Asphalt Mixture Compaction and Aggregate Structure Analysis Techniques: State of the art report

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1. Introduction

1.1 Motivation for Study

Bituminous mixtures for pavement applications have been utilized for over 150 years. Although these first mixtures proved successful as a pavement material, they were not designed with any real engineering sense as with the asphalt pavements of today. As knowledge regarding paving materials expanded, a need for more functional, performance based pavements was realized among roadway engineers. This led to the development laboratory mix design and compaction, which would accommodate existing pavement conditions into the pavement design in order to best fit the application [*1*].

Today, engineers design asphalt mixtures as a function of safety, cost, and performance. Asphalt-aggregate mix and compaction methods are designed based on the influence of mix components on the performance characteristics and properties of the paving mixture. In addition, asphalt mixes are specifically designed and compacted according to the variables which affect these performance properties in the field. The challenge is to design a compaction method in the laboratory that accurately simulates field conditions. For example, proper pavement fatigue resistance must be realized to allow for repeated loading of the pavement without failure. Variables that can alter the fatigue resistance of a pavement include asphalt stiffness, aggregate gradation, asphalt content and degree of compaction. In all, eight properties must be accounted for in every mix design and compaction effort: stiffness, stability, durability, fatigue resistance, fracture characteristics, skid resistance, permeability, and workability. In rigor, proper laboratory compaction should incorporate a sustainable balance of these properties in order to select mix components for a specific paving application [2][3].

To satisfy the need for proper mix design specifications, numerous laboratory mix compaction methods have been developed over time to approximate field conditions. Some of these methods, such as the Hubbard-Field Method, have since fallen out of favor, either because they fail to capture an accurate representation of field conditions, or they have proven inefficient to carry out [4]. Pavement engineers have long recognized that different compaction techniques produce specimens with different physical properties [5]. This review will outline and compare five of the major laboratory mix and compaction methods used throughout the world: Marshall Compaction Method, Hveem Mix Design (Kneading Compaction Method), French Roller Compaction Method, German Sector Compaction Method, and the Super PAVE Gyratory Compaction Method. Finally, the ability of these compaction methods to capture field conditions will be analyzed. Although laboratory mix and compaction methods have evolved greatly over time, the foundation remains unchanged: pavement design and mixture design are intimately related; therefore accurate laboratory methods must be utilized to approximate field conditions.

1.2 History of Mot mix Asphalt Mix Design and Laboratory Compaction Methods

In the late 1860's mixtures of sand, gravel, broken stone, ashes and *coal tar* binder were used in Brooklyn, New York and Washington D.C. as the first real form of 'rigid' pavement. At this same time, natural rock *asphalt* binder pavements were being developed for roadways in Paris. The first true asphalt pavement was a sand mixture laid in Newark, New Jersey in 1870. Not long after, the rest of the United States began using similar mixtures in New York City, Philadelphia, and Washington D.C. Asphalt pavements continued to grow in popularity and roadways utilizing asphalt mixtures quickly developed [*1*].

Engineers quickly realized that dense packing (read adequate compaction) provided resistance to "shoving" under traffic loading. Quickly it was discovered that aggregates with jagged, sharp surfaces and of uniform gradation would better adhere to the asphalt and provide more uniform compaction. Accordingly, laboratory methods, as we know them today, developed as a need for stable and durable field pavements; this meant engineers needed to duplicate field mixtures in the laboratory to accurately represent the mixture as it exists in the pavement [*1*].

1.3 Engineering Considerations in Asphalt Compaction

The question still remains: how can a laboratory compacted specimen accurately approximate field pavement conditions. Although each laboratory mix and compaction method may vary in specimen preparation, compaction type (impact, kneading, gyratory…), and procedure, the final result must be a useful representation of field conditions. The role of compaction in asphaltic mixtures is crucial, as many mix properties depend heavily on both degree and method of compaction [4].

Perhaps the greatest consideration into laboratory compaction is the approximation of field loading conditions. The percentage of large axle loads (as well as the loads themselves) has increased dramatically in the last quarter century, requiring pavements to carry heavier loads for more cycles [*1*]. Approximation of field conditions must start with the construction process; field compaction has evolved with time to include smart compactors, which compact field pavements to a predetermined density or air void content. Understanding of particular pavement failure mechanisms has led to the development of design specifications which directly combat say, rutting [2]. Indeed, many other factors dictate how mixes need be formulated and compacted, and only with a careful balance of consideration, can a favorable mix design be realized. It was recognized early on that often the optimization of one quality comes at the expense of another [4]. Each laboratory compaction method reviewed attempts to isolate specific engineering properties in order to help engineers predict the response of a particular mix to field conditions. Thus, engineering principles will also be reviewed for each method.

2. Mix Design and Compaction Methods

Hot mix asphalt compaction is influenced by not only the method of compaction, but also the physical properties of the materials used in the mix design, construction conditions, and environmental conditions. This review compares only the methods of compaction, assuming proper aggregate selection and static conditions have been accounted for.

2.1 Marshall Hammer Compactor

2.1.1 History of the Marshall Method of Mix Design and Compaction

The Marshall Method of Mix Design and Compaction was conceptually developed in 1939 by Bruce G. Marshall while working for the Mississippi Highway Department. Marshall developed a method of asphalt mix design that sought to select the asphalt binder content at a density that would satisfy the minimum range of flow values and stability [6].

The U.S. Army Corps of Engineers (USACE) revised Marshall's method during World War II for the use of airfield pavement design. During that time, military aircraft wheel loads and tire pressures were increasing dramatically and a need for "…a simple apparatus suitable for use with the present California Bearing Ratio equipment to design and control asphalt paving mixtures…" was realized. Throughout the 1950's, the USACE modified the Marshall Method by adding, among other modifications, a deformation measurement device, traffic loading variables, and weather variables. The resulting laboratory mix design and compaction procedure was adopted by the American Society for Testing Materials (ASTM) as we use it today. The Marshall method of mix design is empirical, with criteria based on the correlation of laboratory and field results [6,7].

2.1.2 Standard Procedure for Marshall Method of Mix Design and Compaction

Preparation and compaction for the Marshall Method of mix design follows ASTM D 6926 – Standard Practice for Preparation of Bituminous Specimens Using Marshall Apparatus [8]. ASTM D 1559 governs the stability and flow testing of Marshall specimens. General Marshall Mix Design includes six steps:

(1) Selection of Aggregates
(2) Selection of Asphalt Binder
(3) Sample Preparation and Compaction
(4) Stability and Flow Test

(5) Density Calculation
(6) Determination of Optimum Asphalt Binder Content

The Marshall method applies only to mixtures containing dense of fine graded aggregates with a maximum aggregate size of 25 mm or less [6,7].

The compaction apparatus, seen in Figure 1, is comprised of essentially three major components: the compaction pedestal and mold holder, the compaction mold, and the compaction hammer. The compaction pedestal is a 200 x 200 x 460 mm wooden column made of wood types with a dry unit weight of 670 to 770 kg/m^3. Typically the wooden column is fashioned from oak or pine. The column is capped with a 305 x 305 x 25 mm steel plate. The entire assembly is fastened to prevent any movement during compaction. The compaction mold is comprised of a circular base plate, cylindrical forming mold and collar extension. The mold has an inside diameter of 101.6 mm and a height of 75 mm. The compaction hammer consists of a 4.5 kg weight attached to a flat, circular tamping face, constructed in order to provide 457 mm of drop height.

Figure 1: *Marshall Impact Hammers*

Once the mix design is complete, the entire batch is placed into a mold heated to a temperature between 95 and 150 C. The mixture is then spaded with a heated spatula 15 times around the perimeter and ten more times in the interior. The surface is smoothed to a slightly rounded shape. The temperature of the specimen immediately after sample preparation and just prior to compaction must be within the limits of compaction temperature calculated in the mix design. Compaction temperature must take place within a range of temperatures that produces a binder viscosity of 280 ± 30 centistokes kinematic. Compaction temperatures are estimated using plots of viscosity (log-log centistokes) versus temperature (log degrees Rankin). The ASTM specification does not allow the sample to be reheated, so it is vital to work quickly to avoid falling below the temperature limits for compaction.

The mold with the prepared specimen is then placed in the mold holder on the compaction column. The specimen is compacted using compressive impact loads delivered by the compaction hammer after a free fall of 457 mm. The design traffic category of the mix dictates how many impact blows to deliver, 35, 50 or 75 blows. The hammer is to be held as close to perpendicular to the mold assembly as possible during compaction using a manual apparatus. Blows to the specimen can be either from manual drops of the hammer or from mechanically controlled hammers; however the ASTM standard refers only to manual compaction. After delivering the designated number of blows, the specimen is turned over and the same number of blows are delivered on the opposite side, again as perpendicular to the mold assembly as possible. Specimens are then left to cool until no deformation will result after removing the mold [1, 4, 6, 8]

After compaction, the specimens are subjected to density measurements, stability testing, and flow testing. Density is measured in both bulk specific gravity and theoretical maximum specific gravity. Specimens are then heated and circumferential loading is applied to the specimen until failure. Similar to other compaction methods, several trial aggregate-asphalt blends are tested in order to capture the optimum asphalt-aggregate content [*Asphalt Concrete Mix Design : Development of More Rational Approaches*][4,6].

Using the density analysis, along with the stability and flow test results, six graphs are plotted: density versus binder content, stability versus binder content, flow versus binder content, air voids versus binder content, voids in mineral aggregate (VMA) versus binder content, and voids filled with asphalt (VFA) versus binder content. Using these plots, the corresponding asphalt binder content associated with specified median air void content, is the optimum asphalt binder content. Compare the corresponding values of specified parameters by referring to the plots and inputting the determined optimum binder content. If the mixture does not meet specified criteria, it must be redesigned [6,9].

2.1.3 Engineering Principles of the Marshall Method of Mix Design and Compaction

The major advantage of the Marshall compaction method is its focus on air voids (density), strength, and durability; the Marshall method recognizes the need for sufficient asphalt to ensure durability, sufficient stability to satisfy structural requirements under loading, sufficient air void content (an upper limit to prevent environmental damage and a lower limit to allow for additional densification from traffic), and workability to facilitate effective compaction [2]. Air void content is a direct result of gradation, asphalt content, compaction effort, and compaction type. To achieve the optimum void content, the Marshall method utilizes impact loading in the form of a falling weight. The impact forces aggregates to

realign and densify, hence decreasing air void content. Impact loading, however, does not create an aggregate structure that accurately simulates field compaction results, elaborated on in later sections [5]. In addition, one study by Khan Et.al determined that Marshall specimens compacted manually versus specimens compacted mechanically do not exhibit similar specimen mechanical properties. For example, the study determined that manual compactor consistently produced denser specimens with higher stability than specimens produced with the mechanical hammer [3].
Resistance to flow under traffic loading is considered with the stability and flow tests. Deformation under loading is recorded, and limited, in order to satisfy performance requirements for a given traffic loading scenario. However, the Marshall method fails to recognize the effects of shear strength on compacted specimens. Further, specimens are loaded perpendicular to the compaction plane, which differs from loading in the field [2,6]. Section 8 of this review will provide greater insight into the shortcomings of the Marshall test method.

2.1.4 Current Usage and Distribution

The Marshall Mix Design and Compaction Method was the primary mix design method utilized by state agencies for nearly 50 years prior to the 1990's. During the 1990's, researchers, on behalf of the Federal Highway Administration, began developing Superpave mix design to address problems with the Marshall design and other design methods. Today Superpave mix design is the most accepted method of design, although the Marshall method is still currently used in at least 38 states to some degree [10].

2.2 California Kneading Compactor (Hveem Design Method)

2.2.1 History of the California Kneading Compactor – Hveem Design Method

During the late 1920's, the State of California began to pave their rural roads with what was a compromise between high performance hot mix asphalt and asphalt oil sprayed on unbound particles. The result was an oil mix; a combination of premixed aggregate and asphaltic oil sprayed on the road and compacted by traffic. Design of these mixes, however, was lacking. Materials and research engineer Francis N. Hveem developed a method to determine the amount of oil needed based on the total surface area of the aggregates, determined from the gradation. Hveem also recognized the need for stability testing after noticing that roadways containing aggregates with harder, rounder surfaces tended to be less stable than those with aggregates which were jagged and had irregular surfaces. Hveem developed the Hveem Stabilometer to measure the differences in stability more accurately. Researchers soon noticed a difference in physical properties (stability) between specimens compacted in the field, with those compacted in the laboratory. This led to the development of the modern day California Kneading Compactor (CNC), which simulated compaction in the field more closely [11].

2.2.2 Standard Procedure for California Kneading Compactor – Hveem Design Method

Preparation and compaction using the California Kneading Compactor follows ASTM D 1561 – Preparation of Bituminous Mixture Test Specimens by Means of California Kneading Compactor [12]. The Hveem design method and subsequent compaction by the CNC follows six basic steps:

(1) Selection of Aggregates
(2) Selection of Asphalt Binder
(3) Sample Preparation and Compaction
(4) Stability Testing (Hveem Stabilometer)
(5) Density Calculation
(6) Determination of Optimum Asphalt Binder Content

The Hveem design method applies to both asphalt cements and liquid asphalts containing aggregates up to 25 mm for the use in dense graded paving mixtures [7,13].

Appropriate specimen mixes and corresponding oil contents are determined with the results of a centrifuge kerosene equivalent test (CKE) and aggregate gradation. The asphalt content can then be determined by direct calculation utilizing surface capacity principles. Mixtures are then tested for stability, void content and other desired parameters. After the desired mix has been formulated, the sample is compacted via the CNC [1].

The compaction apparatus, seen in Figure 2, consists of a mechanical kneading compactor, mold holders, an insulated feeder trough 460 mm long x 102 mm wide x 64 mm deep, a trough paddle, and a round nosed steel rod 9.5 mm in diameter and 406 mm long. The mechanical compactor must be capable of producing a force of 34.5 kPa beneath the tamper foot. The California Kneading Compactor utilizes a hydraulically operated tamper foot which applies pressure on a cylindrical sample. The tamper foot has a compaction face shaped as a sector of a 101.6 mm diameter circle. The tamper foot applies a compression pressure of 3.45 MPa over an area of approximately 2000 mm^2 for approximately 2/5ths of a second. After each compression, the tamper foot lifts and the base of the compactor rotates the sample 1/6 of a revolution [4,13].

Figure 2: *California Kneading Compactor*

Specimens are compacted according to whether they will be tested in the stabilometer or used for a swell test. For stabilometer specimens, the compaction method is as follows:

(1) Compaction molds, feeder trough and steel rod are all heated to the predetermined compaction temperature.
(2) The prepared mixture is then spread evenly on the feeder trough, and approximately one half of the mixture is placed in the mold using the trough paddle.
(3) The specimen in the mold is then spaded 20 times in the center of the specimen and 20 times along the perimeter of the specimen using the round nosed steel rod. After spading, the remainder of the specimen is transferred to the mold, and spaded in the same manner.
(4) The mold assembly is paced in position on the compactor and approximately 20 tamping blows at 1.7 MPa pressure are applied to achieve a semi-compacted specimen. This is done to ensure the full load will not unduly disturb the sample. The number of semi-compaction blows may vary between 10 and 50, and is dictated by the type of material.
(5) Semi-compacted specimens are then adjusted on the compactor to allow for free up and down movement of the mold, and about 3 mm of side to side movement. The compaction pressure is then increased to 3.45 MPa and 150 compressive blows are applied.
(6) After the compaction has completed, the samples are placed in an oven at 60 C for one hour. After which, samples are placed back on the compactor and exposed to a leveling off load of 56 kN utilizing the double plunger method outlined in the ASTM specification.

Swell test specimens are prepared by placing a 19 mm wide strip of paraffin impregnated paper around the inside of the mold. The purpose of the paper is to prevent water from escaping between the specimen and mold during immersion. It is important to note that the molds used for swell test specimens are not heated prior to compaction. After the mold preparation, the compaction method is exactly the same as with the stabilometer specimens, with one minor adjustment. After compaction, the mold is *inverted* before the 56 kN static load is applied [4,13].

Samples are then tested with the Hveem Stabilometer and the Hveem Cohesiometer to determine resistance to deformation and cohesion of the asphalt sample, respectivelty. In addition, samples are tested to determine bulk specific gravity and theoretical maximum specific gravity. The optimum asphalt content is then calculated using the "pyramid" method, which several trial aggregate-asphalt blends are tested in order to capture the optimum asphalt-aggregate content without falling below a minimum stability [9].

2.2.3 Engineering Principles of the California Kneading Compactor – Hveem Design Method

Similar to the Marshall method of compaction, the Hveem method is based around voids, durability and strength.

The California Kneading Compactor was developed to attempt to produce specimens with particle orientation similar to that of field specimens compacted by means of roller compaction, the most prevalent compaction method in California at the time when the CKC was developed. To simulate roller compaction, the CKC utilized a rotating base and a shield shaped tamper foot that does not cover the entire surface area of the specimen being compacted. This produces a kneading action between the particles as the specimen was rotated and compacted with each additional blow. This approximates a particle orientation similar to field samples. Field compaction often is done in several passes, with each pass covering slightly different path than the previous one, again creating a kneading action in the aggregate structure [13].

In addition to a more refined compaction effort, the California Kneading Compactor and Hveem Mix Design Method take into account absorption of asphalt by the aggregates, a previously overlooked phenomenon. Also, the strength parameters developed in the form of stability measurements are direct indications of the internal friction component of shear strength, an improvement over the Marshall Method [Asphalt Concrete Mix Design History].

2.2.4 Current Usage and Distribution

As of 2002, nine states use or have used the Hveem mix design method as the primary design method for roadways. Most of these states are located and bordering California. Many of these states are concurrently using the SuperPAVE design system and are phasing out the Hveem method [14].

2.3 French Roller Compactor

2.3.1 History of the French Roller Compactor

The French Roller Compactor was developed by the Laboratoire Central des Ponts et Chausées (LCPC) in France. The LCPC is a French organization for the applied research and development of infrastructure and laboratory methods. Internationally involved with laboratory asphalt compaction since the 1950's, the LCPC has been instrumental in developing not only rolling wheel compaction, but also gyratory compaction, volumetric design, and failure mechanisms [15].

Investigations into rolling wheel compaction began in the late 1970's with studies of densification characteristics related to compaction characteristics. The LCPC soon developed a unique method of mix design, which standardizes the compaction effort on the road, opposite the Marshall method which standardizes compaction in the Laboratory. The rolling wheel compactor was introduced in order to produce asphalt slabs that could be easily cut apart for subsequent testing, or tested as a slab [15,16].

2.3.2 Standard Procedure for the French Roller Compactor

Sample preparation and compaction using the French Roller Compactor follows European Standard EN 12697-33: Test Methods for Hot Mix Asphalt: Specimen Prepared by Roller Compactor and French standard NF P 98-250.2: Preparation of bituminous mixtures. Part 2 : plates compaction. Compaction using the roller compactor follows three steps:

(1) Preparation of the Bituminous Mixture
(2) Filling the Mold
(3) Specimen Compaction

Preparation of the sample follows a numerical equation to determine total mass of the bituminous mixture as a function of maximum density of the mixture, dimensions of the mold, and the voids content according to EN 12697-35. The mold is then filled evenly and the surface is smoothed before compaction. The mold can be preheated prior to compaction, at the specified compaction temperature for more than two hours [16,17].

The compaction apparatus, seen in Figure 3, utilizes either one or two loaded, tread-less pneumatic rubber tires of 400 mm diameter and 80 mm thickness moving back and forth to create asphalt slabs for laboratory testing. The single wheel compactor produces slabs measuring 500 mm x 180 mm for use in rutting tests, while the double wheel compactor produces slabs measuring 600 mm x 400 mm for modulus and fatigue testing. In both single tire and double tire compactors, the inflation pressure of the tires is held between 0.1 MPa - 0.6 MPa ±0.03 MPa, while imparting a load of 1 kN -10 kN on the specimen. The tire translation velocity varies based on testing conditions, and ranges from 200 mm/s to 500 mm/s, with one wheel pass defined as a one way movement of the tire. Compaction temperature is determined based on binder characteristics and grade. Generally, the compaction temperature is the temperature at which the binder viscosity is 200 mPa.sec. [16,17].

Figure 3: *LCPC French Roller Apparatus*

Compaction procedure depends on the specimen size and whether limiting compaction energy or limiting final bulk density is specified. If compaction energy is specified, compaction procedures are broken down into one of two compaction energy levels; light compaction for large and small slabs, and heavy compaction for large and small slabs. For each energy level, compaction of the specimen is carried out over three zones (Figure 4) covering the width of the slab following a detailed sweep plan. Sweep plans for both light and heavy compaction can be found in the standards. In order to stabilize the specimen, each compaction zone is subjected to a pre-compaction regime of two wheel passes with low tire pressure (0.1 MPa) and low wheel load (1 kN). In the pre-compaction, the apparatus is set to blocked axis mode where vertical motion of the tire is prohibited, hence not allowing the tire to compact the mix past the surrounding mold frame [16,17].

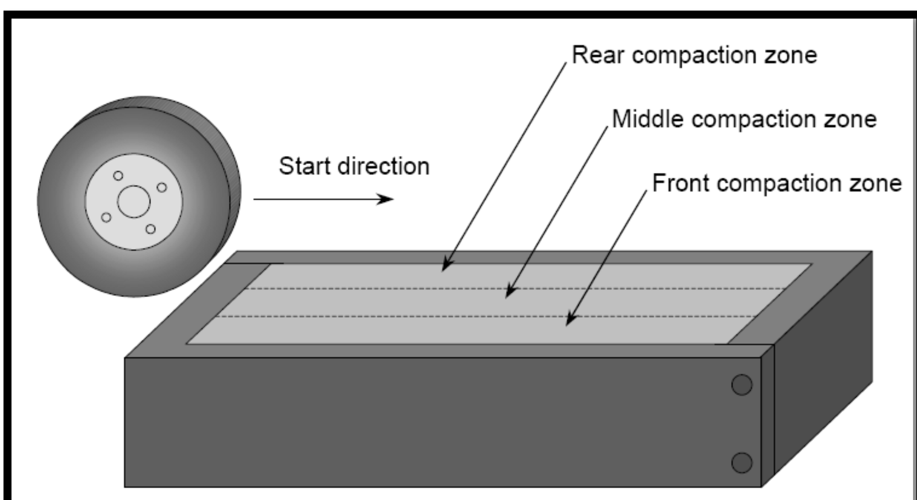

Figure 4: ***Roller Compaction Zones***

Effective compaction is carried out in the freed axis mode, allowing the tire to move vertically, horizontally and transversally. Sweep plans follow an organized step procedure; the compaction tire always starts in the front compaction zone, moves to the rear compaction zone, and finishes with the middle zone. Before each compaction step, the compaction mold is raised so the top of the specimen is just above the mold frame. After the effective compaction has concluded, the specimen is subjected to a leveling, blocked axis procedure consisting of two wheel passes over each zone using 0.6 MPa tire pressure and a wheel load of 5 kN [16,17] Start to finish, the compaction procedure takes 20 to 25 minutes to complete. The slabs are then left to cool at room temperature before removing the mold with a light taps from a hammer. [18].

Compaction of specimens to a specific voids content, or bulk density, requires a modification of the compaction procedure. The user is to choose a compaction regime which gives specimens that are just above the desired void content, and then increase the number of passes until the specified density is reached. The sweep plane must remain even in order to ensure even compaction, and a smooth surface. At the end of compaction, the user must report the testing procedure [16,17].

2.3.3 Engineering Principles of the French Roller Compactor

The purpose of rolling wheel compaction is to create samples that are representative of samples compacted by pneumatic roller compactors in the field. The French Roller compacts a specimen in three distinct wheel paths, creating a kneading action between the aggregates in the sample, similar to the kneading action imparted on aggregates in the field by pneumatic rollers. The kneading action allows coarse aggregates to realign and orient themselves similar to what occurs during field compaction. However, unlike the California Kneading Compactor and the Super PAVE Gyratory Compactor, the French Roller does not incorporate a static leveling load; rather it uses a pre-compaction regime of wheel passes at diminished load. Static leveling may increase particle contact by crushing aggregates together [19]. In addition, the specimen can be compacted in layers of realistic thickness, producing a sample that is dimensionally representative to those taken from the field. The mold can also accommodate larger aggregate sizes, compared to the Marshall hammer, again allowing a mix design more closely related to the field [17,20].

Unfortunately, because of the specimen size and geometry limitations, the compaction at the start and end of the wheel path is not homogenous. When testing samples cut from roller compacted specimens, heterogeneity among front, middle and rear compacted zones may be realized [17].

2.3.4 Current Usage and Distribution

Although appealing due to its likeness with field compaction processes, laboratory usage of the French Roller and other similar rolling wheel compactors is very low for a number of reasons. Most laboratory rolling wheel compactors are comparatively large, not portable, and very expensive. Difficulties controlling air voids in compacted specimens has also been widely recognized. Moreover, compaction procedures are difficult to follow and very time consuming. Mixtures for compaction must also be prepared in comparatively large quantities, adding to the cost of laboratory usage [19].

In the US, Super PAVE mixture design is the most accepted standard for laboratory compaction; consequently rolling wheel compactors see very little practical usage. In parts of Europe however, rolling wheel compactors remain popular due to their similarity to field compaction procedures.

2.4 German Sector Compactor

2.4.1 History of the German Sector Compactor

The German Sector Compactor was conceptually developed in response to a research project funded by the Ministry of Transport at the Institute for Road Building in the Technical University of Braunschweig in the early 1990's. The aim of the project was to support the notion that the mechanical characteristics of an asphalt mixture can be heavily influenced by the type of compaction in the laboratory, an idea conceived at the end of the 1970's at the University [21].

The result of the research project was a laboratory compactor that could produce asphalt slabs with tolerable mechanical properties for practical application in the field. The compactor would utilize a steel roller sector to compact samples within a heat chamber, using path-controlled pre compacting, and power-controlled main compacting features [21].

2.4.2 Standard Procedure for the German Sector Compactor

Sample preparation and compaction using the German Sector Compactor follows European Standard EN 12697-33: Test Methods for Hot Mix Asphalt: Specimen Prepared by Roller Compactor and similar applicable German standards. According to the standard, rolled sector compaction follows three steps:

(1) Preparation of the Bituminous Mixture
(2) Filling the Mold
(3) Specimen Compaction

Preparation of the mixture follows EN 12697-35, while a numerical equation to determine total mass of the bituminous mixture as a function of maximum density of the mixture, dimensions of the mold, and the voids content is provided in the compaction standard as a reference. The compaction device (roller sector, mold and bottom steel plate) is pre-heated to a predetermined temperature and a soapy solution or non-stick film is placed on the roller prior to compaction [16].

The compaction apparatus, seen in Figure 5, utilizes a steel roller arc that is the sector of a circle of radius up to 550 mm, usually 500 mm or 550 mm, to impart a calculated downward force, or rolling force, on an asphalt slab in order to achieve a specified sample density. The rolling force can range from 0 kN to 30 kN. The magnitude of the downward force imparted on the sample is calculated so that the specified volume or void content of the final compacted sample is reached at a number of roller passes between 10 and 50. One roller pass is defined as the one way movement of the steel roller. A frequency controlled motor shifts the mold left to right during the compaction process and compaction is done in a smooth continuous motion without interruption. Compaction temperature is again binder dependent, with a typical compaction temperature of 135 ± 5 C [16].

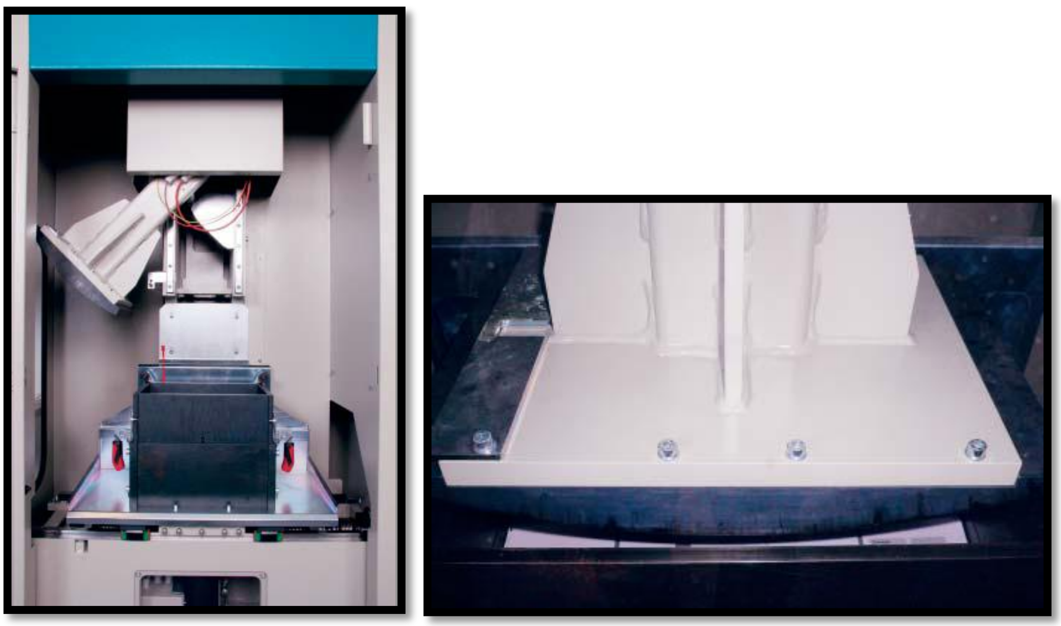

Figure 5: *Left: German Sector Compactor before use. Right: Sector compactor during use*

Compaction of samples by sector roller can be accomplished by either compaction by a specified energy, compaction with a controlled compaction energy, or compaction to obtain specified voids content and compaction degree. Each compaction method follows a detailed pre-compaction and main compaction procedure where deflection or force in controlled, respectively. A typical compaction regime according to German standards is detailed below [21]:

- Pre Compaction – Deflection Controlled

  When the roller segment reaches the edge of the compaction mold, the load is stopped for 0.5 sec.

(1) Reducing the height of roller sector by 0.5 mm per cycle until a force of 0.1 kN/cm slab width (for 26 cm wide moulds: 2.6 kN) is reached.
(2) Holding the height constant for 5 passes
(3) Lifting of roller sector by 0.5 mm per pass until the force is reduced to 0 kN

- Main Compaction – Force Controlled

  When the roller segment reaches the edge of the compaction mold, the load is stopped for 1 sec.

  (1) 15 Cycles with applying a constant load of 0.02 kN/cm slab width (for 26 cm wide moulds: 0.52 kN)
  (2) 15 cycles with increasing the load by 0.05 kN/cm slab width (for 26 cm wide moulds: 1.27 kN) per cycle until a maximum force of 0.75 kN/cm slab width (for 26 cm wide moulds: 19.5 kN) are reached
  (3) 15 cycles with reducing the load by 0.05 kN/cm slab width (for 26 cm wide moulds: 1.3 kN) per cycle until force is reduced

  - Compaction procedure courtesy of the Technical University at Braunschweig - Pavement Engineering Center

After the compaction procedure has concluded, the asphalt specimen is de-molded via hydraulic jack or light hammer, and placed on a steel plate at room temperature. A compacted asphalt slab is shown in Figure 6.The asphalt slab can be cut for beam testing, or mechanically tested as a whole [21].

Figure 6: *Specimen after Compaction*

2.4.3 Engineering Principles of the German Sector Compactor

The German Sector Compactor was developed as a means to provide samples with comparable mechanical characteristics to those in the field. The compactor utilizes a steel arc to impart a kneading action and downward force to the specimen, intuitively appealing considering common field compaction methods. The German Sector Compactor was designed to simulate field compaction in both pre-compaction and actual compaction. The pre-compaction is way-controlled, and simulates the pre-compaction effect of the pressure bar on the paver screed and the tamper. The actual compaction effort is force controlled, and simulates the effective compaction by roller compactors in the field [21]. The sample does not experience any impact loading during compaction and much like the French Roller Compactor, the German Sector does not impart a static leveling load at the onset on the compaction regime. Static loads during leveling (pre-compaction) can crush aggregates together, orientating them in a way that differs from field samples [19].

2.4.4 Current Usage and Distribution

Laboratory usage of the German Sector Roller and the like is very limited. The German Sector Roller is a large, costly machine that is not easily transported. With the acceptance of the Super PAVE system within the U.S., the usage of the Sector Roller is primarily limited to laboratory testing, with very little practical design usage aside from comparative testing. Also limiting the usage and understanding of the German Sector Roller is the lack of available information regarding the roller and compaction procedure in English.

2.5 Super PAVE Gyratory Compactor

2.5.1 History of Gyratory Compaction

In the late 1980’s, in an effort to combat the deteriorating highway infrastructure within the United States, congress authorized the Strategic Highway Research Program (SHRP). The SHRP was a five year, applied research initiative, aimed at providing insight and developing techniques and new technologies to improve roadway performance. A major concern within the SHRP was developing a laboratory compaction method that could compact specimens in the laboratory to densities realized under field pavement loading conditions. The SHRP identified two major goals in the development of the compaction device: capability of measuring compatibility in order to identify potential tender mix and compaction problem behavior, and adequate portability of the device for quality control purposes. Building on the technologies of the three prevalent gyratory compactors in use at the time, the Texas Gyratory Compactor, French Gyratory Compactor, and the Army Corps of Engineers Gyratory Compactor, the SHRP developed the Super PAVE gyratory compactor. Development of gyratory compaction as a principle was an iterative process utilizing properties of each gyratory compaction method. Alongside the Super PAVE Gyratory compactor, Australia also developed a version of gyratory compaction worth noting [22,23].

2.5.1.1 Texas Gyratory Compactor

Gyratory compaction as a procedure was developed in the late 1930's by the Texas Department of Transportation. Specimens are placed in a 4 inch diameter cylindrical mold, and then the mold is placed between two parallel plates. The parallel plates are spaced one half inch further apart than the sample height. The extra one half inch allows the mold to be tilted to an angle of approximately 6 degrees. A pressure of 50 psi is applied to the specimen through a hydraulic jack, and the mold is tilted to the compaction angle. The mold is then gyrated three times, with the vertical pressure changing with each gyration. Generally, the pressure will first increase with the application of the compaction angle, then decrease with each subsequent gyration. Once the three gyrations are complete, the specimen is level, and the 50 psi load is re-applied and the process begins again. Sets of three gyrations continue until the vertical pressure increases to 150 psi with one stroke of the hydraulic jack. A level up load of 2500 psi is then applied to complete the compaction process. The Texas Gyratory Compactor offered several advantages over conventional laboratory compaction at the time. The compaction process was very simple, compared to the California Kneading Compactor, and offered the possibility of producing models using larger sized aggregate [15,22,23]. Laboratory comparisons, discussed in more detail in Section 3, confirmed the Texas Gyratory Compactor was more adequate in predicting field conditions.

2.5.1.2 Army Corps of Engineers Gyratory Compactor

Following the need for airfield pavements capable of withstanding substantial load during World War II, the US Army Corps of Engineers developed a gyratory testing apparatus to measure forces during the compaction process. More specifically, the USACE hypothesized that angle of compaction was related to permanent deformation in the field pavement, and the forces measured were related to shear strength in the mix. Building on the technologies of the Texas Gyratory Compactor, the USACE changed the method of how the compaction angle was applied. The USACE Compactor applies the compaction angle at two points across the diameter, as opposed to the Texas Gyratory Compactor which applied the angle at three points across the diameter. The advantage to using two points to hold the compaction angle constant is allowing the mold a degree of freedom to rotate and swivel about the diameter [15,22,23].

2.5.1.3 French (LCPC) Gyratory Compactor

The French Gyratory Compactor is a result of the French gyratory compaction protocol of the 1960's and 1970's. The gyratory protocol was implemented to research the gyratory mechanism in laboratory compaction; more specifically, research into the effects of aggregate gradation on densification curves, mineral fillers, and asphalt properties along the densification curve. The result of the studies was a laboratory mix design and compaction method that standardized the effort on the road, opposite of the Marshall design which standardizes the mix in the laboratory. The LCPC compactor utilizes a compaction angle of just one degree while a constant vertical pressure in maintained throughout the compaction process. The gyrations are applied at a steady rate of 6 gyrations per minute. The number of total gyrations is dependent on the asphalt lift thickness in the field; as the lift thickness increases, the number of gyrations also increases [15,22,23].

2.5.1.4 Australian Gyratory Compactor (Servopac Gyratory Compactor)

Developed in 1992 as an adaptation of the Super PAVE gyratory compactor Australia, the Australian Servopac Gyratory Compactor meets all Super PAVE gyratory specifications in terms of vertical pressure, compaction angle and specimen height monitoring while offering additional components for measuring shear stress in the mix during compaction. The compactor is servo-controlled to apply a static vertical pressure while supplying the gyratory motion, similar to the Super PAVE compactor. The device also offers the user the option of quickly adjusting the compaction parameters (force, angle) to obtain forces applied to the specimen, used in shear stress calculations [22].

2.5.2 Standard Procedure for Super PAVE Gyratory Compaction

Sample preparation and compaction using the Super PAVE Gyratory Compactor follows ASTM D 6925 – Standard Test Method for Preparation and Determination of the Relative Density of Hot Mix Asphalt by Means of the Super PAVE Gyratory Compactor. In general, specimens are prepared and compacted following one of two mixture methods depending on the ultimate testing of the sample. If the sample will be used for volumetric property analysis, the sample aggregate mix is adjusted to achieve a desired specimen height following a specified number of gyrations. If specimen air voids are to be controlled, the aggregate mix is adjusted to create a specified density in a known volume [24]. The number of gyrations depends on the design traffic loading for the specimen, more in Section 2.5.3.

The aggregate mixture and asphalt binder are heated to a mixing temperature range that will produce an un-aged binder kinematic viscosity of 170 ± 20 mm^2/sec. After conditioning the aggregate mix and asphalt binder at the required mixing temperature, mix the aggregates and asphalt binder to create a uniform distribution of asphalt binder within the mix. After mixing, the loose aggregate-asphalt mix is conditioned at the compaction temperature for two hours, stirring at one hour to maintain uniformity. The compaction temperature is defined as the temperature range that produces an un-aged binder kinematic viscosity of 280 ± 30 mm^2/sec. The compaction mold is also conditioned for no less than 45 minutes prior to the compaction process at the compaction temperature [24].

Following the conditioning period, the mold and mixture is removed from the oven, and the mixture is transferred to the compaction mold. The mold is then loaded into the compaction apparatus, shown in Figure 7. Once loaded into the compactor, the apparatus will apply the required vertical pressure and angle of gyration and begin compacting. In general, the compactor operates with a constant vertical pressure of 600 kPa, and with an angle of gyration of 1.25 degrees at a gyration rate of 30 rpm. The top and bottom platens of the mold remain parallel throughout the compaction process; hence the angle of gyration revolves around the sample. Height of the specimen is automatically recorded with each gyration, allowing density calculations to be carried out at each height, given mass of the sample.   Specimens are either compacted to a specified number of gyrations, or compacted to a specified height for determination of volumetric or physical properties, respectively [24].

Figure 7: *Super PAVE Gyratory Compactor Apparatus*

After the compaction process has completed, samples are allowed to cool at room temperature for subsequent testing for volumetric or physical properties.

2.5.3 Engineering Principles of Super PAVE Gyratory Compaction

The Super PAVE Gyratory Compactor was developed in response to the need for a portable, easy to use laboratory compactor that could compact specimens under the influence of both normal and shear stresses. The Super PAVE Gyratory Compactor utilizes several important design principles to achieve these goals.

2.5.3.1 Angle of Gyration

The Super PAVE Gyratory Compactor utilizes an angle of gyration of 1.25 degrees to compact laboratory specimens. The use of a constant vertical pressure, constant angle of gyration compaction regime allows the formulation of compaction curves. Research into the densification curves created by both the Texas Gyratory Compactor and the French Gyratory Compactor provided insight into selecting an appropriate angle of gyration. The 5 degree angle utilized by the Texas Gyratory produced allowed for very rapid compaction of specimens, results in a compaction curve that is hard to accurately read. The 1 degree compaction angle utilized by the French Gyratory produced samples that exhibited inadequate density. Further “trial and error” research by the SHRP resulted in a compaction angle of 1.25 degrees [15,22,23].

Angling of the mold during the compaction process creates both normal and shear forces in the mixture. The gyratory movement of the compactor induces shear displacement in the mix. Using known equations, shear stresses in the mix can be approximated as a function of friction between aggregates, vertical pressure, specimen dimensions, and forces create the angle. These calculated shear stresses can then be compared to shear stresses experienced under field compaction techniques [22].

2.5.3.2 Vertical Pressure

A vertical pressure of approximately 600 kPa is imparted on the sample during compaction. The vertical pressure is an estimate to field loading conditions developed for use in the LCPC (French) Gyratory as an approximation to field compaction using static rollers. Further development of the compaction pressure was again based on an iterative approach as a function of shear stresses produced, compaction degree, and compaction time and mixture properties. Pressures exceeding 600 kPa tend to compact specimens too fast, and vice versa, leading to a problem similar to the gyration angle determination [15,22].

2.5.3.3 Rate of Gyration

The rate of gyration currently specified for use in the Super PAVE Gyratory is 30 rpm. Studies into the gyration rate, angle of gyration, and vertical pressure conducted by the SHRP in the development phase of the compactor indicated that booth vertical pressure and speed of gyration proved to have little effect of the final density. However, a constant rate of gyration is important to allow the angle to revolve while the top and bottom platens remain parallel, creating a kneading effect in the mix [15].

2.5.3.4 Design Number of Gyrations

The number of gyrations used in compaction with the Super PAVE Gyratory Compactor is determined primarily by the design traffic level. Equivalent single axle loads (ESALs) are used to determine three compaction levels in the compaction process. The numbers of gyrations to produce each compaction level are labeled as N-initial abbreviated as N_{ini}, N-Design abbreviated as N_{Des}, and N-Maximum abbreviated as N_{Max} [15,25]. Figure 8 demonstrates the relationship between traffic and gyration number.

TABLE 1 Superpave Design Gyratory Compactive Effort

Design ESALs, (Millions)	Compaction Parameters		
	N_{ini}	N_{des}	N_{max}
< 0.3	6	50	75
0.3 to< 3	7	75	115
3 to< 30	8	100	160
^{3} 30	9	125	205

NOTE—ESALs are based on 20 year design life regardless of actual design life.

Figure 8: *Gyratory Compactive Effort from ASTM Standard*

In volumetric mix design, the asphalt content is selected to produce a specimen with 4-percent air voids at N_{Des}. Four percent air voids represents the density of a mix in the field during the service life of the pavement. N_{Ini} is also selected based on traffic level and climate and primarily serves to avoid tender mixes and rutting. At N_{ini} , the specimen should have at least 11-percent air voids, representative of air void content just after construction and compaction. N_{Max} is selected to represent the air void content in the mixture at the terminal life of the design pavement. The air voids in the mixture at N_{Max} are to be less than 2-percent. Generally, multiple mixes are designed in attempt to capture the optimum asphalt content; the asphalt content that satisfies the density requirements at each design gyration number [15,25].

2.5.3.5 Specimen Size

Specimens compacted by the Super PAVE Gyratory Compactor have a diameter of 150 mm and a sample height of approximately 115 mm (specimens can be compacted to a predetermined height) [24]. The sample size is considerably larger than that of the samples produced by either the Marshall Hammer or the California Kneading Compactor, see Figure 9. The larger sample size allows users to compact samples using larger maximum aggregate size and differing mix designs, better approximating field samples.

Figure 9: *Gyratory specimen shown on left, California Kneading Compactor specimen on right.*

2.5.4 Current Usage and Distribution

As of late 2001, 48 states have implemented the Super PAVE binder specifications, and as of late 2002, 46 states have or will implement the Super PAVE mix design method, including compaction using the gyratory compactor.

3. Laboratory Comparison

The Army Corps of Engineers specifies that compaction of hot mix asphalt can be significantly affected by materials in the mixture, ambient conditions during construction, and compaction method. The goal of any laboratory compaction method is to produce a realistic test specimen for testing that will approximate field conditions. Accordingly, methods of compaction must be evaluated against each other, and against field specimens to determine the appropriateness of usage of any laboratory compaction method.

3.1 Comparison Studies

Specimen internal structure, indentified by void distribution, aggregate orientation, and aggregate contacts, is directly related to the mechanical properties of said specimen. Different laboratory, as well as field, compaction methods will produce specimens with different internal structures, and hence, mechanical properties. Adequacy of any one laboratory compaction method in approximating filed conditions requires a mechanical comparison, via internal structure of each compaction method. Several authors have conducted laboratory experiments investigating the comparison of laboratory compaction methods.

Consuegra et al. (1989)

The objective of this laboratory study was to evaluate the ability of laboratory compaction methods to simulate field cores, more specifically, the ability to represent the mechanical properties of field samples. Engineering properties tested in this study were resilient modulus, indirect tensile strength and strain at failure, and tensile creep. The study included five laboratory compaction methods, (1) mobile steel wheel simulator, (2) Texas Gyratory Compactor, (3) California Kneading Compactor, (4) Marshall Impact Hammer, and (5) Arizona Kneading Compactor compared at five project locations throughout the U.S. Field compaction was done to state standard specification for each project location. The study used average absolute difference and mean squared error (MSE) between laboratory compacted specimen properties and field specimen properties to evaluate differences between methods. Figures 10 and 11 demonstrate the results of the study.

Compaction Device	Creep Compliance at 77°F	Indirect Tensile Strength	Tensile Strain at Failure	Resilient Modulus
Arizona Compactor	0.77	0.51	0.47	0.41
Marshall Hammer	0.80	0.35	0.45	0.55
California Kneading	0.59	0.21	0.27	0.42
Steel Wheel Simulator	0.51	0.31	0.11	0.26
Texas Gyratory Shear Compactor	0.44	0.14	0.16	0.37

Note: A zero difference indicates that the laboratory specimens had identical properties of the cores (no difference).

Figure 10: *Average Absolute Difference between Compaction Methods and Field Cores*

Laboratory Compaction Method	Average MSE Rankings by Mixture		
	Project	Property	Temperature
Arizona Compactor	5.0	4.8	4.7
California Kneading	2.0	2.0	2.0
Marshall Hammer	4.0	3.5	3.3
Mobile Steel Wheel	1.7	2.8	2.0
Texas Gyratory	2.0	1.5	1.3

Figure 11: *MSE between Compaction Methods and Field Cores*

From the results obtained, the Texas Gyratory Compactor produced specimens with properties most closely related to field samples, in terms of lowest absolute difference and lowest MSE. The California Kneading Compactor ranked second in ability to approximate field cores. Interestingly, the Marshall Hammer provided the worst approximation of field cores in this study.

Sousa et al. (1991)

The primary objective of this study was to evaluate the effect of compaction method on engineering properties of HMA. This study recognized the need for laboratory compacted specimens to represent the service conditions of HMA pavement, in terms of on-site mixing, placement, and compaction. Three compaction methods were tested for permanent deformation and fatigue properties and compared to field cores. The three compaction methods tested were (a) Texas Gyratory Compactor, (2) California Kneading Compactor, and (3) rolling wheel compactor. The primary test results determined that specimens produced via kneading compaction were most resistant to permanent deformation, but were most sensitive to aggregate characteristics, while specimens produced by rolling wheel exhibited less resistance to permanent deformation, and were most sensitive to asphalt characteristics. The California Kneading Compactor produced specimens with the most aggregate contact, providing insight into the permanent deformation resistance. Gyratory specimens exhibited the most resistance to fatigue, while the California Kneading Compactor exhibited the least resistance of the methods tested.

Button et al. (1994)

This study investigated the ability of four laboratory compaction methods to simulate field compaction. The four laboratory methods used were (a) Exxon Rolling Wheel Compactor, (b) Texas Gyratory Compactor, (c) Rotating Base Hammer, and (d) Linear Kneading Compactor. Field cores were taken from five sites, and laboratory specimens were produced to match field aggregate gradation and binder characteristics. Evaluation of the laboratory specimens was conducted via indirect tension, resilient modulus, Marshall and Hveem Stability, and compressive creep. Testing results for laboratory and field specimens were compared and a percentage was assigned to each compaction method. The percentage represented the number of samples that closely represented field cores divided by the total number of samples. The results indicated that the Texas Gyratory Compactor most similarly represented field cores (73-percent), followed by the rolling wheel and linear kneading (both at 64-percent).

Khan et al. (1998)

The purpose of this study was to evaluate five laboratory compaction methods based on their ability to represent field samples. The five methods evaluated were (a) Marshall Automatic Impact Hammer, (b) Marshall Manual Impact Hammer, (c) California Kneading Compactor, (d) Gyratory with angle of gyration 1.25 degrees, and (e) Gyratory with angle of gyration 6 degrees. Four filed locations were selected to compare samples. Used in comparison of the laboratory specimens were resilient modulus, air voids, bulk density, and static creep. Shown in Figure 12 is the comparison using just modulus of resilience.

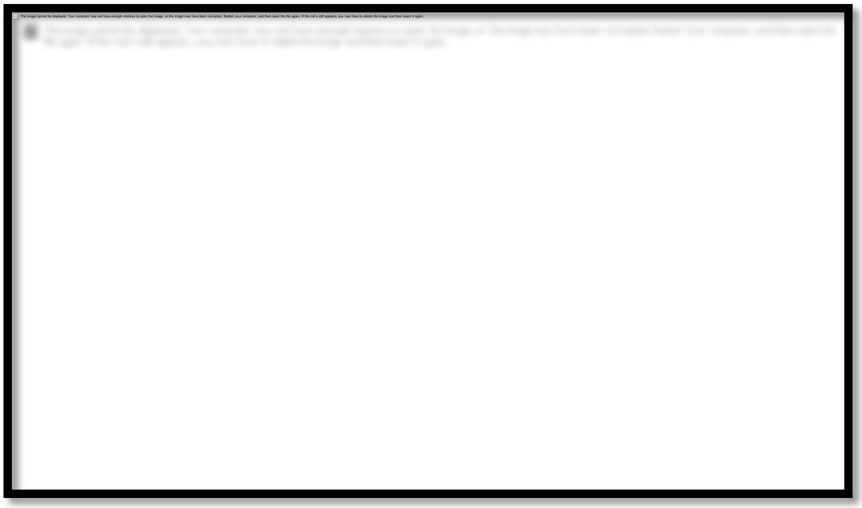

Figure 12: *Resilient Modulus of Samples Compacted with Select Compaction Methods*

In general, it was found that specimens compacted with the Gyratory Compactor with gyration angle 1.25 degrees most similarly represented field cores. This suggests that the Super PAVE gyratory compactor is most suitable for predicting field pavement behavior based on ability to simulate field cores and ease of operation. However, stability of cores compacted with the 1.25 degree Gyratory was below that of the Marshall and Kneading compactors. The Marshall Hammer again did the poorest job simulating field cores.

Renken (2000)

The purpose of this study was to demonstrate the effectiveness of the German Roller Sector Compactor in simulating field cores based on mechanical properties and comparison with other compaction methods. The study used Marshall specimens, gyratory specimens, Lamella Compactor Specimens (sliding plates move the sample right and left while a roller compacts the specimen), and German Sector Roller specimens to compare static and dynamic creep, tensile strength test , dynamic tensile test, and cooling down test results with field cores. Renken discovered that the German Sector Roller produced specimens with nearly the same mechanical characteristics as field samples. The German Sector produced specimens that considerably outperformed Marshall specimens as well as gyratory specimens. Due to their “practice-adequate” properties, the German Sector specimens were also found to be superior to Lamella Compacted specimens.

Jönsson et al. (2002)

The purpose of this study was to compare compaction methods using X-ray computer tomography in order to optimize compaction processes. Three compaction methods were studied and compared based on their homogeneity and isotropy during compaction, LCPC Rolling Wheel Compaction, Gyratory Compaction, and Marshall Compaction. Three primary conclusions resulted from this study. First, when compared to Marshall specimens, Gyratory specimens were less evenly compacted near the platens, suggesting the kneading process just below or above the plate is not effective. Second, the rolling wheel compactor experienced significant shoving in the early stages of compaction when compared to the other compaction methods. Most importantly, this study demonstrated that none of the compaction methods could create homogenous samples capable of representing field cores adequately. Compaction method must be refined further.

Peterson et al. (2004)

This study measured and compared the mechanical properties of asphalt mixtures based on varying the control parameters of the Super PAVE Gyratory Compactor. The parameters studied were angle of gyration, specimen height, compaction pressure, and temperature of mold and base plates. The gyratory specimens were then compared to field specimens from three areas that used different field compaction procedures. The resulting conclusion was that an angle of gyration of near 1.5 degrees and a specimen height of 50-75 mm would best represent the mechanical properties of field cores. Similar results can be obtained at a 1.25-degree angle of gyration using a 400 kPa vertical pressure. The results confirmed that angle of gyration, specimen height, compaction pressure, and temperature of mold and base plates are the primary variables affecting mechanical properties of Super PAVE Gyratory specimens.

4. Summary

Laboratory compaction of asphalt mixtures is an obligatory process in pavement design. Laboratory compacted specimens are used for volumetric and mechanical testing in order to predict field mixture behavior. Accordingly, laboratory compacted specimens must exhibit comparable properties and characteristics with field data. Many compaction methods exist and are used in laboratory practice today, each producing specimens used for mechanical and volumetric testing. Five compaction methods were outlined and compared: (a) Marshall Impact Hammer, (2) California Kneading Compactor, (3) French Roller, (4) German Sector Compactor, and (5) Super PAVE Gyratory Compactor in order to outline not only the concepts behind their usage, but their likeness to field specimens. Several important conclusions can be drawn from the caparison:

- Method and degree of compaction affect the mechanical and volumetric properties of samples.
- Compaction that included a kneading action in the mixture provided specimen properties closest to field data.
- Gyratory compaction more closely simulates field mixtures than does impact or kneading compaction alone.
- Roller compaction is capable of producing specimens similar to field cores, and in some cases, more so than gyratory compaction.
- Ease of apparatus use, cost, and portability of a compaction method all factor into the feasibility of usage of a particular method.

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(1) Image Capturing and Analysis Related to Internal structure
   a. Digital Imaging & X-Ray Tomography
   b. Air Void Distribution (effect of compaction method)
   c. Aggregate Orientation (angle of inclination and vector magnitude)
   d. Aggregate Contacts
   e. Aggregate Segregation

(2) Effect of Compaction Methods on Mechanical Properties of Asphalt Mixtures: Consuefra ety al. (1989), Sousa et al. (1991), Harvey and Monismisth (1993), Button et al. (1994), Peterson et al. (2004), European Synthesis report, and Masad et al. (2009)

(3) Effect of Compaction Methods on Air Void Distribution Using Image Analysis Techniques: Masad et al. (1999a), Masad et al. (1999b), Shashidhar (1999), Tashman et al. (2001), Partl et al. (2003 and 2007), and Masad et al. (2009)

(4) Imaging Standard (prepared by M. Emin Kutay, Enad Mahmoud, and Husain Bahia)

Standard Method for

Determining Aggregate Structure in Asphalt Mixes by Means of Planar Imaging

Designation: xx-xx

Standard Method for

Determining Aggregate Structure in Asphalt Mixes by Means of Planar Imaging

Designation: xx-xx

1. SCOPE

1.1. *This standard covers the measurement of aggregate structure indicators of asphalt mixes using digital image analysis techniques.*

1.2. *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. REFERENCED DOCUMENTS

2.1. AASHTO Standards*:*

- M043 Standard Specification for Standard Sizes of Coarse Aggregate for Highway Construction
- M092 Standard Specification for Wire-Cloth Sieves for Testing Purposes
- M231 Weighing Devices Used in the Testing of Materials
- M283 Standard Specification for Coarse Aggregate for Highway & Airport Construction
- R35 Standard Practice for Superpave Volumetric Design for Hot-Mix Asphalt (HMA)
- T11 Amount of Material Finer Than 75µm in Aggregate
- T19 Standard Method of Test for Bulk Density ("Unit Weight") and Voids in Aggregate,
- T2 Sampling of Aggregates
- T248 Standard Method of Test for Reducing Samples of Aggregate to Testing Size
- T27 Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates
- T84 Standard Method of Test for Specific Gravity and Absorption of Fine Aggregate
- T85 Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate

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3. TERMINOLOGY

3.1. *Aggregate size: Sieve size in which material is retained*

3.2. *Aggregate Gradation: Weight-based aggregate particle size distribution.*

3.3. *Image Resolution: The side length of each square pixel of an image. It is denoted as mm/pixels or inches/pixels.*

3.4. *Mix Volumetrics: The volumetric properties of asphalt mixtures including the air void content, binder content, specific gravity of aggregates and asphalt binder.*

3.5. *Median Filter: It is a non-linear digital image filtering technique, often used to remove noise from images or other signals. The procedure involves (1) storing the neighboring pixels in an array, (2) sorting the array in numerical order and (3) picking the median from the sorted array and replace the pixel value with this median value.*

3.6. *H_{max} Filter: It is a non-linear digital image filtering technique that is used to suppress all the maxima in an image whose height is less than a selected threshold value.*

3.7. *Threshold: A grayscale value that is used to convert a grayscale image to a binary (black and white) image. All pixels in the input image with luminance greater than the "Threshold" is replaced with the value 1 (white) and all other pixels are replaced with the value 0 (black).*

3.8. *Contact Point: The location of contact between two aggregates. When the distance between the surfaces of two different aggregates is smaller than a pre-selected threshold value, the aggregates are assumed to be in contact.*

3.9. *Aggregate Particle Orientation: The angle of the principal axis of an aggregate from the horizontal axis as well as an radial axis that starts from the center of a circular image.*

3.10. *Aggregate Particle Segregation: Spatial distribution of different sized aggregates in horizontal and radial directions.*

4. SIGNIFICANCE AND USE

4.1. *This standard is used to characterize the internal structure properties for aggregate within asphalt mixes. The internal structure properties include: Contact Points, Aggregate Orientation, and Aggregate Segregation.*

4.2. *The internal structure properties of aggregates are essential for evaluating different compaction and construction methods.*

4.3. *Aggregate structure properties can be related to the mechanical properties of hot mix asphalt, and thus it can be used to predict it.*

4.4. *The method in this standard can be used as a quality control measure for compaction and construction methods.*

4.5. *This test method may be used to characterize the aggregate internal structure properties of asphalt mixes samples of circular and rectangular shape of any size.*

5. APPARATUS

5.1. Digital Image Acquisition System—*A computer controlled instrument for capturing digital images at variable resolutions:*

5.1.1. Digital flatbed scanner with a minimum resolution of 600 dpi

5.1.2. X-Ray Computed Tomography (CT)

5.2. Digital Image Analysis System—*Analysis software that include algorithms for calculating Aggregate Orientation, Contact Points, and Aggregate Segregation from the digital images of the asphalt mixtures.*

5.3. Miscellaneous— *Equipment to perform sample preparation.*

5.3.1. For Digital Scanner Images: Circular saw with water shower to obtain flat planes to capture images.

5.3.2. For X-Ray CT Images: One 5-gal bucket of clean dry cement to be used for wedge calibration before X-Ray CT scanning.

6. HAZARDS

6.1. *Use standard safety precautions and protective clothing when handling materials and preparing material samples.*

7. STANDARDIZATION

7.1. *Verify the analysis software by using Figures B1 and B2 in Appendix B, and checking the output with the true values shown in the Figures.*

8. PREPARATION OF APPARATUS

8.1. *Digital Scanner:*

8.1.1. Confirm the machine operation settings are correct for the analysis to be performed.
8.1.2. Clean the scanner surface.

8.2. *X-Ray CT:*

8.2.1. Follow the calibration steps given by the manufacturer's instructions. Special care should be taken on the material used in the Wedge calibration. For asphalt mixtures, clean dry cement is recommended for Wedge calibration.

9. SAMPLE PREPARATION

9.1. *Digital Scanner:*

9.1.1. The sample is characterized by processing a 2-D image of its internal structure.
9.1.2. A laboratory compacted or field cored samples both can be used.
9.1.3. A horizontal and/or vertical cut of the sample is obtained by means of saw cutting.
9.1.4. Flatness of the surface should be checked before capturing the image

9.2. *X-Ray CT:*

9.2.1. Surrounding the specimens with the wedge material used during calibration may increase the quality of the X-ray CT image.

10. IMAGE CAPTURING

10.1. *Digital Scanner:*

10.1.1. Position the saw cut surface of the sample against the scanner.
10.1.2. Select appropriate resolution.
10.1.3. Start the scanning process.

10.2. *X-Ray CT:*

10.2.1. Follow the manufacturer's instructions.

11. IMAGE PROCESSING AND ANALYSIS

11.1. *Using Equation B1 in Appendix B, calculate image resolution ($\Delta x = \Delta y$) by measuring the distance (in pixels) along a known dimension (e.g. diameter) in the image.*

11.2. *From the known Mix Volumetrics of the asphalt specimen, calculate the volumetric percentage of aggregates (P_{sv}) with respect to the total volume using Equation B2 in Appendix B.*

11.3. *Calculate the fraction of the coarse aggregates (CF) visible in the image with respect to the total volume of the aggregates.*

11.3.1. First, identify the minimum size of the aggregate (D_{min}) visible in the image. This is approximately 10-20 times the resolution of the image and can be obtained by visually examining the image and measuring the number of pixels along the longest axis of smallest aggregate clearly visible in the image.

11.3.2. Calculate Coarse Fraction (*CF*)*;* the fraction of the aggregates larger than D_{min} from the Mix Volumetrics (not from the image) using Equation B4 in Appendix B. Coarse Fraction (*CF*) is defined as the volume of the coarse aggregates (V_c) divided by the total volume of the aggregates (V_t).

11.4. *Calculate percent coarse aggregate (P_{sv}^{c}) using Equation B5 in Appendix B, which is defined as the volume of the coarse aggregates (V_c) divided by the total volume of the entire sample (V)*

11.5. *Apply digital image processing filters to the image*

11.5.1. Apply Median Filter to remove the random noise in the image (Figure 1b). The size of the median filter (S_{med}) should be selected based on the size of the image and is recommended to be $0.1\%*S_{im} < S_{med} < 1\% *S_{im}$, where $S_{im} = \min\{S_x, S_y\}$.The S_x and S_y are the size of the image in x- and y- directions, respectively.

11.5.2. Apply H_{max} Filter to eliminate the variation in pixel intensity of the aggregates so that they have uniform gray value (Figure 1c). H_{max} Filter allows this without changing the intensities of the darker (i.e. lower intensity) regions. Details of this image processing technique is given in Soille (1999). This step is very important for a successful watershed transformation.

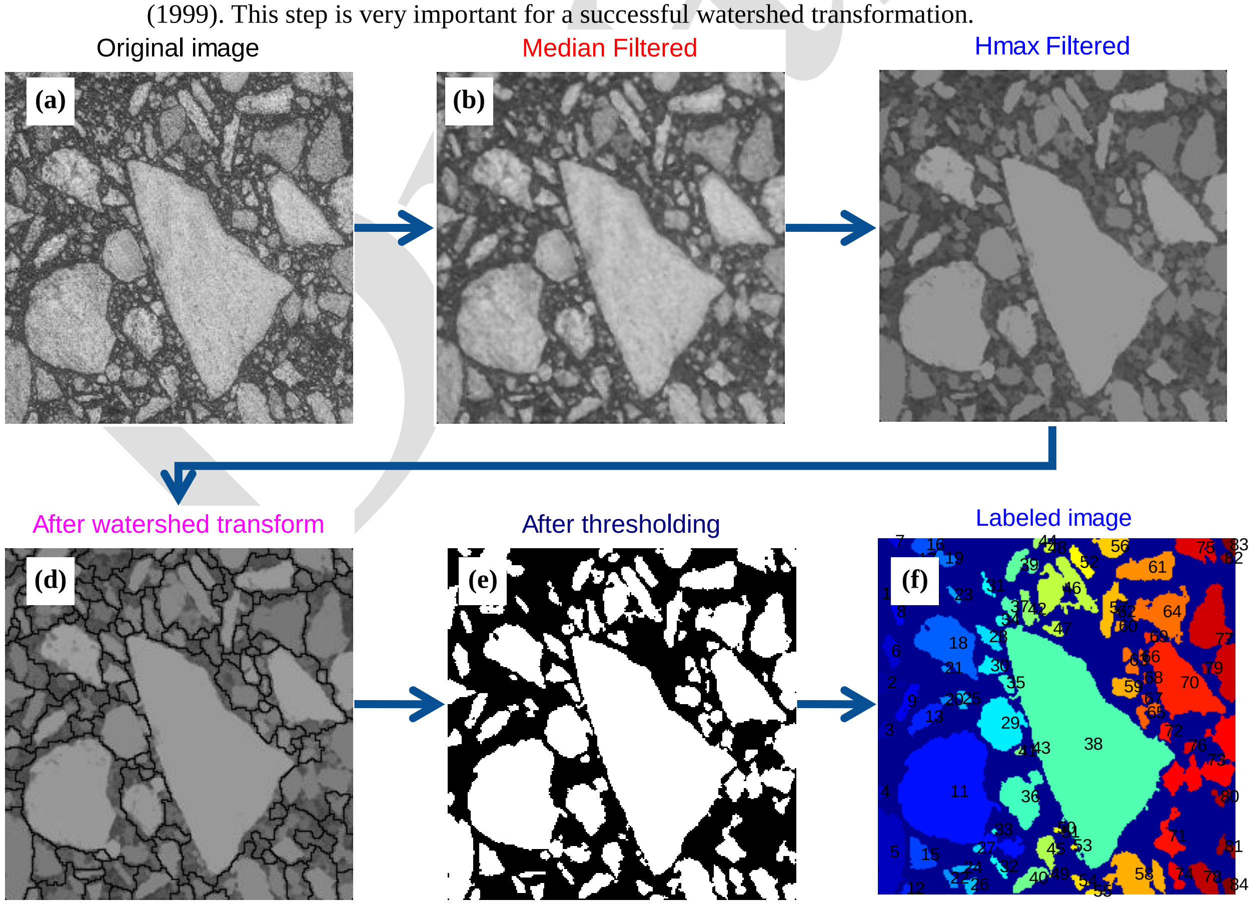


Figure 1. Illustration of steps of image processing filters.

11.5.3. Invert the image, i.e. subtract all the pixels from 255, and perform Watershed Transformation (Figure 1d) where the image is divided into unique watershed regions and their boundaries are determined (Meyer 1994).

11.5.4. Convert the image from grayscale to binary using a threshold value (Figure 1e).

11.5.5. Perform binary labeling operation to change the pixel intensities of islands of white pixels (aggregates) to unique integers (Figure 1f). This can be accomplished by using a connected components algorithm (Haralick and Shapiro 1992).

11.6. *Calculate the coarse aggregate fraction (P_{sv}^{im}) and gradation (PR_i^{im}) from the image.*

11.6.1. Calculate the following geometric properties of each labeled region in the labeled image: Area , Equivalent Diameter and Centroid, which are given in Appendix B Equations B6, B7 and B8, respectively.

11.6.2. Eliminate the labeled regions in the image with equivalent diameter less than the minimum aggregate size ($D_j^{eq} < D_{\min}$) calculated previously.

11.6.3. Calculate the total area of the coarse aggregates from the image (A_c) using Equation B10 in Appendix B. A_c corresponds to the total area aggregates larger than $D_{\min}$

11.6.4. Calculate the total area of all aggregates (A_t) including the aggregates not visible in the image using Equation B10 in Appendix B.

11.6.5. Calculate the percentage of aggregates retained in each sieve size (e.g., D_i = 2.36, 4.75, 9.5 mm…etc.) PR_i^{im} using Equation B11 in Appendix B.

11.6.6. Calculate percent coarse aggregate (P_{sv}^{im}) from the image using Equation B12 in Appendix B.

11.7. *Compare the P_{sv}^{im} value with P_{sv} as well as PR_i^{im} with PR_i . Repeat steps 11.5 and 11.6 until these values match. Once they are close enough, proceed calculations of contact points, orientation and segregation.*

12. CALCULATIONS

12.1. *Calculate contact points*

12.1.1. Contact points are calculated using the surface pixels of each aggregate. Surface pixels are isolated from the rest of the pixels using the following the rule: a pixel is part of the surface if it is non-zero and it is connected to at least one zero-valued pixel. Then, the minimum distance between the surfaces of neighbouring aggregates are calculated. If this distance is less than a pre-selected surface distance threshold (*SDT*) value, the aggregates are assumed to be in-contact. Figure 2 shows example contact points calculated for an aggregate.

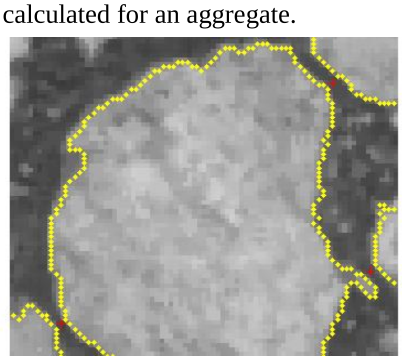


Figure 2. Illustration of contact points.

12.2. *Calculate aggregate orientation*

12.2.1. First step in computation of the orientation is the determination of the major principal axis (D_{max}) of an aggregate. The D_{max} is determined using Equation B13 in Appendix B

12.2.2. Calculate the angles from the horizontal axis (α) and from the radial axis (θ) using Equations B14 and B15 in the Appendix B, respectively. The angles α and θ are shown in Figure 3.

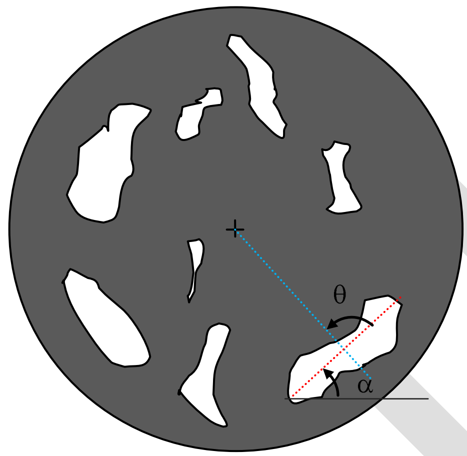


Figure 3. Illustration of orientation angles

12.2.3. Plot the histogram of the radial and horizontal angles as shown in Figure 4.

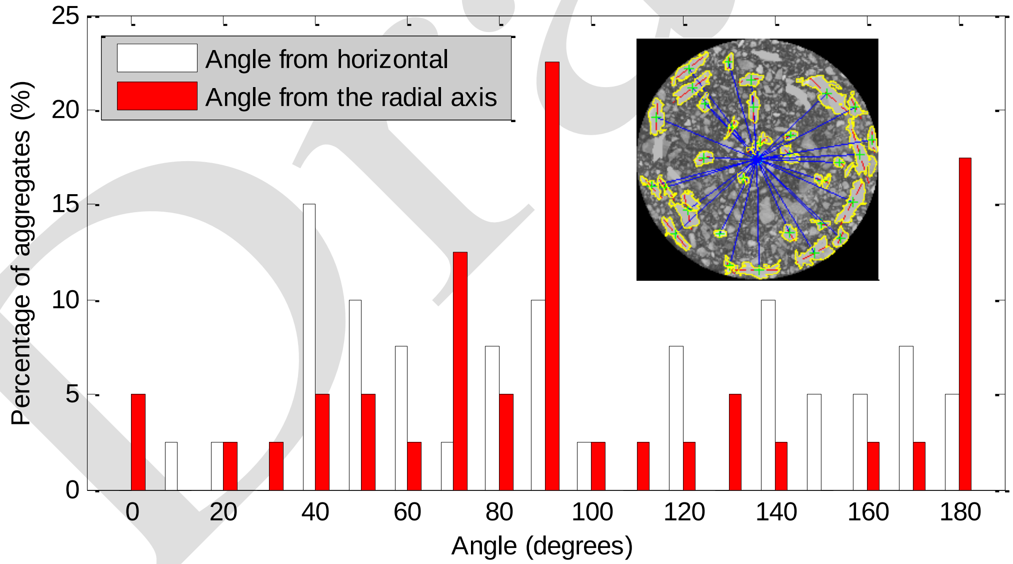


Figure 4. An example histogram of radial and horizontal angles computed for an asphalt specimen

12.3. *Calculate aggregate segregation*

12.3.1. Divide image into three radial groups as shown in Figure 5. These three regions (radially) are: Group 1 (aggregates within $R_{im}/3$ circle where $R_{im} = \min(S_x,S_y)/2$); Group 2 (aggregates in a ring shaped area between 2/3 R_{im} and 1/3 R_{im}) and Group 3 (aggregates in a ring shaped area between between R_{im} and 2/3 R_{im}).

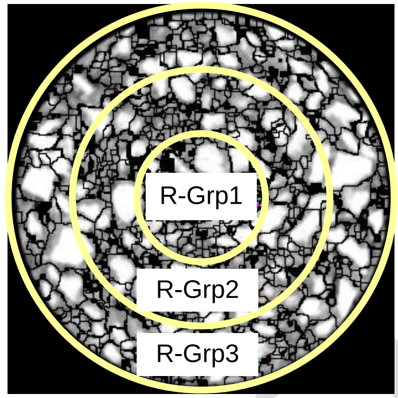


Figure 5. Illustration of radial segregation groups

12.3.2. Determine the aggregates whose centroids are within each group. Then plot the percentage of aggregates in each group for each aggregate size (i.e., the histogram). An example of such histogram is shown in Figure 6.

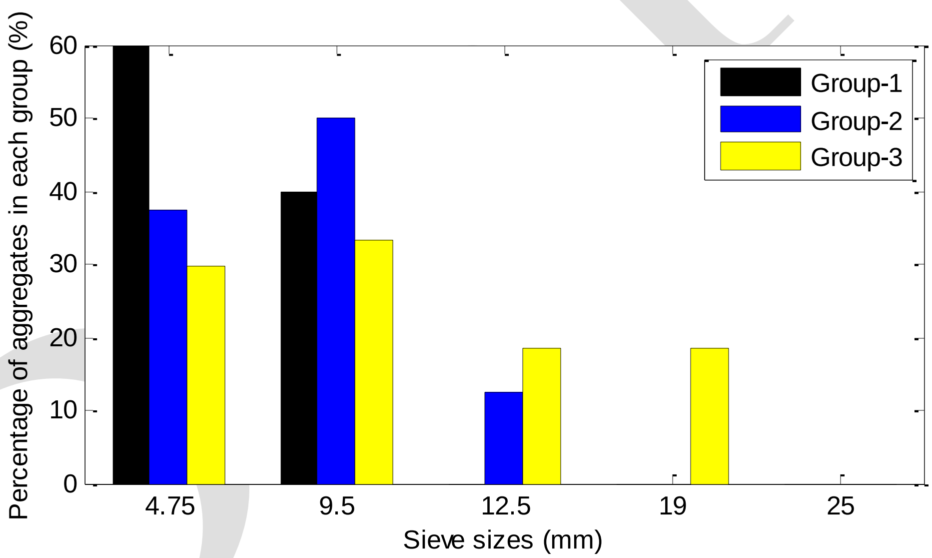


Figure 6. Example histogram of distribution of different aggregate sizes in each group.

13. REPORT

13.1. *Report the following information:*

13.1.1. Project name: ____________________

13.1.2. Date of the analysis: ____________________

13.1.3. Asphalt mix identification: ____

13.1.4. Resolution of the original image: ___________________

13.1.5. Final image processing/analysis filter values selected:

13.1.5.1. Median: ___________________

13.1.5.2. H_{max}: ___________________

13.1.5.3. Threshold: ___________________

13.1.5.4. Minimum aggregate size (mm): __________________

13.1.6. Analyzed by: __________________

13.2. *CONTACT POINTS*

13.2.1. Surface Distance Threshold (SDT): __________________

13.2.2. Minimum size of aggregate searched for contact: __________________

13.2.3. Number of contact points: __________________

13.3. *ORIENTATION*

13.3.1. Minimum size of aggregate where the orientation is calculated: __________________

13.3.2. Histogram of angles: **(FIGURE)**

13.4. *SEGREGATION*

13.4.1. The percentage of aggregates in each group for each aggregate size:

13.4.2. Histogram of sizes in each group: **(FIGURE)**

13.5. *A sample report format is presented in Appendix A*

14. PRECISION AND BIAS

14.1. Precision—*The research required to determine the precision of this procedure has not been completed.*

14.2. Bias—*The research required to determine the bias of this procedure has not been conducted.*

15. KEYWORDS

Aggregate; internal structure; asphalt mixes, gradation, orientation, contact points, segregation

ANALYSIS REPORT

2D IMAGE ANALYSIS OF ASPHALT MIXTURES FOR AGGREGATE CONTACT POINTS, SEGREGATION AND ORIENTATION

Project name: __UW-Warm Mix___

Date of the analysis: ___10/22/2009______

Asphalt mix identification: ____19mm Chippewa-600kPa-1.25__

Resolution of the original image: ___0.04 mm/pixel______

Final image processing/analysis filter values selected:

Median: ___5______________

H_{max}: ___40_____________

Threshold: ___95_____________

Minimum aggregate size (mm): ___4.75___________

Analyzed by: ___M. Emin Kutay, Ph.D., P.E._

RESULTS

CONTACT POINTS

Surface Distance Threshold (SDT): _____0.1 mm______

Minimum size of aggregate searched for contact: ______4.75 mm___

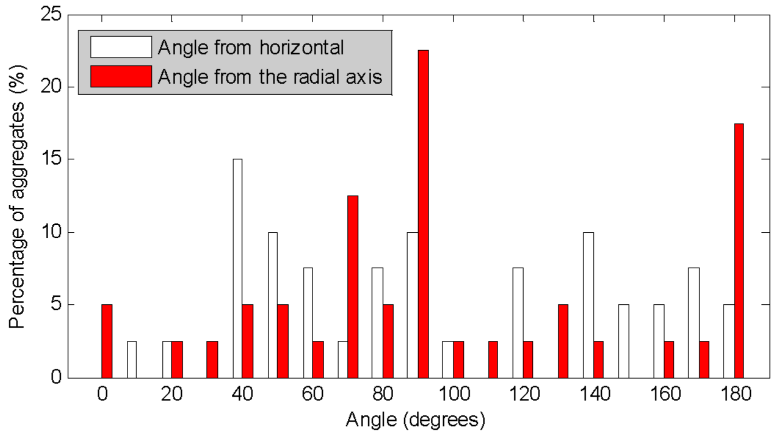
Number of contact points: ______60 _________

ORIENTATION

Minimum size of sggregate where the orientation is calculated: ______4.75 mm___

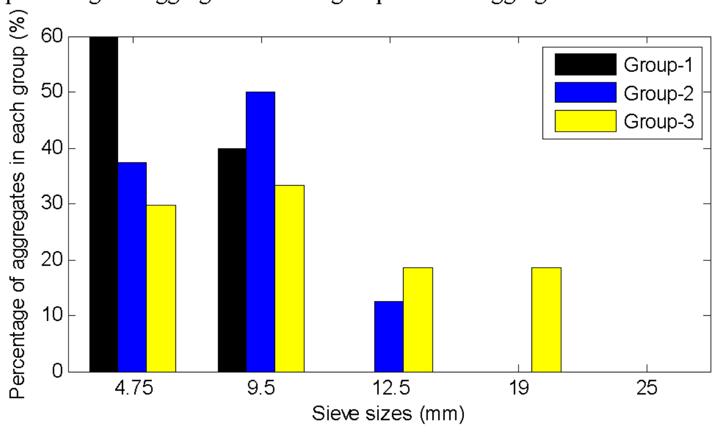
1

Histogram of angles:



SEGREGATION

The percentage of aggregates in each group for each aggregate size:



2

Appendix B: FORMULATIONS USED IN THIS STANDARD

B.1. Image resolution

$$\text{Image Resolution:} \quad \Delta x = \Delta y = \frac{D(mm)}{D_{im}(pixels)} \qquad (B1)$$

where: D = known distance in physical units (e.g., mm)
D_{im} = distance measured in the image in pixels.

B.2. Volumetric percentage of aggregates with respect to the total volume (P_{sv})

$$P_{sv} = \frac{V_s}{V} = \frac{(1 - VTM)}{(P_b \frac{G_s}{G_b} + 1)} \qquad (B2)$$

where: V = total volume of the asphalt mixture (mix)
V_s = Volume of aggregates in the mix
G_b = Specific gravity of binder
G_s = Specific gravity of aggregates in the mixture (assumed to be constant for all aggregates in the mixture)
VTM = Voids in total mix (a.k.a. V_a)
P_b = Binder content (by weight)

The derivation of this equation (Equation *B2*) is given in Appendix C.

B.3. Volumetric Gradation: Percent Retained (PR)

It is noted that volumetric gradation of the aggregates is identical to weight-based gradation measured in the laboratory, provided that the specific gravity is constant for all aggregates in the mixture.

$$\text{Percent Retained} = \quad PR = \frac{W_i}{W_t} = \frac{G_s \gamma_w V_i}{G_s \gamma_w V_t} = \frac{V_i}{V_t} \qquad (B3)$$

where: W_t = Total weight of the aggregates
W_i = Weight of aggregates retained on i^{th} sieve
V_t = Total volume of the aggregates
V_i = Volume of aggregates retained on i^{th} sieve

B.4. Coarse aggregate fraction (*CF*)

CF = Fraction of the aggregates larger than D_{min} calculated using the Mix Volumetrics (not from the image). Coarse Fraction (*CF*) is defined as the volume of the coarse aggregates (V_c) divided by the total volume of the aggregates (V_t) as follows:

$$CF = \frac{\sum_i V_i}{V_t} = \frac{V_c}{V_t} \quad for\, every \;\; i \in D_i > D_{\min} \qquad (B4)$$

B.5. Calculate percent coarse aggregate (P_{sv}^c),

P_{sv}^c is defined as the volume of the coarse aggregates (V_c) divided by the total volume of the entire asphalt mixture sample (V) as follows:

$$P_{sv}^c = \frac{V_c}{V} \qquad (B5)$$

where V = total volume of the specimen including the aggregates, binder and air voids.

B.6. Area (A_j), Equivalent Diameter (D_j^{eq}) and Centroid (x_j^c , y_j^c) of the aggregates in the image

$$Area: \; A_j = N_j * \Delta x^2 \qquad (B6)$$

where: A_j =area of the labeled region (i.e., aggregate) *j*.

N_j is the number of pixels in the labeled region (i.e., aggregate) *j*.

Δx = resolution of the image.

$$Equivalent\ Diameter: \; D_j^{eq} = \sqrt{\frac{4A_j}{\pi}} \qquad (B7)$$

$$Centroid: \; x_j^c = \frac{1}{N_j}\sum_{k=1}^{N_j} x_k \;\; , \;\; y_j^c = \frac{1}{N_j}\sum_{k=1}^{N_j} y_k \qquad (B8)$$

where: x_j^c and y_j^c are the x- and y- coordinate of the centroid of the labeled region *j*, respectively, and x_k and y_k are the individual coordinates of each pixel within labeled region (aggregate) *j*.

B.7. Total area of the coarse aggregates (A_c) in the image.

This corresponds to the total area of the coarse aggregates (i.e., aggregates larger than $D_{\min}$):

$$A_c = \sum_{j=1}^{N_{ag}} A_j \qquad (B9)$$

where: N_{ag}= the total number of aggregates (labeled regions)

B.8. Total area of all aggregates (A_t)

A_t includes the aggregates that are not visible in the image and calculated using the CF, which was determined from the known mix volumetrics. Equation B4 can be rewritten for a 2D image (i.e., in terms of area rather than volume), assuming that the property in 3rd dimension is homogeneous:

$$A_t = \frac{A_c}{CF} \qquad (B10)$$

where A_t = Total area of the aggregates (including the aggregates not visible in the image)

B.9. Percentage of aggregates (PR_i^{im}) retained on each sieve size (e.g., D_i = 2.36, 4.75, 9.5 mm…etc.) calculated from the image

$$\textit{Percent Retained} = \quad PR_i^{im} = \frac{A_i}{A_t} = CF\,\frac{A_i}{A_c} \qquad (B11)$$

where $A_i = \sum_{j=1}^{N_i} A_j \;\Leftrightarrow\; j \in \; D_i < D_j^{eq} < D_{i+1}$

B.10. Percent coarse aggregate (P_{sv}^{im}) from the image

$$P_{sv}^{im} = \frac{V_c}{V} \cong \frac{A_c}{A} \qquad (B12)$$

where A = total area of the specimen including the aggregates, binder and air voids in the image.

B.11. Major principal axis ($D_{\max}$)

First step in computation of the orientation is the determination of the major principal axis (D_{max}) of an aggregate. The D_{max} is determined using the formula:

$$D_{\max} = \max\left(\sqrt{(x_i - x_{-i})^2 + (y_i - y_{-i})^2}\right) \qquad (B13)$$

where x_i, and y_i are x- and y- of a surface pixel, x_{-i}, and y_{-i} are x- and y- coordinate of a surface pixel at the opposite side of a line going through the centroid of the aggregate.

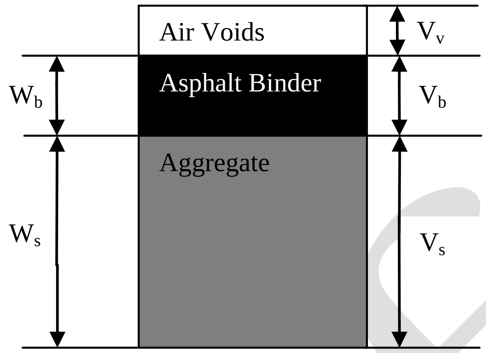
B.12. The angles from the horizontal axis (α) and from the radial axis (θ)

$$\alpha = \cos^{-1}\left(\frac{x_i - x_{-i}}{D_{\max}}\right) \qquad (B14)$$

$$\theta = \cos^{-1}\left(\frac{x_{ci} - x_{-ci}}{D_{\max}}\right) \qquad (B15)$$

where: α and θ are shown in Figure 3 and

APPENDIX C: CALCULATION OF VOLUMETRIC PERCENTAGE OF AGGREGATES



$$V_t = V_v + V_b + V_s \qquad \text{(C1)}$$

$$G_b = \frac{W_b}{V_b \gamma_w} \rightarrow V_b = \frac{W_b}{G_b \gamma_w} \qquad \text{(C2)}$$

$$G_s = \frac{W_s}{V_s \gamma_w} \rightarrow V_s = \frac{W_s}{G_s \gamma_w} \qquad \text{(C3)}$$

$$V_v = VTM\ V_t \qquad \text{(C4)}$$

$$P_b = \frac{W_b}{W_s} \qquad \text{(C5)}$$

where:

V_t = total volume of the asphalt mixture (mix)

V_v = Volume of voids in the mix

V_b = Volume of binder in the mix

V_s = Volume of aggregates in the mix

G_b = Specific gravity of binder

G_s = Specific gravity of aggregates in the mixture (assumed to be constant for all size aggregates)

γ_w = Unit weight of water

VTM = Voids in total mix (a.k.a. V_a)

P_b = Binder content (by weight)

Dividing Eq. C2 by C3 reveals:

$$\frac{V_b}{V_s} = \frac{W_b}{W_s}\frac{G_s}{G_b} = P_b \frac{G_s}{G_b} \rightarrow V_b = V_s P_b \frac{G_s}{G_b} \qquad \text{(C6)}$$

Plugging Eqs. C4 and C6 into C1 reveals:

$$V_t = VTM\ V_t + V_s P_b \frac{G_s}{G_b} + V_s \tag{C7}$$

Rearranging Eq.C7 yields:

$$V_t (1 - VTM) = V_s (P_b \frac{G_s}{G_b} + 1) \tag{8}$$

$$\boxed{P_{sv} = \frac{V_s}{V_t} = \frac{(1 - VTM)}{(P_b \frac{G_s}{G_b} + 1)}} \tag{9}$$

where P_{sv} in Eq. C9 represents the volumetric percentage of aggregates with respect to the total volume.

Appendix D: STANDARD IMAGES FOR ORIENTATION AND SEGREGATION

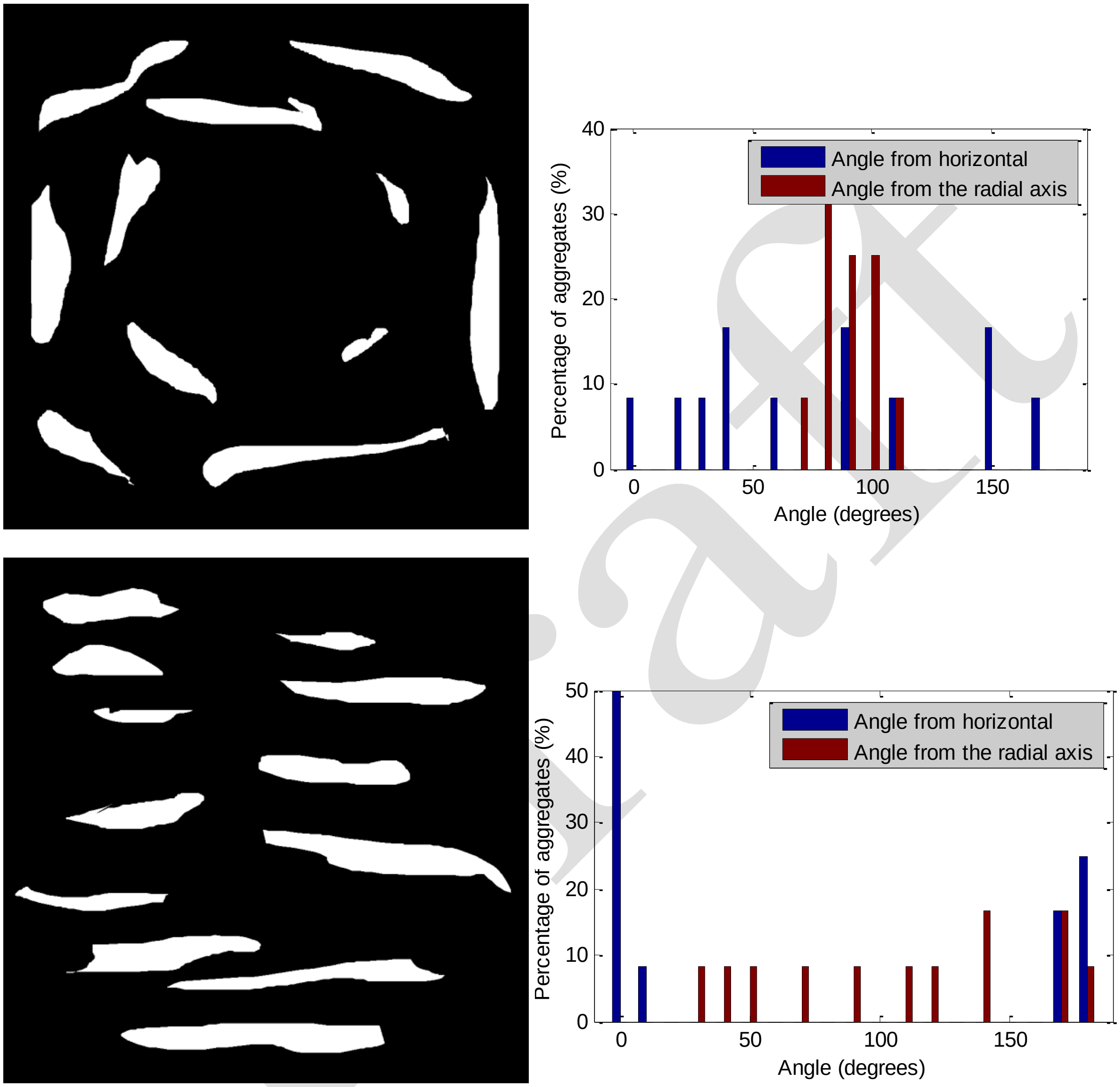


Figure B1. Standard (a) radial orientation image, (b) orientation results of radial orientation image, (c) horizontal orientation image and (d)

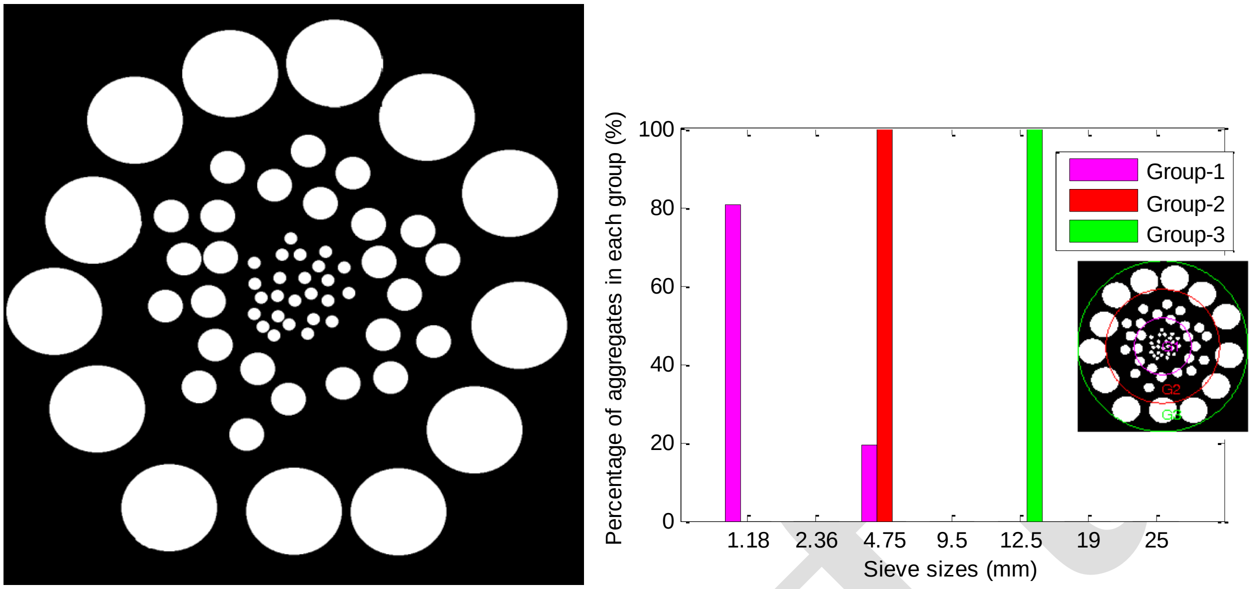


Figure B2. Standard radial segregation image