalt.

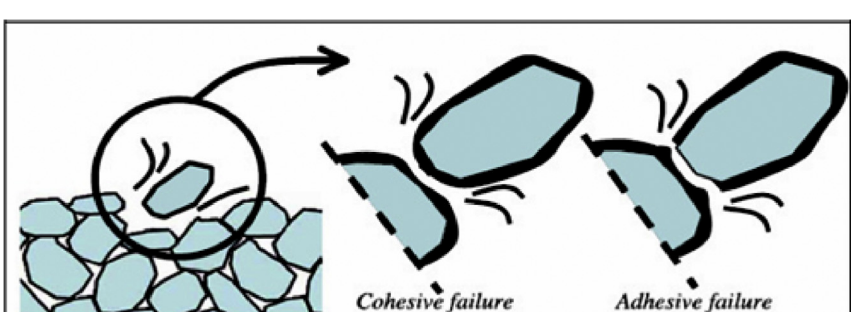

Fig. 8. Failure modes in porous asphalt (Kringos, 2007).

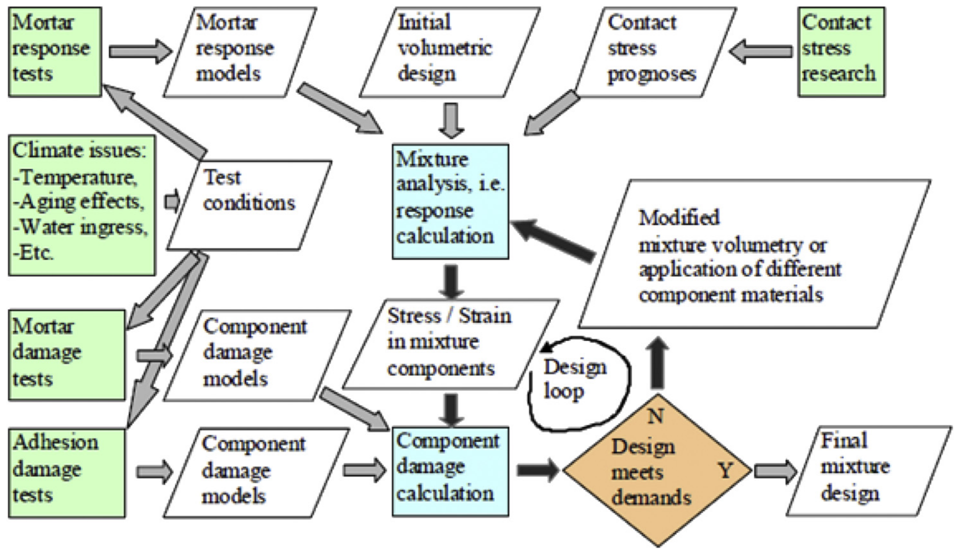

Fig. 9. Simplified schema of life time optimization tool (LOT) design strategy (Huurman et al., 2010).

7. Discussion

The previous studies suggest that most of the work done to identify moisture damage in asphalt mixtures is marginal, taking into account the fact that there is no global agreement among researchers on a single procedure for evaluating the moisture damage (Haghshenas et al., 2015). However, other studies have indicated quite a good potential for asphalt mix in prolonging the lifespan of the pavement and increasing its resistance against water penetration (Modarres et al., 2014). In this study, most of the data were gathered from available datasets, such are the data about the assessment of moisture susceptibility in hot and warm mix asphalt and related investigations. This review article aims to elucidate the key mechanisms of moisture damage in asphalt mixtures and its components. The authors have collectively presented studies conducted by different investigators. As explained in Section 1, there is a need to shift the paradigm that seeks to repair damage to one that seeks to take preventive measures. Many of the standardized and non-standard laboratory tests as described and categorized in Table 2 have been practiced to identify or quantify the material resistance against moisture damage in asphalt pavement. It is extremely difficult to fully reap the benefits of these testing procedures and approaches (presented in Table 3 and Sections 5 and 6), as it is impractical to take into account all of the various factors such as aging, binder diffusion, environmental effects, pore pressure due to traffic loading under wet conditions and types of drainage system of the pavement. Therefore, simulating these factors in the laboratory is vital concern for pavement researchers, and the inclusion of in-situ testing techniques involving both destructive and non-destructive methods for moisture damage evaluation may avoid the concerns and issues discussed above.

8. Summary and future developments

Moisture damage in asphalt mixtures plays a very prominent role in the performance of asphalt pavement and needs serious attention. Currently, there are many laboratory testing methods to assess the susceptibility of moisture damage in asphalt mixtures and specifications vary from region to region. Thus far, no such laboratory testing procedures can precisely estimate the moisture damage based on the design and selection criteria of asphalt materials because moisture damage is a long term phenomenon and appears during the design life of the pavement. Moisture damage involves many other factors such as aging, binder diffusion and the combined action of traffic loading and environmental effects. The process is also influenced by changes in weather and the rate of heat energy transfer to the asphalt aggregate under moist field conditions in the field and is consistently neglected by many investigators. Therefore it is impractical to develop a laboratory-based testing method that combines all of these factors. Hence it is recommended that in-situ testing techniques that involve both destructive and non-destructive methods to assess moisture damage should be included. This can be used as an input for material characterization along with the laboratory-based testing techniques. The analytical approach may also be involved for predicting more precise measurements. Finally, the gap between laboratory and field simulations can be minimized and the results of in-situ testing techniques can be combined with laboratory-based research outputs.

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