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TECHNOLOGY OF ASPHALT CONCRETE DESIGN MIXES

A REVIEW ARTICLE

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Summary

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The Superpave mix design system integrates material selection and mix design into procedures based on the project's climate and design traffic. Superpave uses a completely new system for testing, specifying, and selecting asphalt binders. While no new aggregate tests were developed, current methods for selecting and specifying aggregates were refined and incorporated into the Superpave mix design system. Performance testing uses new equipment and procedures to ensure that Superpave mixtures exhibit acceptable amounts of the distress types considered by Strategic Highway Research Program (SHRP) researchers: permanent deformation, fatigue cracking, and low temperature cracking.

Moisture damage is weakens the adhesiveness and cohesiveness of the Asphalt Concrete (AC) due to the following attributes: (1) The material properties of the aggregate in terms of mineralogy, external compounds, moisture content, and surface roughness. (2) The material properties of the binder in terms of permeability and chemical composition. (3) The mixture properties in term of void structure, aggregate gradation, and binder content. (4) Additional causes such as environmental conditions, traffic volume and loads, pavement design, and construction practices (Sebaaly 2007).

Surface Free Energy (SFE) is a method to evaluate asphalt concrete’s susceptibility to moisture damage. Liquid anti-strip agents and chemical lime additives have been used to reduce the susceptibility of the asphalt concrete to moisture damage.

Chemical, wax or other organic additives, and foaming technologies obtained by means of special bitumen modifiers, represent a promising technical solution to reduce the temperatures required for warm mixtures asphalt production and pavement construction.

Nanotechnology has the potential to create many new materials and devices with wide-ranging purposes. Nanomaterials are generally important modifiers in improving pavement performance, nanoclay, carbon nano tubes, nanosilica, nano-hydrated lime, nano-sized plastic powders, or polymerized powders, and nano fibers.

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Chapter 1

Overview and Scope

Chapter 1

Overview and Scope

1.1 Introduction

Asphalt has been used as a construction material from the earliest days of civilization, so it has long been used in roadway construction. Asphalt mixture consists of asphalt, coarse and fine aggregate, and a number of additives occasionally used to improve its engineering properties. The purpose of mixture design is to select an optimum asphalt content for a desired aggregate structure to meet prescribed criteria. The highway network is not only the economic backbone of the country, but it also provides the only transportation access to a growing number of communities. Since the 1940s most of Hot Mix Asphalt (HMA) mixtures have been designed using either the Marshall or Hveem mixture design methods.

The Superpave mix design system integrates material selection and mix design into procedures based on the project's climate and design traffic. Superpave uses a completely new system for testing, specifying, and selecting asphalt binders. While no new aggregate tests were developed, current methods for selecting and specifying aggregates were refined and incorporated into the Superpave mix design system.

The Superpave system allows the designers to use reliability measurements to assign a degree of design risk to the high and low pavement temperatures used in selecting the binder grade. Reliability is the percent probability (about 98 percent), in a single year that the actual temperature (one-day or seven-day high) will not exceed the design temperature (Cominsky et. Al. 1994), [16].

The Superpave mix design procedures calculate volumetric properties values for compacted paving mixtures. The Superpave mixture design and analysis system requires accelerated performance depending on traffic level.

Performance testing uses new equipment and procedures to ensure that Superpave mixtures exhibit acceptable amounts of the distress types considered by Strategic Highway Research Program (SHRP) researchers: permanent deformation, fatigue cracking, and low temperature cracking.

Superpave predicts pavement performance for various combinations of asphalt binder and mineral aggregate for design level 2 and 3. The Superpave Simple Shear Test (SST) to predict permanent deformation and fatigue cracking and the Indirect Tensile Tester (IDT) for predicting low temperature cracking (Cominsky et. al. 1994), [17].

Thus moisture damage weakens the adhesiveness and cohesiveness of the Asphalt Concrete (AC) due to the following attributes: (1) The material properties of the aggregate in terms of mineralogy, external compounds, moisture content, and surface roughness. (2) The material properties of the binder in terms of permeability and chemical composition. (3) The mixture properties in term of void structure, aggregate gradation, and binder content. (4) Additional causes such as environmental conditions, traffic volume and loads, pavement design, and construction practices (Sebaaly 2007).

Surface Free Energy (SFE) is a method to evaluate asphalt concrete's susceptibility to moisture damage. Once the SFE measurements of an asphalt binder and aggregate are collected, a quantitative measurement of the bond between the two materials can be calculated (Lambert et. al. 2013).

Treatments to reduce the sensitivity of asphalt concrete to moisture damage have been successfully and widely used in the asphalt paving industry. There are two dominant treatment types called *liquid anti-strip agents* and *chemical lime additives* that are each respectively applied to the asphalt binders and aggregates.

Hydrated lime has been used to reduce the susceptibility of the asphalt concrete to moisture damage. This additive modifies the asphalt binder and surface chemistry of aggregates, through Indirect Tensile Testing (ITS) (Huang et. al. 2005).

Rising energy costs and increased environmental awareness have brought attention to the potential benefits of Warm-Mix Asphalt (WMA) in the world. Lower production temperatures can be achieved by means of various WMA technologies broadly classified as organic and chemical additives, and foaming technologies (either by using water-bearing additives or water-based processes), (Diab 2014).

Chemical additives, are described as an "asphalt flow improvement" and are used to improve the ability of asphalt binder to coat the aggregate particles at lower temperatures rather than reduce the binder's viscosity and they are Asphamin, Sasobit, and Evotherm (Hurley et. al. 2007). Wax or other organic additives, obtained by means of special bitumen modifiers, represents a promising technical solution to reduce the temperatures required for asphalt production and pavement construction (D'Angelo et. al. 2008).

WAM-Foam is one of the foaming technologies that uses the separate chamber to introduce water and air into hot asphalt binder (Diab 2014).

Nanotechnology has the potential to create many new materials and devices with wide-ranging purposes. Nano-sized particles have been used in numerous applications to improve the properties of various materials. The utilization of nanotechnology in civil engineering is expected to increase and may become an attractive alternative for asphalt binder modification (Xiao at. al. 2011). Nanotechnology is the science devoted to cover the design, construction and utilization of functional structures with at least one dimension in the nanometer range. A nanometer is one billionth of a meter. This technology is dominated by developments in basic physics and chemistry researches, where phenomena on atomic and molecular level are used to provide materials (having at least one dimension ≤ 100nm) and structures with arts are not promising using the materials in their typical macroscopic form (bulk materials) (Diab 2014, Steyn 2008, and Kelsall et. al. 2004).

Modification of the asphalt mixture is one approach used to achieve good mixtures. Nanomaterials are generally important modifiers in improving pavement performance, nanoclay, carbon nano tubes, nanosilica, nano-hydrated lime, nano-sized plastic powders, or polymerized powders, and nano fibers (You 2013).

1.2 Objectives of Study

According to the previous aspects, the main objective of this study is to review the state of the art as well as the future of the following:

1. The Superpave mix design system,

2. Asphalt concrete’s susceptibility to moisture damage,
3. Warm-Mix asphalt technologies, and
4. Improving the performance of asphalt concrete with nanotechnology.

1.3 Scope of Study

The article contents are organized as follows:

Chapter 1: It introduces the article via situating the subject and clarifying the motivating objectives of this article. It also highlights the organization of the article.

Chapter 2: It highlights the Superpave asphalt mixture design procedures. The Superpave asphalt binder specification; the aggregate and mix design specifications are discussed. Resilient modulus (MR) and creep compliance (D(t)) testing according to the Superpave Indirect Tensile test are discussed. A number of asphalt additives were discussed in short brief.

Chapter 3: It presents the state of the art of moisture damage in asphalt pavements. Evaluation of asphalt concrete's susceptibility to moisture damage with Surface Free Energy (SFE) was discussed. *Liquid anti-strip agents* and *chemical lime additives* are used to improve the resistance of the AC mixture to moisture damage.

Chapter 4: It presents short brief of Warm-Mix Asphalt (WMA) technology, also the effect of different additives such as chemical, organic (wax) and foaming technology on WMA and their benefits.

Chapter 5: It highlights the state of the art and the future of different types of nanomaterials which will be or are used in Hot-Mix Asphalt (HMA), such as nanoclay, carbon nano tubes, nanosilica, and nano-hydrated lime.

Chapter 6: It summarizes the general conclusions of this article. Also, it exhibits some suggestions and recommendations for future research related to technology of AC design mix which remain unsolved yet.

- List of references is given in the bibliography at the end of this article.
- All symbols and notations are defined wherever they appear.

Chapter 2

Superpave Hot-Mix Asphalt

Chapter 2

Superpave Hot-Mix Asphalt

2.1 Introduction

Interest in the Superpave performance-based mix design and analysis system, developed through the asphalt research program of the Strategic Highway Research Program (SHRP), is rapidly growing. A general approach to field control procedures was developed under SHRP to assist field technicians in adjusting mix design and monitoring production.

The Superpave mix design system is a comprehensive method of designing paving mixes tailored to the unique performance requirements dictated by traffic, environment (climate), and structural section at a particular pavement site. It facilities selecting and combining asphalt binder, aggregate, and any necessary modifier to achieve the required level of pavement performance (Sebaaly 2007).

The Superpave system is applicable to virgin and recycled, dense-graded, Hot-Mix Asphalt (HMA), with or without modification. In addition, the Superpave performance tests are applicable to the characterization of a variety of specialized paving mixes such as stone matrix asphalt. It can be used when constructing new surface, binder, and base layers, as well as overlays on existing pavements. Through materials selection and mix design, it directly addresses the reduction and control of permanent deformation, fatigue cracking, and low-temperature cracking. It also explicitly considers the effects of aging and moisture sensitivity in promoting or arresting the development of these three distresses (Lytton et. al. 1993, and Reberts et. al. 2002).

2.2 Background to Marshall and Hveem Methods

Most agencies currently use the Marshall mix design method. Developed by Bruce Marshall of the Mississippi State Highway Department, the U.S. Army Corps of Engineers refined and added certain features to Marshall's approach and it was formalized as ASTM D 1559 and AASHTO T 245. The Marshall method entails a laboratory experiment aimed at developing a suitable asphalt mixture using stability/flow and density/voids analyses.

One advantage of the Marshall method is its attention to density and voids properties of asphalt mixtures. This analysis ensures the proper volumetric proportions of mixture materials for achieving a durable HMA. Another advantage is that the required equipment is relatively inexpensive and portable, and thus, lends itself to remote quality control operations. However, many engineers believe that the impact compaction used with the Marshall method does not simulate mixture densification as it occurs in a real pavement. Furthermore, Marshall stability does not adequately estimate the shear strength of HMA. These two situations make it difficult to assure the muting resistance of the designed mixture. Consequently, there has been a growing feeling among asphalt technologists that the Marshall method has outlived its usefulness for modern asphalt mixture design (White 1985, Swami et. al. 2004).

The Hveem mix design procedure was developed by Francis Hveem of the California Department of Transportation. Hveem and others refined the procedure, which is detailed in ASTM D 1560 and ASTM D 1561. The Hveem method is not commonly used for HMA outside the western United States.

The Hveem method also entails a density/voids and stability analysis. The mixture's resistance to swell in the presence of water is also determined. The Hveem method has two primary advantages. First, the kneading method of laboratory compaction is thought to better simulate the densification characteristics of HMA in a real pavement. Second, Hveem stability is a direct measurement of the internal friction component of shear strength. It measures the ability of a test specimen to resist lateral displacement from application of a vertical load (Crawford 1989).

A disadvantage of the Hveem procedure is that the testing equipment are somewhat expensive and not very portable. Furthermore, some important mixture volumetric properties that are related to mix durability and not routinely determined as part of the Hveem procedure. Some engineers believe that the method of selecting asphalt content in the Hveem method is too subjective and may result in non-durable HMA with too little asphalt (Vallerga et. al. 1985).

To augment the standard Marshall and Hveem methods, agencies have increasingly adopted laboratory design procedures, methods and/or systems that they have found suitable for their conditions. The Georgia loaded wheel tester is an example of equipment used to replace or supplement procedures in other design systems. The advantage of these systems is that agencies can develop very clear criteria, backed up by performance data from real pavements. However, agencies also have to conduct many experiments to achieve this experience. Even then the experience is only applicable to the materials and environmental conditions tested. New products and materials require additional experimentation. Furthermore, no degree of performance is measured, making these systems difficult to use for economic comparisons of alternate materials.

2.3 Superpave Asphalt Mixture Design Procedures

Individual steps are typically used to select asphalt and aggregate materials and conduct mix design procedures to combine the materials. The Superpave mix design system integrates material selection and mix design into procedures based on the project's climate and design traffic.

The Superpave mixture design and analysis system requires accelerated performance tests to be conducted when traffic level exceeds one million Equivalent Single Axle Load (ESAL). Level 2 mix design is used for traffic up to ten million ESAL, and is anticipated to be the most predominant Superpave mix design used in typical highway applications. A level 3 mixture design is required for traffic levels exceeding ten million ESAL (Cominsky et. al. 1994) [17].

The Superpave asphalt binder specification; the aggregate and mix design specifications are discussed hereafter.

2.3.1 Performance Graded Asphalt Binder Specification

The Superpave asphalt binder specification differs from other asphalt specifications in that the tests used to measure physical properties that can directly related to field performance by engineering principles.

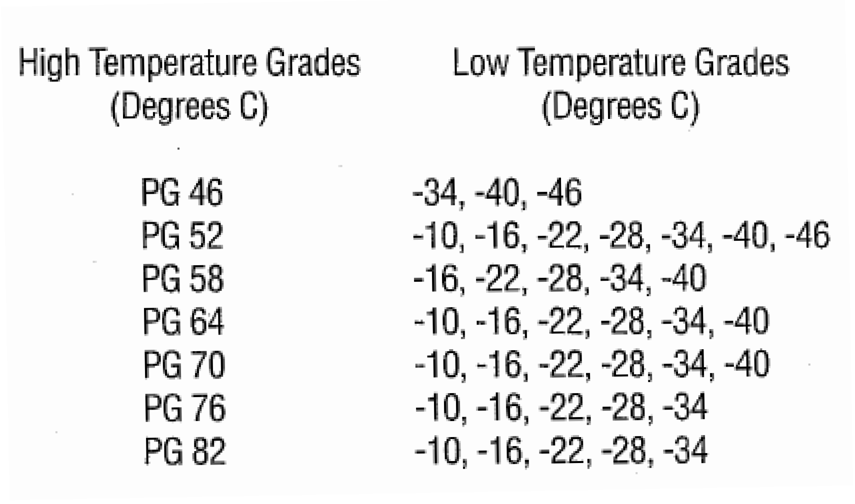
A unique feature of the Superpave binder specification is that additional performing test at a constant temperature and varying the specified value, the specified value is constant and the test temperature at which the value must be achieved is varied. as an example, consider two constructed projects – one at the equator and one at the Arctic Circle. Good asphalt performance is expected in both locations, but the temperature condition under which good binder performance is achieved are vastly different (Asi 2007).

Performance graded (PG) binders are defined by a term such as PG64-22. The first number, 64, is the "high temperature grade". This means that the binder possesses adequate physical properties up to at least 64°C (Bahia et. al. 2000). This would correspond with the high pavement temperature in the climate which the binder is expected to serve. Likewise, the second number (-22°C), "low temperature grade" and means that the binder processes adequate physical properties in pavements down to at least -22°C, as shown in Figure 2.1.

Tests performed on the original asphalt represent first stage of transport, storage, and handling. The second stage represents the asphalt during mix production and construction, and is simulated in the specification by aging the binder in a rolling thin film oven. This procedure exposes thin binder films to heat and air and approximates the exposure of asphalt during hot mixing conditions. The third stage occurs as the binder ages over a long period as part of the hot mix asphalt pavement layer. This stage is simulated in the specification by the pressure aging vessel. This procedure exposes binder samples to heat and pressure conditions that simulate years of in-service aging in a pavement (McGennis et. al. 1994).

Figure 2.1: Performance graded Binder Testing Devices

Table 2.1: Superpave binder Grades (Cominsky et. al. 1994) [16].



High Temperature Grades (Degrees C)	Low Temperature Grades (Degrees C)
PG 46	-34, -40, -46
PG 52	-10, -16, -22, -28, -34, -40, -46
PG 58	-16, -22, -28, -34, -40
PG 64	-10, -16, -22, -28, -34, -40
PG 70	-10, -16, -22, -28, -34, -40
PG 76	-10, -16, -22, -28, -34
PG 82	-10, -16, -22, -28, -34

The Superpave binder specification and its test methods are currently being evaluated by both AASHTO and ASTM. The tests performed on the asphalt binders included, the Rotational viscometer, Dynamic Shear Rheometer (DSR), Bending Beam Rhemoeter (BBR) and Fourier Transform Infrared Spectroscopy (FTIR). Table 2.2 lists the new binder test evaluated and a brief description of its use in the new specification and the test results relationship to field performance are presented .

Table 2.2: Superpave Binder Test Equipment (Cominsky et. al. 1994) [16].

Equipment	**Purpose**
Rolling Thin Film Oven (RTFO) Pressure Aging Vessel (PAV)	Simulate binder aging (hardening) Characteristics
Dynamic Shear Rheometer (DSR)	Measure binder properties at high and intermediate temperature
Rotational Viscometer (RV)	Measure binder properties at high temperatures
Bending Beam Rheometer (BBR) Direct Tension Tester (DTT)	Measure binder properties at low temperatures

2.3.2 Mineral Aggregate

Mineral aggregate properties are obviously important to asphalt mixture performance. However, the Marshall and Hveem mix design methods do not incorporate aggregate criteria into their procedures. Conversely, aggregate criteria are directly incorporated into Superpave mix design procedures. While no new aggregate test procedures were developed, existing procedures were refined to fit within the Superpave system. Two types of aggregate properties are specified in the Superpave system: consensus properties and source properties.

Consensus properties are those that SHRP researchers believed were critical in achieving high performance HMA. These properties must be met at various levels depending on traffic volume and position within the pavement. High traffic levels and surface mixtures (i.e., shallow pavement position) require more strict values for consensus properties. Many agencies already use these properties as quality requirements for aggregates used in HMA. The Superpave consensus properties are coarse aggregate angularity; fine aggregate angularity; flat and elongated, particles; and clay content.

By specifying coarse and fine aggregate angularity, Superpave seeks to achieve HMA with a high degree of internal friction and thus, high shear strength for rutting resistance. Limiting elongated pieces ensures that the HMA will not be as susceptible to aggregate breakage during handling and construction and under traffic. Limiting the amount of clay enhances the adhesive bond between asphalt binder and the aggregate.

2.3.2.1 Consensus Aggregate Properties

The pavement experts agreed that certain aggregate characteristics were critical to well perforating HMA. These characteristics were called "consensus properties" because there was wide agreement in their use and specified values. Those properties are coarse aggregate angularity; fine aggregate angularity; flat, elongated particles; and clay content.

The criteria for these consensus aggregate properties are based on traffic level and position within the pavement structure. Materials near the pavement surface subjected to high traffic levels require more stringent consensus properties. The criteria are intended to be applied to a proposed 'aggregate blend rather than individual components. However, many agencies currently apply such requirements to individual aggregates so that undesirable components can be identified.

2.3.2.1.1 Coarse Aggregate Angularity

This property ensures a high degree of aggregate internal friction and rutting resistance. It is defined as the percent by weight of aggregates larger than 4.75 mm with one or more fractured faces (Brian et. al. 2005).

2.3.2.1.2 Fine Aggregate Angularity

This property ensures a high degree of fine aggregate internal friction and rutting resistance. It is defined as the percent air voids present in loosely compacted aggregates smaller than 2.36 mm [AASHTO TP 33, "Test Method for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, & Grading]. Higher void contents mean more fractured faces. In the test procedure, a sample of fine aggregate is poured into a small calibrated cylinder through a standard funnel (Figure 2.2). By measuring the mass of fine aggregate (W) in the filled cylinder of known volume (V), the void content can be calculated as the difference between the cylinder volume and fine aggregate volume collected in the cylinder. The fine aggregate bulk specific gravity (G_{sb}) is used to compute the fine aggregate volume (Cominsky et. al. 1994 [18], and Brian et. al. 2005).

2.3.2.1.3 Flat and Elongated Particles

This characteristic is the percentage by mass of coarse aggregates that have a maximum to minimum dimension ratio greater than five (Cominsky et. al. 1994) [19].

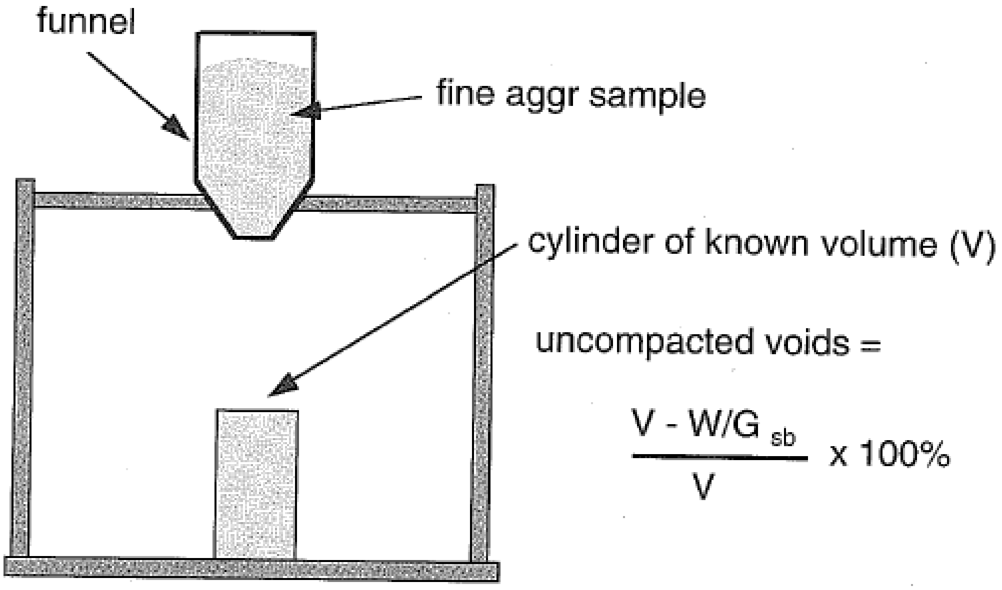


Figure 2.2: Fine aggregate angularity apparatus

2.3.2.1.4 Clay content

Clay content is the percentage of clay material contained in the aggregate fraction that is finer than a 4.75 mm sieve. It is measured by AASHTO T 176, "Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test" (ASTM D 2419). A sample of fine aggregate is mixed with a flocculating solution in a graduated cylinder and agitated to loosen clayey fines present in and coating the aggregate. The flocculating solution forces the clayey material into suspension above the granular aggregate.

2.3.2.2 Source Aggregate Properties

In addition to the consensus aggregate properties, SHRP researchers believed that certain other aggregate characteristics were critical. However, critical values of these properties could not be reached by consensus properties was recommended. Specified values are established by local agencies. While these properties are relevant during the mix design process, they may also be used as source acceptance control. Those properties are toughness, soundness, and deleterious materials.

2.3.2.2.1 Toughness

Toughness is the percent loss of material from an aggregate blend during the Los Angeles Abrasion test (AASHTO T 96 or ASTM C131 or C535). This test estimates the resistance of coarse aggregate to abrasion and mechanical degradation during, handling, construction, and in-service. It is performed by subjecting the coarse aggregate, usually larger than 2.36 mm. to impact and grinding by steel spheres. The test result is the mass percentage of coarse material lost during the test due to the mechanical degradation. Maximum loss values typically range from 35 to 45 percent**.**

2.3.2.2.2 Soundness

Soundness is the percent loss of material from an aggregate blend during the sodium or magnesium sulfate soundness test (AASHTO T 104 or ASTM C88). This test estimates the resistance of aggregate to in-service weathering. It can be performed on both coarse and fine aggregate. The test is performed by exposing an aggregate sample to repeated immersions in saturated solutions of sodium or magnesium sulfate followed by oven drying. One immersion and drying is considered one soundness cycle. During the drying phase, salts precipitate in the permanent void space of the aggregate. Upon re-immersion the salt rehydrates and exerts internal expansive forces that simulate the expansive forces of freeze water. The test result is total percent loss over various sieve intervals for a required number of cycles. Maximum loss values typically range from 10 to 20 percent for five cycles (Brian et. al. 2005).

2.3.2.2.3 Deleterious materials

Deleterious materials are defined as the mass percentage of contaminants such as clay lumps, shale, wood, mica in the blended aggregate (AASHTO T 112 or ASTM C142). The analysis can be performed on both coarse and fine aggregate.

Values range from as little as 0.2 percent to as high as 10 percent, depending on the exact composition of the contaminant.

2.3.2.3 Gradation

To specify aggregate gradation, Superpave uses the 0.45 power gradation chart with gradation control limits and a restricted zone to develop a design aggregate structure as shown in Figure 2.3. A Superpave design aggregate structure must pass between gradation control points while avoiding a gradation restricted zone. The restricted zone is used by Superpave to avoid mixtures that a high proportion of fine sand relative to total sand, and to avoid gradation that follow the maximum density line, which do not normally have a suitable voids in the mineral aggregate (VMA) (Cominsky et. al. 1994) [17].

In many instances, the restriction will discourage the use of fine natural sand in an aggregate blend and encourage the use of clean manufactured sand. The design aggregate structure approach ensures that the aggregate will develop a strong, skeleton to enhance resistance to permanent deformation while allow sufficient void space to enhance mixture durability.

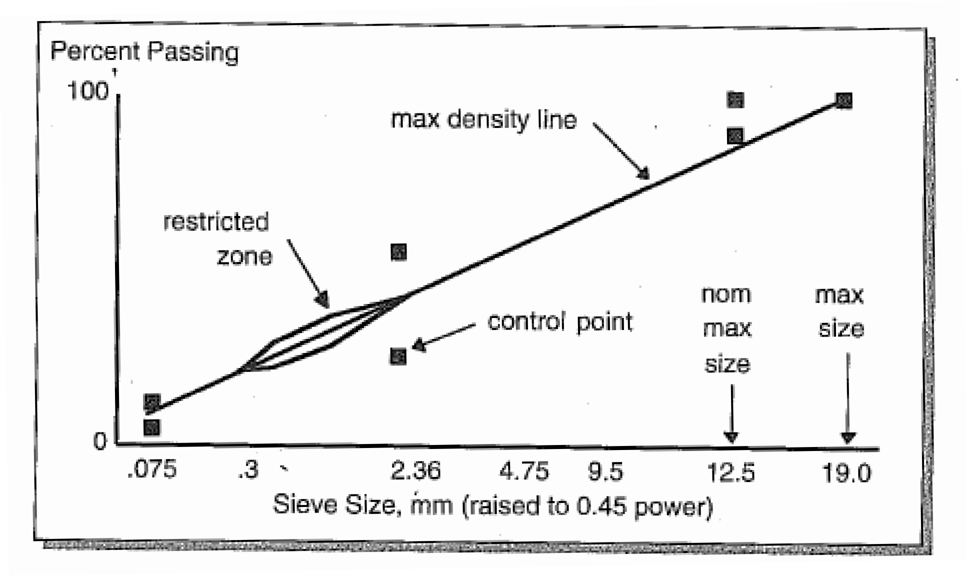


Figure 2.3: Superpave gradation limits

2.4 Superpave Mixture Design

A factor that must be taken into account when considering asphalt mixture behavior is the volumetric proportions of asphalt binder and aggregate components, or more simply, asphalt mixture volumetric properties.

The volumetric properties of a compacted paving mixture [air voids (V_a), voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), and effective asphalt content (P_{be}) provide some indication of the mixture's probable pavement service performance. It is necessary to understand the definitions and analytical procedures described below to be able to make informed decisions concerning the selection of the design asphalt mixture.

The information here applies to both paving mixtures that have been compacted in the laboratory, and to undisturbed samples that have been cut from a pavement in the field (Pavement interactive 2011, Kingdom of Saudi Arabia 2001, and Reberts et. al. 1991).

2.4.1 Volumetric Properties

A volumetric mix design will be conducted for asphalt concrete sample in order to determine the bulk specific density (G_{mb}, air void content, voids in mineral aggregate (VMA), and maximum theoretical specific gravity (G_{mm}) as per ASTM D2726, D3203, D6995, and D2041 respectively (Lambert et. al. 2013).

2.4.1.1 Percent air voids in compacted mixture

The air voids V_a, in the total compacted paving mixture consist of the small air spacemen between the coated aggregate particles. The volume percentage of air voids in a compacted mixture can be determined using the following equation:

$$V_a = 100x \quad \frac{G_{mm} - G_{mb}}{G_{mm}}$$

where V_a = air voids in compacted mixture, percent of total volume.

2.4.1.2 Percent VFA in compacted mixture

The percentage of the voids in the mineral aggregate that are filled with asphalt, VFA, not including the absorbed asphalt, is determined using the following equation:

$$VFA = 100 \times \frac{VMA - V_a}{VMA}$$

where, VFA = voids filled with asphalt, percent of VMA

2.4.2 Superpave gyratory compactor (SGC)

Two new, key features in Superpave system are laboratory compaction and performance testing Laboratory compaction is accomplished using a Superpave gyratory compactor (SGC) (Witczak et. al. 2002). The basis for the SGC was a Texas gyratory compactor modified to use the compaction principles of a French gyratory compactor. The modified Texas gyratory accomplished the goals of realistic specimen densification and it was reasonably portable. Its 6-inch sample diameter (ultimately 150 mm on an SGC) could accommodate mixtures containing aggregate up to 50 mm maximum (37.5 nominal) size. SHRP researchers modified the Texas gyratory compactor by lowering its angle and speed of gyration and adding real time specimen height recording capabilities as shown in Figure 2.4.

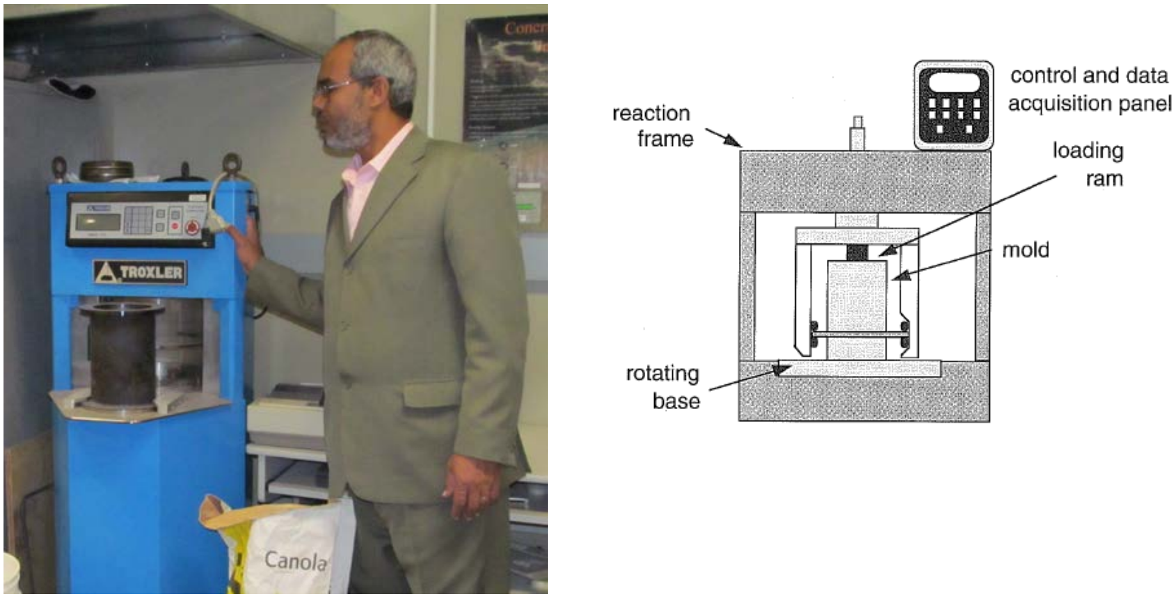


Figure 2.4: Superpave Gyratory Compactor (SGC).

2.5 Data Analysts

Superpave gyratory compaction data is analyzed by computing the estimated bulk specific gravity, corrected bulk specific gravity, and corrected percentage of maximum theoretical specific gravity for each desired gyration. During compaction, the height is measured and recorded after each gyration. G_{mb} of the compacted specimen and G_{mm} of the loose mixture are measured.

The estimated G_{mb} is corrected by a ratio of the measured to estimated bulk specific gravity according the following equation:

$$C = \frac{G_{mb}\text{ (measured)}}{G_{mb}\text{ (estimated)}}$$

where, C = correction factor,

G_{mb}(measured) = measured bulk specific gravity after N_{max},

N_{max} = maximum number of gyration for compaction.

G_{mb},(estirnated) = estimated bulk specific gravity at N_{max}.

The estimated G_{mb} at any other gyration level is then determined using:

G_{mb}(corrected) = C x G_{mb}(estimated)

where, G_{mb}(corrected) = corrected bulk specific gravity of the specimen at any gyration.

2.6 Design Asphalt Binder Content

Once the design aggregate structure is selected from the trial blends, specimens are compacted at varying asphalt binder contents. The mixture properties are then evaluated to determine a design asphalt binder content.

A minimum of two specimens are compacted at the trial blend's estimated asphalt content, at ± 0.5% of the estimated asphalt content, and a +1.0% of the estimated asphalt content. The four asphalt contents are the minimum required for Superpave level 1 analysis. A minimum of two specimens are also prepared for determination of maximum theoretical specific gravity at the estimated binder content.

Mixture properties are evaluated for the selected blend at the different asphalt binder contents, by using the densification data at N_{ini}, N_{des} and N_{max}.

Where N_{ini} = initial number of gyration for compaction,

N_{des} = design number of gyration for compaction.

The volumetric properties are calculated at N_{des} for each asphalt content. From these data points, the designer can generate graphs of air voids: VMA and VFA versus asphalt content The design asphalt binder content is established at 4.0 percent air voids. All other mixture properties are checked at the design asphalt binder content to verify that they meet criteria.

2.7 Moisture Sensitivity

The final step in the level 1 mix design process is to evaluate the moisture sensitivity of the design mixture. This step is accomplished by performing AASHTO T 283 testing on the design aggregate blend at the design asphalt binder content. Specimens are compacted to approximately 7 percent air voids. One subset of three specimens are considered control specimens. The other subset of three specimens are considered. The conditioned specimen are subjected to partial vacuum saturation followed by an optimal freeze cycle, followed by a 24 hour thaw cycle at 60^{o}C. All specimens are tested to determine their indirect tensile strengths. The moisture sensitivity is determined as a ratio of the average tensile strengths of the conditioned subset divided by the average tensile strengths of the control subset. The Superpave criterion for tensile strength ratio 80 percent minimum.

2.7.1 Indirect Tensile Test

Resilient modulus (MR) and creep compliance (D(t)) testing according to the Superpave Indirect Tensile test quantifies the time dependent phenomenological mechanical response of Asphalt Concrete (AC) when subjected to a dynamic and static load respectively (Lambert et. al. 2013). The MR and D(t) respectively quantifies the elastic modulus and stiffness of the AC.

The Long Term Pavement Performance (LTPP) Protocol P07 (Federal Highway Administration, 2001), used in this research project, provides procedures to determine the M_R and D(*t*) of AC. Both the M_R and D(*t*) tests are carried out on a cylindrical sample that has a diameter of 150 mm and a thickness that ranges between 25 mm and 50 mm. The M_R test is performed by applying a repetitive haversine waveform load with a 0.1 s load period followed by a 0.9 s rest period to the sample's vertical diameter axis, as shown in Figure 2.5, at temperatures of 5°C, 25°C and 40°C. The magnitude of the peak dynamic load is chosen such that the horizontal deformation falls within the range of 38 µm and 89µm. Once an appropriate load is selected, the sample is subjected to five cyclic loads in order to produce deformation and load data. The resulting instantaneous and total resilient deformations measured, as shown in Figure 2.6, are averaged over three load cycles. Based on the measured values the M_R is calculated according to the following equation:

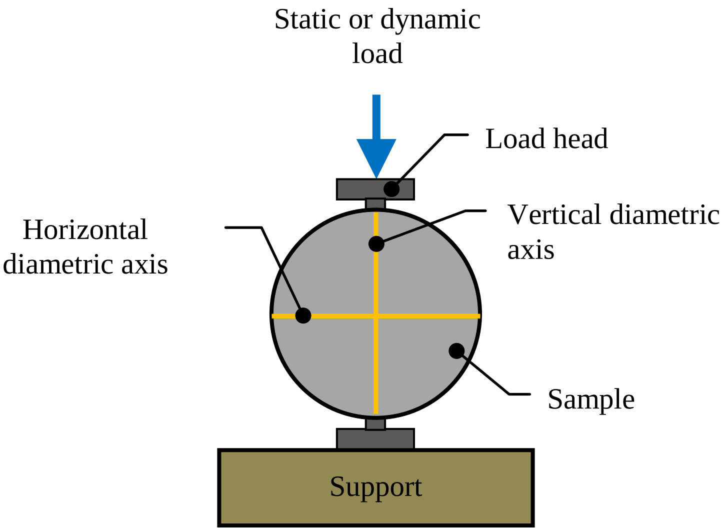


Figure 2.5: Load application on cylindrical sample (Federal Highway Administration, 2001).

$$M_R = \frac{\sigma}{\varepsilon}$$

Where, M_R = Resilient modulus [GPa], σ = applied repeated stress, ε = the resilient strain.

The D(*t*) test is performed by applying a static compressive load with constant magnitude to the sample's vertical diametric axis, as shown in Figure 2.5, for a duration of 100±2 s at temperatures of -10°C, 5°C and 25°C. The magnitude of the fixed compressive load is chosen such that the horizontal deformation falls within the range of 38 μm and 89 μm. The resulting deformations measurements at time intervals 1 s, 2 s, 5 s, 10 s, 20 s, 50 s and 100 s, as shown in Figure 2.7, are used to calculate the creep compliance of the AC based on the following equation:

$$D(t) = \frac{\varepsilon(t)}{\sigma}$$

Where, $D(t)$ = Creep compliance at time t [1/GPa], ε = the resilient strain at time t and σ = applied stress at time t.

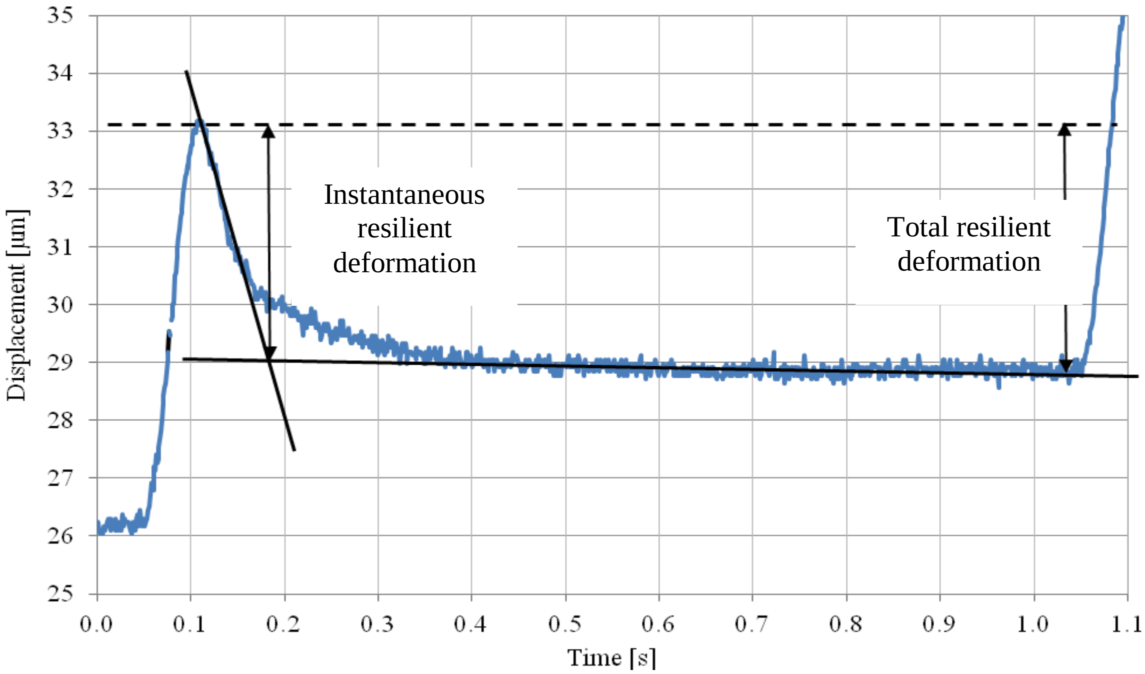


Figure 2.6: Example of resilient modulus deformation measurements.
(Federal Highway Administration, 2001) and (Lambert et. al. 2013)

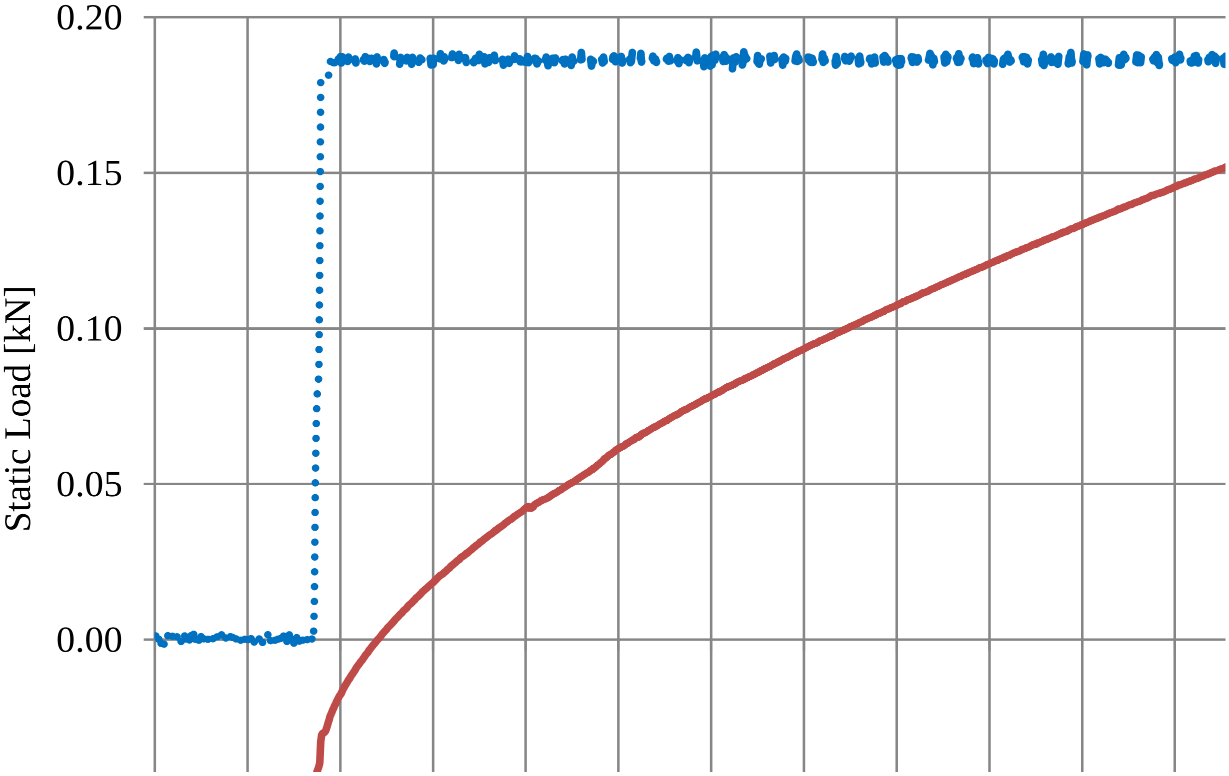


Figure 2.7: Example of creep compliance measurements.
(Federal Highway Administration, 2001) and (Lambert et. al. 2013)

2.8 Asphalt Concrete Additives

A number of asphalt additives are on the market; some have benefits and some do not. The performance of these additives is difficult to evaluate in laboratory; hence, field test sections are often constructed using several mixtures with various additives along with control sections. These test sections are expensive to build and it usually takes a number of years before evaluation can be completed.

Additives had been classified modifiers into ten types as shown in Table 2.3 (Terrel et. al, 1988). Each of these modifier types has properties unique to that category. Several additives exist under each category; however, this is a dynamic list is rapidly changing. A brief discussion of each modifier type is provided in the following paragraphs.

There are a number of materials that can be used as fillers including crushed fines, lime, Portland cement, fly ash, carbon black, and sulfur. Fillers may be used to (1) fill voids and hence reduce optimum asphalt content, (2) meet specifications for aggregate gradation, (3) increase stability, and (4) improve bond between asphalt and aggregate. Typically, an increase in filler lowers the optimum asphalt content, increases the density, and increases the stability (Terrel, 1988). All fillers must be fed to the asphalt mixture consistenly and in the correct proportions; otherwise, the mix properties are adversely affected. Excessive amounts of filler usually reduce the VMA to a point that sufficient asphalt cement for a durable mix cannot be added. High filler content also increases the aggregate surface area and thus greatly reduces the asphalt film thickness. Some specifications place limits on the dust to asphalt cement ratio. A typical specification requires the dust to asphalt cement ratio to be between 0.6 and 1.2 by weight. If the dust to asphalt cement ratio is too high, the mix durability is affected. If this number is too low, the mix does not have sufficient stability. Fillers are added to the HMA mixtures at the HMA facility during mix production, (Reberts 1991).

Extenders which include sulfur and lignin are used to reduce the amount of asphalt cement used in the mixture. The extenders, which are normally cheaper than asphalt cement, replace some percentage of the asphalt cement, thus reducing the price of the mixture.

Another potential reason for using extenders is to conserve the use of asphalt cement and thus increase the amount of HMA for a given amount of asphalt cement. The extender could be added to the asphalt cement at the refinery or at the HMA facility.

Rubber has been used for a number of years in various forms to improve certain properties of the HMA mixtures. Rubber may be added in the form of latex or as crumb rubber. Rubber in the form of latex has been used to improve the bond asphalt cement to aggregate. Rubber has also been to increase the stiffness of a HMA mixture, thereby improving its rutting resistance. Rubber has been used to improve the flexibility of HMA mixtures especially at low temperatures. When rubber is used, the temperature of the mixture has to be increased significantly for mixing, placing, and compaction. The rubber may be added at the refinery, or at the HMA facility by a specialist contractor.

Plastics can be added in a number of forms. Special equipment is needed to blend the plastic with the asphalt cement; this can be performed at the refinery or at the HMA facility. Plastics generally stiffen the HMA mixture and thus are used for improved resistance to rutting. Plastics have also been used to modify the temperature susceptibility of asphalt cements and to improve performance at low temperatures.

Fibers have been used to increase the stiffness of HMA mixtures and hence to improve the resistance to rutting. They have also been used to minimize reflection cracking by improving the tensile strength of the mix. The fibers are added at the HMA facility during production. Fibers have also been used to increase the optimum asphalt content and thus improve the durability. The use of fibers to improve durability is not economical with high price of asphalt cement. Compaction may be difficult with some of these mixtures due to rebound of the mix while being rolled.

Oxidants are used to stiffen the asphalt cement and thus the HMA mixtures during the construction process and for some time afterwards; hence, this additive is used to minimize rutting. One problem that has been observed with oxidants is that the increased mix stiffness, especially in the surface courses, often results in premature cracking. An oxidant is likely beneficial if the low-temperature properties of the mix are controlled so that low-temperature cracking does not occur. The oxidant is added to the asphalt cement at the refinery.

Antioxidants are used in asphalt mixtures to minimize oxidation and thus to improve durability. Antioxidants reduce the rate at which asphalt oxidizes and thus the rate at which cracking of the asphalt mixture occurs. Many engineers believe that some aging is necessary to provide enough stiffness to resist rutting. If this is true, the use of antioxidants may result in an increase in rutting. These materials are usually added at the refinery.

Table2.3: Classification of Asphalt Modifiers (Terrel et. al. 1988)

Type		Examples
1. Filler		Mineral filler: Crusher fines Lime Portland cement Fly ash Carbon black Sulfur
2. Extender		Sulfur Lignin
3. Rubber a. Natural latex b. Synthetic latex c. Block copolymer d. Reclaimed rubber	POLYMERS	Natural rubber Styrene-butadiene (SBR) Styrene-butadiene-styrene (SBS) Recycled tires
4. Plastic		Polyethylene Polypropylene Ethyl-vinyl-acetate (EVA) Polyvinyl chloride (PVC)
5. Combination		Blends of polymers in 3 & 4
6. Fiber		Natural: Rock Wool Man-Made: Polyester Fiberglass
7. Oxidant		Manganese salts
8. Antioxidant		Lead compounds Carbon Calcium salts
9. Hydrocarbon		Recycling and rejuvenating oils Hardening and natural asphalts
10. Antistrip		Amines Lime

Hydrocarbons have been used to modify asphalt cement properties. They can be used to stiffen asphalt by adding a harder asphalt cement to a softer one. They can also be used to soften asphalt cement by adding a softer asphalt cement or recycling agent to a harder asphalt cement. These asphalts can be blended at the HMA facility or at the refinery.

Antistripping agents are used to improve the bond between asphalt cement and aggregate. The antistripping agent can be in the form of filler or liquid. Lime, which is the most popular antistripping agent, can be added as a filler or as a lime slurry. The lime is added at the HMA facility whereas the liquid antistripping agents can be added at the refinery or the HMA facility. Antistripping agents have been shown to improve performance of most water susceptible mixtures; however, care must be used in selecting the type of antistripping agent for a specific aggregate and asphalt**.**

A few of these additives will be discussed in detail in the next chapters and flay ash additives will be discussed hereafter:

The studying of the effect of fly ash on the mechanical properties of asphalt mixtures; and to evaluate the effect of using fly ash in mitigating pavement distress and improving performance of asphalt concrete pavement were carried out. Four groups of specimens with various fly ash contents were studied (Ali et. al. 1996). The mechanical properties (resilient modulus, creep, permanent deformation, and fatigue) were determined at three different temperatures. Moisture damage tests were carried out. Results from their study indicated that fly ash can be used as a mineral filler to improve resilient modulus characteristics and stripping resistance. The addition of fly ash did not significantly reduce field performance of asphalt concrete mix in terms of rut depth and present serviceability index but increase the amount of surface cracking in the pavement (Ali et. al. 1996).

Tapkin, (2008), investigates the effect of fly ash as a filler replacement on the mechanical properties of asphalt–aggregate mixtures. Utilization of fly ash, which is the by-product of coal-fired power generation, is of great importance from an environmental and economical point of view.

In Tapkin study, a dense bituminous mixture composed of calcareous aggregate was selected as the reference mixture. It was observed that there was a definite increase in Marshall stability and decrease in flow values, especially when calcareous filler was replaced by Soma-type fly ash, which was one of the three types of fly ashes used.

The mechanical properties, namely elastic strain, elastic modulus, and permanent strain, of the asphalt mixtures were determined by carrying out fatigue tests for three types of fly ashes, Portland cement, lime, and control specimens. The changes in mechanical properties are important in the sense that they affect the behavior of asphalt concrete pavement under applied loads. This mechanism can be explained basically by bitumen extension (Ali et. al. 1996).

Figure 2.8: Fly ash.

Chapter 3

Hot-Mix Asphalt Moisture Damage

Chapter 3

Hot-Mix Asphalt Moisture Damage

3.1 Introduction

Moisture damage is a mechanism that causes distress and failure in asphalt concrete pavements due to a loss of durability resulting from the presence of moisture, in the form of a vapour or liquid, originating internally or externally. This reduces the pavements performance by promoting distresses such as: longitudinal cracking, spalling, rutting, shoving, stripping, and ravelling. When moisture originates or is introduced in the asphalt concrete a weakening of adhesion and cohesion of the material occurs, due to: binder properties, aggregate properties, volumetric mix properties, environmental conditions, traffic volume and loads, pavement design, and construction practices (Little et. al. 2003).

Moisture damage of HMA pavements is not a distress by itself but represents a conditioning process after which several distresses may occur individually or simultaneously. The moisture first inflicts damage on the HMA mix by destroying the bond between the aggregate and the asphalt binder or by destroying the internal cohesive strength of the binder. Both actions create a weaker HMA mix that is unable to resist the stresses imposed by the combined effects of traffic loads and environment. As moisture damage reduces the internal strength of the HMA mix. This leads to overstress from traffic loads and lead to fatigue cracking or rutting of the pavement layer. In the case of environmental stresses, a weaker HMA mix is unable to resist the thermal stresses leading to transverse cracking and aging stresses that create block cracking of the HMA layer, (Sebaaly, 2007). Moisture damage in asphalt pavements, also known as stripping or moisture susceptibility, can simply be defined as the breaking of the aggregate-binder bond by the intrusion of water. As water is exposed to asphalt pavements, it seeps through tiny cracks in the asphalt surface (Boyes, 2011).

3.2 Moisture Damage causes

Asphalt concrete's susceptility to moisture damage is related to numerous factors:

- Pavement construction, the aggregates stored in the stockpile are carried and heated to be combined with the hot asphalt binder and loaded in trucks to be transported to the field site. To mitigate the moisture susceptibility of a compacted mix, segregation and improper aggregate drying need to be avoided during the production process. Proper methods for moisture content measurements should be used during the heating process to guarantee the aggregates are completely dry before being mixed with the asphalt binder (Diab 2014).

- Moisture-related problems occur due to the presence of water and traffic loading, which provides energy to break the adhesive bonds and cause cohesive failures. The traffic loading is a major contributing factor as well, especially when a pavement is in a saturated state, since the increased pore pressure and the tension/compression phenomenon caused at the surface by the moving wheels can accelerate the occurrence of moisture-related failures (Kiggundu et. al. 1988).

- The poorly designed drainage system, both surface and subsurface, causes moisture-related distresses. Surface sealing of a moisture-sensitive mix can also be a factor in accelerating the moisture-induced damage, and

- Aggregate-asphalt binder adhesion, generally, the aggregate constitutes 90 to 95% by weight and 75 to 85% by volume of asphalt mixtures. The moisture susceptibility of asphalt concrete is in part dependent the adhesion that exists between the aggregate and asphalt binder. Where the adhesion of one material to the other results from the interactions of electro dynamic intermolecular forces found along the surface of an aggregate and those found within an asphalt binder that form a bond. When moisture is introduced to the adhesion system, a loss of adhesion between the aggregate and asphalt binder can be observed.

The Tensile Strength Ratio (TSR) and dynamic modulus (E*) tests were employed to evaluate the moisture susceptibility of the mixtures (Curtis et. al. 1990, and Diab 2014).

3.3 Treatments Counteractive to Moisture Damage

Treatments to reduce the sensitivity of asphalt concrete to moisture damage have been successfully and widely used in the asphalt paving industry. There are two dominant treatment types called *liquid antistrip agents* and *chemical lime and other additives* that are each respectively applied to the asphalt binders and aggregates.

3.3.1 Liquid Antistrip Agents

Liquid antistrip agents are surfactants or chemical compounds that reduce the surface tension of asphalt binders and increases its relative wettability with aggregates (Epps et al. 2003 and Hicks, 1991).

Liquid antistrip agents (LAS) are used to reduce the susceptibility of asphalt concrete (Ac) mixes to moisture damage. Liquid antistrip agents reduce the surface tension or surface free energy of bitumen in order to better coat aggregate surfaces and at the same time reduce the interaction of the material with water (Hicks 1991).

The concept of interfacial forces are based on Newtonian principles, but can also be expressed in terms of thermodynamic principles based on the work required to bring molecules from the bulk of the material to the surface in order to form a new surface. This work or *work of adhesion* is referred to as Surface Free Energy (SFE) found within a system and has a quantitative unit of J/m^2 or ergs/ m^2.

Surface Free Energy is a method to evaluate asphalt concrete’s susceptibility to moisture damage. It has been used to measure the intermolecular forces that cause asphalt binders and aggregates to adhere to each other. The SFE measurements are used to quantify the cohesiveness of asphalt binders or to quantify the adhesiveness of asphalt binder on aggregate surface. This type of testing is carried out on either an asphalt binder or on an aggregate sample.

When evaluating the SFE of an asphalt binder or aggregate, the use of five test methods can be utilized (Little et al., 2006). The test methods are presented in Table 3.1. Each test method requires its own set of equipment and procedures in order to calculate the SFE of an aggregate or asphalt binder. Once the SFE measurements of an asphalt binder and aggregate are collected, a quantitative measurement of the bond between the two materials can be calculated.

Table 3.1: Surface free energy test methods (Little et. al. 2006).

Test Method	Type of material
Contact angle measurements	Asphalt binder
Isotherm adsorption measurements	Aggregate
Atomic force microscopy	Asphalt binder
Micro Calorimetric	Aggregate
Inverse gas chromatography	Aggregate and asphalt binder

Contact angle measurements are used to: (1) quantify the *surface tension*, (2) quantify the *surface free energy* (SFE), and (3) qualify the *wettability* of a solid, liquid, or gas by using Rame-Hart standard contact angle as shown in Figure 3.1. These quantities, which represent the intermolecular forces or attractive interaction between molecules, provide a fundamental insight into the adhesion and cohesion bonds of a given substance, (Lambert et. al. 2013).

The term (γ), refers to the intermolecular forces that act between molecules of a liquid or solid in order to form a bulk mass. The unit of surface tension is expressed in Newton per meter (N/m). SFE is defined as the work of cohesion (W) required to bring molecules from the bulk of the material to the surface in order to form a new surface, (Erbil 2006 and Van Oss et. al. 1994). The unit of SFE is expressed in Erg per centimeter square (ergs/cm^2). The term *wettability* refers to the relative tendency of a liquid to spread over a solid surface.

Figure 3.1: Rame-Hart standard contact angle.

In 1805, Thomas Young described the interfacial energy between a solid and liquid by measuring the contact angle (θ) of a liquid drop deposited on a solid flat horizontal surface (Erbil 2006 and Van Oss et. al. 1994). An illustration of the contact angle formed between a solid and liquid is shown in Figure 3.2. A summary of the 4 states of wettability is presented in Table 3.2.

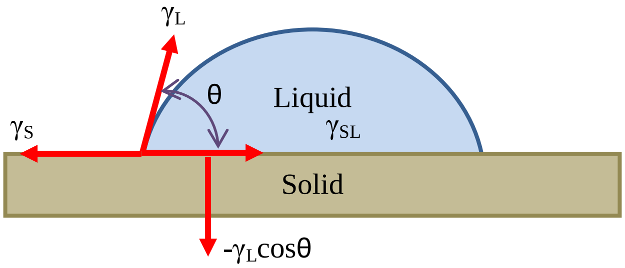


Figure 3.2: Contact angle of a solid-liquid interface.

Table 3.2: States of wettability.

Contact Angle	State of Wettability
θ = 90°	Perfect wetting
0° < θ < 90°	High wetting (hydrophilic)
90° < θ < 180°	Low wetting (hydrophobic)
θ = 180°	Perfectly non-wetting

The assumption that the surface energy of a substance constituted of Lifshitz-van der Waals (LW) interactions, was later modified to include dipole and polarization interactions referred to as Lewis Acid-Base (AB) interactions (Erbil 2006 and Van Oss et. al. 1994). As such, (LW) and (AB) intermolecular forces have been used to define surface tension (γ) of a substance as expressed by Equation 3.1.

$$\gamma_i = \gamma_i^{LW} + \gamma_i^{AB} \qquad (3.1)$$

From the given surface energy and work of cohesion definitions provided a relationship between the two is defined in Equation 3.2, which states that the surface tension used in creating a new unit area is equivalent to separating two half unit areas from each other.

$$\gamma_i \equiv \frac{1}{2} W_{ii} \qquad (3.2)$$

The relationship between the interfacial tension and work of adhesion between two substances is given by Dupré's equation.

$$W_{ij} = \gamma_i + \gamma_j - \gamma_{ij} \qquad (3.3)$$

In order to fully estimate the work of adhesion, W_{ij}, resulting from the interfacial energy an approach was developed by Van Oss et al. 1988, separating the interfacial force interactions into Lifshitz-van de Waals (LW) and Lewis Acid-Base (AB) components which are presented in the following in Equations 3.4, 3.5, and 3.6:

$$W_{ij} = W_{ij}^{LW} + W_{ij}^{AB} \tag{3.4}$$

$$W_{ij}^{LW} = 2\sqrt{\gamma_i^{LW}\gamma_j^{LW}} \tag{3.5}$$

$$W_{ij}^{AB} = 2\sqrt{\gamma_i^{+}\gamma_j^{-}} + 2\sqrt{\gamma_i^{-}\gamma_j^{+}} \tag{3.6}$$

Where: γ^{k-} = surface energy of substance k due to Lewis Base forces, γ^{k+} = surface energy of substance k due to Lewis acid forces.

From this definition a mathematical model called the Young's equation shown bellow in the next equation, was developed in order to relate the interfacial energy of the system to the surface energy of the solid (S) and liquid (L).

$$\gamma_S = \gamma_{SL} + \gamma_L \cos\theta \tag{3.7}$$

By combining Young's and Dupré's equation, a relation between the contact angle and work of adhesion is established as follows:

$$W_{SL} = \gamma_L(1 + \cos\theta) \tag{3.8}$$

By combining the Young-Dupré equation with Equations 3.4, 3.5, and 3.6, a relation between contact angle and the surface energy of the solid and liquid is obtained in Equation 3.9:

$$\gamma_L\,(1 + \cos\theta) = 2\left(\sqrt{\gamma_S^{LW}\gamma_L^{LW}} + \sqrt{\gamma_S^{+}\gamma_L^{-}} + \sqrt{\gamma_S^{-}\gamma_L^{+}}\right) \tag{3.9}$$

Equation 3.9 allows the use of contact angle measurements to determine the SFE of solid surfaces through a system of linear equations that provide a unique solution. A list of common immiscible liquids used in contact angle measurements and their respective Lifshitz-van de Waals and Lewis Acid-Base components are presented in Table 3.3 (Lambert et. al. 2013).

Table 3.3: SFE values of common liquids (Lambert et. al. 2013).

Liquid	γ^{Total} [mJ/m^2]	γ^{LW} [mJ/m^2]	γ^{+} [mJ/m^2]	γ^{-} [mJ/m^2]
Water	72.80	21.80	25.50	25.50
Glycerol	64.00	34.00	3.92	57.40
Formamide	58.00	39.00	2.28	39.60
Ethylene glycol	48.00	29.00	1.92	47.00

In order to solve for the surface energy of an asphalt binder, three probe liquids are used to conduct contact angle measurements. The resulting contact angle measurements along with the known surface energy values of the probe liquids are substituted into a system of linear equations based on the previous equation. The system of linear equations is presented in Equation 3.10:

$$B = Ax \tag{3.10}$$

$$x = A^{'}B \tag{3.11}$$

Where: $A' = \begin{bmatrix} \sqrt{\gamma_{L1}^{LW}} \sqrt{\gamma_{L1}^{+}} & \sqrt{\gamma_{L1}^{-}} \\ \sqrt{\gamma_{L2}^{LW}} \sqrt{\gamma_{L2}^{+}} & \sqrt{\gamma_{L2}^{-}} \\ \vdots & \\ \sqrt{\gamma_{Ln}^{LW}} \sqrt{\gamma_{Ln}^{+}} & \sqrt{\gamma_{Ln}^{-}} \end{bmatrix}^{-1}$, $B = \begin{bmatrix} \frac{\gamma_{L1}}{2}(1 + \cos\theta_1) \\ \frac{\gamma_{L2}}{2}(1 + \cos\theta_2) \\ \vdots \\ \frac{\gamma_{Ln}}{2}(1 + \cos\theta_n) \end{bmatrix}$, and $x = \begin{bmatrix} \sqrt{\gamma_S^{LW}} \\ \sqrt{\gamma_S^{-}} \\ \sqrt{\gamma_S^{+}} \end{bmatrix}$

Where: n = number of probe liquids.

In order to solve for the unknown surface energies of the asphalt binder in matrix x, the system of linear equations in Equation 10, is modified as follows:

$$E = Ax - B \qquad (3.12)$$

Where: E = Error matrix.

By using the Equation 3.12, an iterative solution method can be used to determine the value of x such that the square of the sum of the error matrix (E) is minimized, (Little et. al. 2006). The concentration of liquid antistrip per unit weight of asphalt binder had a range of 0.5% to 5.0% (Lambert et. al. 2013). Lambert et. al., (2013) found that (1) a liquid antistrips concentration of 0.5% had the lowest wettability potential and lowest SFE values, and (2) regardless of the LAS concentration, the LAS loses 30% of its volatile mass after short-term aging.

3.3.2 Chemical Lime Additives

Chemical lime additives are derived from limestone to produce quicklime or hydrated lime. The limestone is naturally present in sedimentary rock formations that have high levels of calcium or magnesium carbonate or both, with or without the presence of dolomite. The production of quicklime is achieved by calcining the limestone in kilns that heat the rock to temperatures beyond 1090°C. From the quicklime, hydrated lime is produced. In order to produce hydrated lime, the quicklime is hydrated with water which produces a fine powder that is dry (Diab et. al. 2013).

Hydrated lime, as shown in Figure 3.3, is perhaps one of the most commonly used asphalt antistripping additives. Generally, lime is added as part of the mineral fill portion (less than #200 sieve) consisting of 1% to 2% of the total aggregate weight. It may be added to dry or damp aggregate, combined with water to form a slurry, or mixed with asphalt binder. Most transportation departments require adding hydrated lime to wet aggregate or in the form of lime slurry (National Lime Association, 2004).

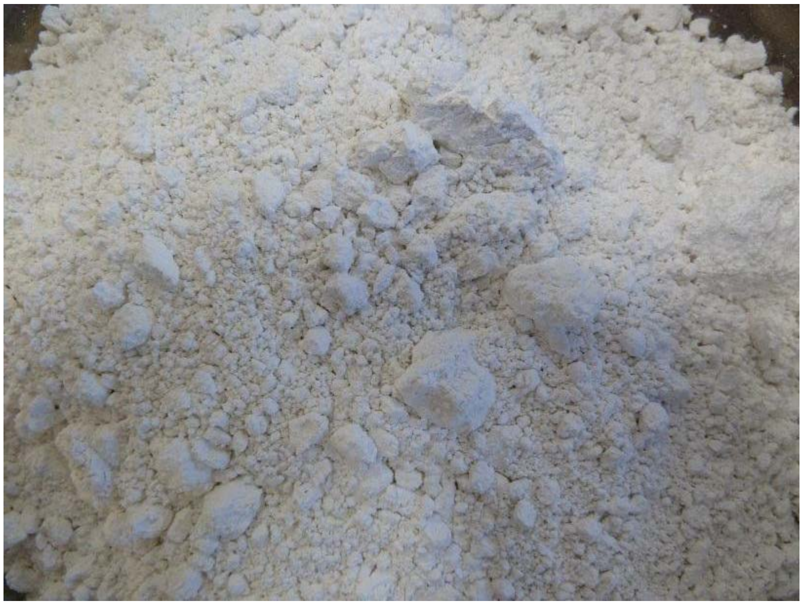


Figure 3.3: Hydrated Lime

Hydrated lime has been used to reduce the susceptibility of the asphalt concrete to moisture damage. This additive modifies the asphalt binder and surface chemistry of aggregates. When hydrated lime is added to an asphalt binder it forms new insoluble compounds with carboxylic acid and 2-quinolene functional groups (Huang et al., 2002). It is believed that these insoluble compounds are de-bonded at the asphalt-aggregate interface and allow for the formation of new bonds between other functional groups, present in the asphalt binder, with the aggregate surface, (Hicks et. al. 2001). As a result of adding hydrated lime to asphalt concrete, an increase in the stiffness, and reduction in the moisture damage sensitivity of the asphalt concrete is observed (Sebaaly 2006).

The Regular-sized Hydrated Lime is widely known as a multifunctional additive, especially as an antistripping agent in HMA. In a study carried out by Huang et al., (2005), it was demonstrated that the susceptibility of asphalt concrete to moisture damage, through ITS testing, is affected by adding hydrated lime to the mix.

Apart from reducing the susceptibility of asphalt concrete to moisture damage, hydrated lime has an effect on the viscosity and stiffness of the asphalt binder. This was observed by Lesueur et al., (1999) when rheological measurements were conducted on two different types of asphalt mixtures, each containing a different asphalt binder, which were either modified or not with hydrated lime. When subjected to a Dynamic Shear Rheometer (DSR) test, the asphalt mix containing hydrated lime had higher complex shear modulus values than that of samples not containing hydrated lime. The DSR measurements were used to show that the viscosity and stiffness of the material is increased as shown in Figure 3.4.

Hydrated lime is the most commonly used chemical lime additives. It is added to the asphalt material during production by either using a *dry lime on dry aggregate, dry lime on damp aggregate*, or *lime slurry on dry aggregate* method. In order to reduce the susceptibility of asphalt concrete to moisture damage, the concentration of hydrated lime required by unit weight of dry aggregate is in the range of 1% to 2.5% (Epps et al., 2003).

Figure 3.4: Dynamic Shear Rheometer (DSR)

Chapter 4

Warm-Mix Asphalt Technology

Chapter 4

Warm-Mix Asphalt Technology

4.1 Introduction

In recent years, environmental consciousness is becoming a significant issue in asphalt production with the increase in demand of new highway networks. Although hot mix asphalt (HMA) is widely used in all over the world, some recent investigations suggest using another process that reduces the amount of greenhouse gases emissions by reducing the fuel used during production energy consumption due to the reduction of mixing and compaction temperatures, improves workability and obtains a strength and durability that is equivalent to or better than HMA, (Xiao et. al. 2010, and Chowdhury et. al. 2008).

Warm Mix Asphalt (WMA) technologies allow the producers of asphalt material to lower the temperatures at which the material is mixed and compacted on the road. These technologies allow for producing asphalt mixtures at temperatures lower than those in the production of classic HMA. Such a dramatic reduction has the obvious advantages of cutting fuel consumption and decreasing the production of greenhouse gases. In addition, engineering benefits include better mixture compaction on the road, extending the paving season, and the ability to haul paving mixture for longer distances (Diab 2014, and Capito et. al. 2012).

4.2 Warm-Mix Asphalt

Warm-mix asphalt (WMA) is a group of technologies that allow a reduction in the temperatures at which asphalt mixes are produced and placed. These technologies tend to reduce the viscosity of the asphalt and provide for the complete coating of aggregates at lower temperatures. WMA is produced at temperatures 20 to 55 °C lower than those of typical hot-mix asphalt (HMA). In 2007, a team of U.S. materials experts visited Belgium, France, Germany, and Norway to evaluate various WMA technologies through the Federal Highway Administration's International Technology Scanning Program. The scan team learned that the benefits of WMA technologies include reduced fuel usage and emissions in support of sustainable development, improved field compaction, which can facilitate longer haul distances and cool weather pavement, and better working conditions. A range of technologies is available to produce WMA. European agencies expect WMA performance to be the same as or better than the performance of HMA, (Rubio et. al. 2012, and D'Angelo et.al. 2008).

The use of Warm Mix Asphalt technology has many advantages that are not related to the reduction of gas emissions, WMA technology is also good for the environment because it produces asphalt at temperatures 20- 55° lower in comparison to Hot Mix Asphalt (Diab et. al. 2013). The temperature reduction achieved by WMA comes from the use of various technologies that have been developed in recent years, and which can be classified in the following three groups: *organic additives*, *chemical additives*, and *water-based or water-containing foaming* processes. Although all of them pursue the same goal, the manufacturing process differs. Thus, their aim is mainly to reduce bitumen viscosity, which in turn improves mix workability, produces fewer emissions, and generally creates better working conditions (Prowell et. al. 2008).

4.3 Warm-Mix Asphalt Additives

Lower production temperatures can be achieved by means of various WMA technologies broadly classified as organic and chemical additives, and foaming technologies (either by using water-bearing additives or water-based processes). Examples of the available WMA products and processes are listed in Table 4.1. More information and summary of the recent related studies of the corresponding technologies are presented in the following sections.

Table 4.1**:** List of Commonly Used WMA Technologies (Diab, 2014)

Technology or additive	**Manufacturer**	**Description**	**Asphalt production temperature (or reduction ranges), °C**
Organic (wax) Additives			
Sasobit	Sasol Wax International (USA)	2.5–3.0% by mass of binder	(20–30)
Licomont BS 100	Clariant (Switzerland)	3.0% by mass of binder	
Asphaltan B	Romonta GmbH (Germany)	2.0–4.0% by mass of binder	
Chemical Additives			
Asphamin, Sasobit	MeadWestvaco (USA)	0.5% by mass of binder	88
Evotherm	MeadWestvaco (USA)	0.5% by mass of binder	115
Revix or Evotherm 3G	MeadWestvaco (USA)	0.5% by mass of binder	(30–40)
Rediset	Akzo Nobel (Netherlands)	2% by mass of binder	(30)
Cecabase RT	CECA (France)	0.3–0.5% by mass of binder	(30)
Iterlow T	Iterchimica (Italy)	0.3–0.5% by mass of binder	120
Foaming (Water-bearing Additives)			
Aspha-Min	Eurovia GmbH (Germany)	0.3% by mass of the mixture	(20–30)
Advera WMA Zeolite	PQ Corporation (USA)	0.25% by mass of the mixture	120
Foaming (Water-based Processes)			
WAM Foam	Shell (UK) and Kolo-Veidekke (Norway)	2–5% water by mass of hard binder	100–120
LEA – Low Energy Asphalt	LEA-CO (France)	3-4% water introduced with fine sand	<100
Double – Barrel Green	Astec Industries (USA)	~ 2% water by mass of binder	116–135
Terex WMA system	Terex (USA)	~ 2% water by mass of binder	130
Gencor Ultrafoam GX	Gencor Industries Inc. (USA)	1.25- 2 % water by mass of binder	110-120
Accu-Shear	Stansteel (USA)	combination of water and/or additives (dependent on the additive/manufacturer)	122-158
Aquablack WMA	Maxam Equipment Inc. (USA)	1.5% - 3.0% water by mass of binder	125-140
LT Asphalt (Nynas Low temperature asphalt)	Nynas (Netherlands)	Foam binder with hydrophilic additive the amount of which 0.5–1.0% by mass of binder	90
LEAB	Royal BAM Group (Netherlands)	Foam binder with a special additive (0.1% by mass of binder)	90

4.3.1 Chemical Additives

Several new processes have been developed to reduce the mixing and compaction temperatures of hot mix asphalt without sacrificing the quality of the resulting pavement. Three potential warm mix asphalt processes were studied. They were Asphamin, Sasobit, and Evotherm (Goh et. al. 2008, and Geaham et. al. 2005). A laboratory study was conducted to determine the applicability of these processes to typical paving operations and environmental conditions commonly found in the United States, including the performance of the mixes in quick traffic turn-over situations and high temperature conditions. All three processes were shown to improve the compatibility of mixtures in both the Superpave gyratory compactor (SGC) and vibratory compactor. Statistics indicated an overall reduction in air voids. Improved compaction was noted at temperatures as low as 88°C, (Hurley et. al. 2007). Superpave gyratory compactor results indicated that Asphamin, Sasobit, and Evotherm may lower the optimum asphalt content. The addition of Asphamin, Sasobit, or Evotherm did not affect the resilient modulus of an asphalt mix nor did they increase the rutting potential of an asphalt mix as measured by the Asphalt Pavement Analyzer. The rutting potential did increase with decreasing mixing and compaction temperatures, which may be related to the decreased aging of the binder resulting from the lower temperatures. There was no evidence of differing strength gain with time for the mixes containing the three processes as compared to the control mixes indicating that a prolonged cure time before opening to traffic is not an issue. The lower compaction temperature used when producing warm asphalt may increase the potential for moisture damage. In general, Asphamin, Sasobit, and Evotherm appear to be viable tools for reducing mixing and compaction temperatures that can be readily added to hot mix asphalt. Reductions in mixing and compaction temperatures are expected to reduce fuel costs, reduce emissions (Hurley et. al. 2007).

Also WMA mixes produced by an emulsion process were evaluated under accelerated loading in three total sections of the National Center for Asphalt Technology Test Track and used as the surface mix for two of the sections. Evotherm was incorporated into the same mixes used previously on the track. In-place densities of the WMA surface layers were equal to or better than the hot-mix asphalt (HMA) surface layers, even when compaction temperatures were reduced by 8°C to 42°C. Laboratory rutting-susceptibility tests conducted in the asphalt pavement analyzer indicated similar performance for the WMA and HMA surface mixes with the PG 67-22 base asphalt. However, laboratory tests indicated an increased potential for moisture damage with the WMA mixes. The WMA section and the HMA section showed excellent rutting performance in the field after the application of 515,333 equivalent single-axle loads in a 43-day period. One of the WMA sections was also evaluated for quick turnover to traffic and showed good performance (Hurley et. al. 2008).

Figure 4.1: Sasobit Flakes, (Hurley et. al. 2008).

The Rediset is a surfactant-based chemical additive produced by the Akzo Nobel with the same objective of reducing the interfacial friction between thin films of the asphalt binder and coated aggregates, thereby improving the workability and allowing for mixing and compaction at reduced temperatures. The additive includes built-in anti-strip agents to promote the interfacial adhesion between aggregate and asphalt binder. The last example in this category is Cecabase RT produced by the CECA of France. The additive has the same hypothesized mechanism to produce WMA as that of surfactants such as Rediset. Iterlow T is a liquid chemical additive, when added to asphalt binder, allows for the production of WMAs at temperature around 120 °C (Diab, 2014).

4.3.2 Organic (wax) Additives

Organic additives are used to decrease asphalt binder's viscosity above the melting point of the binder, whereas below the melting point, they tend to increase the binder stiffness (D'Angelo et. al. 2008).

Wax or other organic additives, obtained by means of special bitumen modifiers, represent a promising technical solution to reduce the temperatures required for asphalt production and pavement construction. In this experience, an extended program of rheological analyses was carried out in order to evaluate the effects of different types of wax on bitumen viscous flow and dynamic properties at high pavement service temperatures. Five different organic additives, including both natural and synthetic waxes, were considered and eleven bitumen-wax blends were produced and had been studied using rheological testing. Viscosity measurements performed in the domain of the mixing and paving temperatures have shown essential changes in binders' rheological behavior mainly due to the crystallizing/melting properties of waxes. Changes in viscosity functions depended on the chemical structure of wax as well as on its physical characteristics. However, the viscosity of all blends at 120°C was lower than the viscosity of the base bitumen and the consequent reductions in mixing and compaction temperatures were quantitatively evaluated for all binders. The study of the flow characteristics of the bitumen-wax blends at high pavement service temperatures was carried out using complex viscosity master curves evaluated in the linear viscoelastic domain. Increasing resistance to viscous deformation referable to wax modifications was recorded by analyzing viscoelastic properties in the low frequency domain and different contributions were found with regard to each type of wax. For the polyamidic wax-modified binders, the results indicated the presence of a complex behavior characterized by the absence of a Newtonian region of flow. The final contribution of the experience is related to the development of wax modification of asphalt binders in order to produce WMA for pavement engineering applications (Giuliani et. al. 2009).

The organic additives can be introduced to the mixture or to the asphalt binder. Different organic additives can be used to lower the viscosity of the binder at temperatures above about 90 °C. The type of additive must be selected carefully so that its melting point is higher than the expected in-service temperatures otherwise permanent deformation may occur, and to minimize embrittlement of the asphalt at low temperatures. Organic additives typically give a temperature reduction between 20–30 °C.

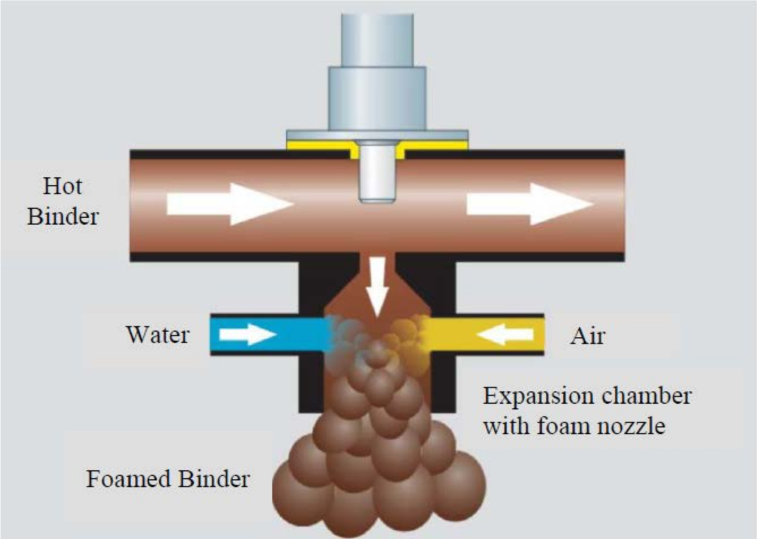
4.3.3 Foaming Technology

The potential of foamed bitumen for use as a soil binder was first realized in 1956 by Dr. Ladis H. Csanyi, at the Engineering Experiment Station in Iowa State University. Since then, foamed asphalt technology has been used successfully in many countries, with corresponding evolution of the original bitumen foaming process as experience was gained in its use. The original process consisted of injecting steam into hot bitumen. The steam foaming system was very convenient for asphalt plants where steam was readily available but it proved to be impractical for in-situ foaming operations, because of the need for special equipment such as steam boilers. In 1968, Mobil Oil Australia, which had acquired the patent rights for Csanyi's invention, modified the original process by adding cold water rather than steam into the hot bitumen. The bitumen foaming process thus became much more practical and economical for general use. Foaming increases the surface area of the bitumen and considerably reduces its viscosity, making it well suited for mixing with cold and moist aggregates. Foamed bitumen can be used with a variety of materials, ranging from conventional high-quality graded materials and recycled pavement materials to marginal materials such as those having a high plasticity index. Foamed asphalt can be manufactured in-situ or in a central plant. Binder contents are based on the mix design, and are determined as percentage (by weight) required for the mix to have optimum properties (Ruckel et. al. 1983, Muthen, 1998, and Saleh et. al. 2007).

The following advantages of foamed asphalt are well documented:

- The foamed binder increases the shear strength and reduces the moisture susceptibility of granular materials. The strength characteristics of foamed asphalt approach those of cemented materials, but foamed asphalt is flexible and fatigue resistant.
- Foam treatment can be used with a wider range of aggregate types than other cold mix processes.
- Reduced binder and transportation costs, as foamed asphalt requires less binder and water than other types of cold mixing.
- Saving in time, because foamed asphalt can be compacted immediately and can carry traffic almost immediately after compaction is completed.
- Energy conservation, because only the bitumen needs to be heated while the aggregates are mixed in cold (no need for drying).
- Environmental side-effects resulting from the evaporation of volatiles from the mix are avoided since curing does not result in the release of volatiles.
- Foamed asphalt can be stockpiled with no risk of binder runoff or leeching. Since foamed asphalt remains workable for very extended periods, the

usual time constraints for achieving compaction, shaping and finishing of the layer are avoided.



(a)

(b)

Figure 4.2**:** Laboratory-Scale Foaming Device (WLB 10 S): (a) Foaming Nozzle and (b) Foaming Device [83], (Diab 2014).

4.4 Benefits of WMA Technology

The WMA technologies have been developed to lower the production and placement temperatures of asphalt mixtures. This technology offers several benefits over the conventional HMA [82]. Potential benefits such as reduced plant emissions, workability at lower temperatures, extension of the paving season into colder weather, and reduced energy consumption at the plant may be realized with different applications (Bonaquist et. al. 2011, and Diefenderfer et. al. 2008).

The most important benefit of WMA is the possibility to reduce the greenhouse emissions since WMA does not emit as much chemical smoke as HMA. This is achieved by the reduced production temperature of WMA. In addition, the reduction of production temperatures provides obvious energy savings as compared to HMA. However, this mostly depends on the production temperature and the kind of fuel used. It was found that WMA provides a reduction of 24% in air pollution and a reduction of 18% on fossil fuel consumption as compared to HMA (Hassan, 2009).

Chapter 5

Nanotechnology in Asphalt Mix

Chapter 5

Nanotechnology in Asphalt Mix

5.1 Introduction

Pavement is one of the main and infrastructure components in highway and must have desirable conditions based on importance in road transportation network, for sake of providing a safe trip attraction, meanwhile supply safe transportation during operation life for highway users. Asphalt is an organic mixture that is widely used in road pavements because of its good viscoelastic properties. Therefore, scientists and engineers are constantly trying to improve the performance of the flexible pavements. It should be performed so as to resist against effects disadvantages of water, icing and temperature changes. Various studies and researches have shown that modifiers have sensible role on mechanical behavior, characteristics and volume ratios of asphalt mixtures (Pauli et. al. 2006).

Characteristics of bitumen and bituminous mixtures can be improved by using various additives such as oil derivations in a kind of diverse polymers and Nanotechnology (Zahedi 2014).

Nanotechnology has the potential to create many new materials and devices with wide-ranging purposes. Nano-sized particles have been used in numerous applications to improve the properties of various materials. The utilization of nanotechnology in civil engineering is expected to increase and may become an attractive alternative for asphalt binder modification, (Xiao et. al. 2011).

5.2 Nanotechnology

Nanotechnology is the science devoted to cover the design, construction and utilization of functional structures with at least one dimension in the nanometer range. A nanometer is one billionth of a meter. This technology is dominated by developments in basic physics and chemistry researches, where phenomena on atomic and molecular level are used to provide materials (having at least one dimension ≤ 100nm) and structures with arts are not promising using the materials in their typical macroscopic form (bulk materials) (Steyn 2008).

On a nanoscale, some physicochemical material properties can significantly differ from those of the bulk-structured materials of the same chemical composition. Therefore, many material properties must be revisited in light of the fact that a considerable increase in surface-to-volume ratio is associated with the production of materials with the nanosize, often prominently effect material performance.

Originally, nanotechnology has been concerned with developments in the fields of microelectronics, medicine and materials sciences. Recently, the developments in the nanotechnology field in the area of civil engineering and construction materials are growing. After more than a decade of progress in other industrial sectors, the nanotechnology revolution has just begun to impact highway and bridge materials and construction [81].

5.3 Nano Asphalt

Nano-materials, structural elements and components of bitumen and asphalt, forming micro-and nanoscale are the use of nanotechnology could lead to improved properties of these materials. Including applications in nano materials can be recovered asphalt properties such as resistance to damage from moisture, strength and longevity, saving on maintenance costs of asphalt, to improve key properties such as compressive strength, tensile strength and stability to tolerate loads at high temperatures. The other important features, reduce traffic noise from the cars on the asphalt, the respondents are self-correcting. This modification has the following advantages of the respondents, (Parviz 2011):

A - limiting greenhouse gas emissions.

B - less energy consumption.

C - reducing the noise of traffic and cars on the asphalt.

D - more comfortable and confident driving.

E - machines due to problems on the roads do not see the damage.

5.4 Nanomaterials in Hot-Mix Asphalt

Nanomaterials are generally important modifiers in improving pavement performance. Nanotechnology has been used in various fields. In pavement engineering research, nanotechnology is used as a form of new material, device, and system at the molecular level. A number of researchers have used nanomaterials in Portland cement materials. However, nanomaterial use in asphalt pavement started relatively late. In recent years, some researchers have started to work on the improvement of asphalt materials with nanomaterials in asphalt cement and emulsions (Tarefder et. al. 2008). There are various nanomaterials which have been or have potential to be used in asphalt modification; such as nanoclay, carbon nano tubes, nanosilica, semi-transparent nano asphalt, nano water on the pavement of, nano-hydrated lime, nano-sized plastic powders, or polymerized powders, and nano fibers (You 2013).

5.4.1 Nanoclay

Nanoclay is a mineral that at least one of its dimensions is about nanometer. This mineral because of cheapness and availability, attract many attentions in nanotechnology field to itself, also, small size makes it capable to compete with other materials that exist in this field. Nanocaly, indeed, is a compound of mineral silicates. In relation to composition and morphology, nanoparticles, set in different categorizations that their dimensions are lower than 100nm and have specific surface area equal to 750 m^2 /gr (Pauli 2006).

In the experimental testing montmorillonite by You et. al. (2011), nanoclay at 2% and 4% by weight of asphalt was blended in asphalt binder at a high temperature to exfoliate the nanoclay within the asphalt. The asphalt binder was then characterized using the Superpave rotational viscosity, dynamic shear modulus, and direct tension test. The rotational viscosity results indicate that the addition of the two types of nanoclay, Nanoclay A and Nanoclay B, increased the rotational viscosity by an average of 41% and 112%, respectively, across test temperatures 80, 100, 130, 135, 150 and 175 ° C. It was found that the dynamic shear complex modulus value increases significantly across a range of testing temperatures (from 13 to 70 ° C) and loading frequencies (0.01 – 25 Hz). With 2% nanoclay a reinforcement in the asphalt binder, the complex shear modules generally increased by 66% while the 4% nanoclay a reinforcement in the asphalt binder generally increased the shear complex modules by 125%. The 2% and 4% nanoclay B increased the shear complex modules by 184% and 196%, respectively. In terms of direct tension strength, the use of Nanoclay A and nanoclay B reduced the strain failure rate of the original binder while the secant or direct tension modules showed increase with the addition of the nanoclays (You et. al., 2011).

5.4.2 Carbon Nano Tubes

Fibers for the arming and improved mechanical performance of asphalt are used. Today, metal fibers, glass, poly-propylene, carbon in asphalt is used for arming. Carbon nano tubes were discovered in 1991. Carbon nano tubes 60 and the new structure are much lighter and stronger than steel. In future they will be replaced by carbon fiber composites that are used. Nano tubes have a tensile strength of fibers of each type of concrete are known. Conductor of heat, more than double the diamond, the electrical conductors in copper is about 1000 times. Nano tubes are a new class of products that revolutionized the field of new materials and advanced materials have created. Components of the carbon nano tubes are multi-purpose high performance materials (Parviz 2011).

Investigation and evaluation of the rheological properties of binders containing various percentages of carbon nanoparticles after a short-term aging process were studied. The experimental design included five binder sources (three grades including PG 64-22, PG 64-16, and PG 52-28), three nano percentages (0.5, 1.0, and 1.5% by weight of the virgin binder), and control binders. The rheological characteristics of the rolling thin film oven (RTFO) binders, including failure temperature, performance grade, creep and creep recovery, viscous flow, and frequency and amplitude sweep, were tested. The results of the experiments indicated that the addition of nanoparticles was helpful in increasing the failure temperature, complex modulus, and elastic modulus values and in improving rutting resistance of the RTFO binder. The phase angle of the binders generally decreased with an increase in nano content and RTFO aging procedure. In addition, statistical analysis indicated that the asphalt binder source plays a key role in determining the rheological properties because of significant evaluations (Xiao at. al. 2011).

5.4.3 Nanosilica

In the asphalt industry, silica is played one of the most important role in the adhesion and barrier materials with high performance asphalt. Based on the limited laboratory work done (Yusoff et. al. 2014), it can be concluded that the addition of 4% nano-silica is the optimum content to improve the performance characteristics of polymer-modified asphalt mixture (PMA) in various conditions. The moisture susceptibility of the mixes also improves, indicating that the strength of the asphalt mixes increases with the addition of nano-silica particles. Furthermore, substantial increases in fatigue life and rutting deformation were observed with nano-silica modification at intermediate and high temperatures respectively. Experimental data suggests that nano-silica causes a significant reduction in the susceptibility to oxidative ageing, highlighted by the values calculated for the ageing index introduced in the analysis of experimental data. Finally, the outcomes of the finite element model conducted using ABAQUS software is very promising, as it opens a new era for the accurate and effective explicit formulation of many pavement engineering-related problems (Yusoff et. al. 2014).

5.4.4 Nano-hydrated Lime

Hydrated lime is known as a highly alkaline (basic) inorganic fine powder that has many industrial and environmental applications. It has been widely used as a mineral filler in HMA mixtures for many years and then used as an effective additive for asphalt mixtures. The effectiveness of hydrated lime in asphalt mixtures lie in the strong interactions with the major components, i.e., aggregate and asphalt binder. The mechanisms of hydrated lime in asphalt mixes help in reducing chemical aging of the asphalt binder and stiffen the mastic more than classical mineral fillers, an effect that is only observed above room temperature.

Hydrated lime as an alternative antistripping additive can be introduced to dry or moist aggregates, and in the form of hydrated lime slurries to dry aggregates; detailed description of each addition method will be explained later. Hydrated lime is currently the most commonly used additive for asphalt mixtures (Epps et. al. 2003); tends to change the surface chemistry or molecular polarity of the aggregate surface, results in a stronger adhesion at the interface between the aggregate and asphalt bin.

Also, the National Lime Association reported that hydrated lime can save from 9% to 20% of a pavement’s cost over the course of its life cycle (Hicks et. al. 2001).

Chapter 6

Closure

Chapter 6

Closure

6.1 Conclusions

This article presents the state of the art of Superpave HMA, asphalt concrete sensibility's to moisture damage, warm-mix and nanomaterials technology. Based on the review of the existing literature in Chapters 2, 3, 4 and 5, it can be concluded that:

1. The Superpave mix design system integrates material selection and mix design into procedures based on the project's climate and design traffic.
2. Superpave uses a completely new system for testing, specifying and selecting asphalt binders.
3. The Superpave system allows the designers to use reliable measurements to assign a degree of risk to the high and low permanent temperatures used in selecting the binders grade.
4. The Surface Free Energy (SFE) is a method to evaluate asphalt concrete's susceptibility to moisture damage.
5. Liquid anti-strip, chemical lime and fly ash additives had been used to reduce the susceptibility of the asphalt concrete to moisture damage.

6. Warm Mix Asphalt (WMA) technologies allow for producing asphalt mixture at temperatures (20 to 55 ^{O}C) lower than typical hot-mix asphalt (HMA).

7. The temperature reduction achieved by WMA Comes from the use of various technologies that have been developed in recent years, and which can be classified in the following three groups: organic, chemical additives and water-based or water-containing foaming processes.

8. Nano-materials, structural elements and components of bitumen and asphalt, forming micro-and nano scale are the use of nanotechnology lead to improved properties of these materials.

9. Applications in nano materials can be recovered asphalt properties such as resistance to moisture damage strength and longevity, saving on maintenance costs of asphalt (Parviz 2011).

10. Nano-materials improve asphalt concrete properties such as compressive strength, tensile strength and stability to tolerate loads at high temperatures (Parviz 2011).

11. There are various nanomaterials which have been or have potential to be used in asphalt modification; Such as nanoclay, carbon nano tubes, nanosilieca, nano-hydrated lime, (You 2013).

6.2 Perspectives

According to the previous aspects, the main objective of this study is to review the state of the art as well as the future of the following:

1. Design and develop a field evaluation program to determine if asphalt mixtures used in Egypt are susceptible to moisture damage from a pavement performance point of view based on distresses,
2. The most previous study is limited to the laboratory-scale work only; however, field studies by constructing field sections can provide more information about the organic, chemical and foaming-modified pavement performance,
3. Evaluate the effect of long-term aging on neat and LAS modified asphalt binder in order to quantify change in SFE of the material. This would provide insight into the tendency of aged asphalt binders to be susceptible to moisture damage based on a reduction or gain in a work of adhesion,
4. Design and develop a laboratory program that can discriminate between moisture susceptible and non-susceptible asphalt concrete when designing asphalt mixtures in Egypt, and
5. It is recommended that the Egyptian highway and Bridges agencies establish a database on the compatible combinations of the available aggregates and asphalt binders and provide an appropriate strategy, if needed, to maintain the moisture susceptibility of the asphalt pavement in a satisfactorily condition by using nanomaterials technology.

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Arabic Summary

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طريقة السوبربيف التصميمية تعتمد علي اختبار مواد الخلطة التصميمية علي أساس حالة الطقس للمشروع وحجم المرور. وهي تعتبر نظام جديد تماماً في اختيار وتوصيف واختبار البيتومين والمادة الرابطة. طريقة سوبربيف تتيح للمصمم استخدام دقة وقياسات محددة لإيجاد درجة البيتومين والمادة الرابطة المناسبة لأعلي و أقل درجة حرارة متوقعة في المشروع.

وأيضا طريقة سوبربيف تعتمد علي تقسيم مستويات المرور الي ثلاثة مستويات مستوي (١) أكبر من ١ مليون محور مكافئ (ESAL)، ومستوي (٢) أقل من ١٠ مليون وحدة مكافئة، ومستوي (٣) أكبر من ١٠ مليون وحدة مكافئة. هذا ويمكن تقييم أداء الخلطة الأسفلتية بالنسبة للمستوي الثاني والثالث باستخدام اختبار القص البسيط (SST) واختبار الشد غير المباشر (IDT).

يحدث انهيار للخلطات الخرسانية نتيجة قابليتها لامتصاص الرطوبة ولعدم تدرج الخلطة الإسفلتية ونقص/قصور في المواد الرابطة أو عوامل بيئية أو زيادة أحجام المرور، ويمكن قياسها عن طريق طاقة الشد السطحي (SFE) بين المواد الرابطة والركام. ولتفادي ذلك يمكن استخدام بعض الإضافات لتقليل قابلية الخرسانة الأسفلتية للانهيار مثل السوائل المانعة لتسرب المياه بالرصف (liquid anti–strip)، وكذلك بعض الإضافات الكيميائية مثل الجير المطفي (Hydrated Lime). ويمكن قياس تأثير تلك الاضافات أيضاً باستخدام اختبار الشد غير المباشر (IDT).

نتيجة ارتفاع أسعار الطاقة ولتقليل نسبة الانبعاثات من الخلطات الأسفلتية أثناء الاعداد والرصف وللحصول علي رصف صديق للبيئة تم إنتاج خلطات إسفلتية عند درجات حرارة أقل من الطرق السابقة باستخدام الخلطات الأسفلتية الدافئة (WMA)، وذلك باستخدام تكنولوجيا الإضافات العضوية والكيميائية وتكنولوجيا الرغويات (Foaming Technology). و من أهم الإضافات الكيميائية التي تزيد قابلية تشغيل الخلطات الأسفلتية هي (Asphamin, Sasobit, Evotherm)، وطريقة إنتاج المادة الرابطة الرغوية تتلخص في ضخ الهواء والماء مع الرابط

الساخن فيحدث اختلاط للهواء والماء مع المادة الرابطة الساخنة فى غرفة التمدد فيتكون الرابط الرغوي (Foamed binder).

وأخر ما توصل إليه العلماء هو استخدام تكنولوجيا الحبيبات متناهية الصغر في الخلطات الأسفلتية، حيث تعمل علي تحسين خواص مختلف مكونات الخلطة ومن أهم المواد متناهية الصغر (نانوسيليكا، نانوطين، نانوكربون، نانو جير مطفئ، نانو بدرة البلاستيك، بدرة البلوميرات، وألياف النانو).

كلية الهندسة
قسم الهندسة المدنية

تكنولوجيا تصميم خلطات الخرسانة الأسفلتية

بحث مرجعي

مقدم كجزء من متطلبات نيل لقب أستاذ مشارك
قسم الهندسة المدنية – كلية الهندسة – جامعة أسيوط

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مدرس هندسة الطرق
بقسم الهندسة المدنية
كلية الهندسة
جامعة أسيوط

يونيه ٢٠١٥