Rational Method for Laboratory Compaction of Hot-Mix Asphalt

PHILLIP B. BLANKENSHIP, KAMYAR C. MAHBOUB, AND GERALD A. HUBER

The study *Gyratory Compaction Characteristics: Relation to Service Densities of Asphalt Mixtures* was initiated by the Asphalt Institute for the Strategic Highway Research Program (SHRP), contract A001. N_{Design} is defined as the compactive effort (number of gyrations at a specific pressure) at which air-void level is measured for volumetric design. To determine the number of gyrations (N_{Design}) required to represent various traffic levels in different climates, an experiment was conducted. Once it is shown that gyrations (N_X) must relate to traffic levels (E_X) and once the design gyrations are known, one simply can enter the design gyration (N_{Design}), representing 20-year design traffic, into the compaction curve of the new mix design to obtain the final percent compaction (C_X) of that mix; the target is 96 percent of maximum theoretical specific gravity (MSG). Thus, one can say, at that specific traffic level (gyration) and climate, the mix will compact to C_X of the given MSG.

Asphalt mixture design has been evolving since the early 1900s, from a rule-of-thumb approach to the mixture design system developed under the Strategic Highway Research Program (SHRP). One of the first rule-of-thumb tests for choosing an asphalt cement (AC) content was the Pat Test. It consisted of placing the asphalt concrete mixture on a piece of brown manila paper and determining the optimum AC content from the residual stain (*1*). Since the earliest attempt at mixture design, the objective has always been to mix, compact, and test asphalt mixture in the laboratory to determine its expected performance in service.

Designing an asphalt concrete mixture consists of selecting the proper aggregate blend and the optimum AC content, such that the mix is as durable as possible, yet stable (*2*). The most critical factor is the AC content, because a deviation from the optimum AC of 0.5 percent could result in either too much or too little AC. Too much asphalt produces a mixture with low air voids that is susceptible to rutting and flushing. Low AC content produces a mixture that under-compacts (has high air voids) and is likely to ravel. Indeed, the optimum AC content is the most difficult variable to set in a mix design.

Compaction of an asphalt concrete mixture is defined as "... a stage of construction which transforms the mix from its very loose state into a more coherent mass, thereby permitting it to carry traffic loads ... the efficiency of the compactive effort will be a function of the internal resistance of the bituminous concrete. This resistance includes aggregate interlock, friction resistance, and viscous resistance" (*3*). Another reason for compacting the asphalt pavement is to make it watertight and impermeable to air (*4*). An increase in the mix's density usually will result in a stronger mix but not necessarily a stronger pavement. However, there is a point of optimum density that correlates with the best combination of strength and durability.

P.B. Blankenship, Kentucky Transportation Cabinet, Division of Materials, 1227 Wilkinson Boulevard, Frankfort, Ky. 40622; K.C. Mahboub, Department of Civil Engineering, University of Kentucky, 533 South Limestone Street, Transportation Research Building, Lexington, Ky. 40506; G.A. Huber, Heritage Research Group, 7901 West Morris Street, Indianapolis, Ind. 46231.

Pavements are compacted in two stages: during construction and as they are trafficked (*5*). Hot mix initially is compacted to about 8 percent air voids during construction. After construction, traffic loads densify the asphalt layer, especially during hot months, until it reaches ultimate density.

In one publication it was stated that "... an increasing number of bituminous concrete pavements in Texas as well as other states are not stabilizing at a density equal to that obtained in the laboratory design of a companion paving mixture" (*6*). This is evidence that current methods of laboratory compaction are not sufficient to simulate field conditions. The properties of the asphalt and aggregate based upon the long-term densification of a pavement must be taken into account; that is, consider the resistance of the paving mixture to compactive effort (*6*). If the resistance to compactive effort is weak, the pavement will be sufficient only for low traffic; if the resistance is strong, the pavement will be sufficient for higher traffic.

Pavements densify with an increased volume of traffic until they stabilize. Traffic will compact pavement to ultimate density, which is usually achieved after the third summer's traffic (*7*). A laboratory compactor needs to be able to simulate final density. The heavier the traffic (number of axle loads), the more the density of the pavement increases. Thus, equivalent single (18 kip) axle load (ESAL) is a convenient way to account for the effects of the traffic volume (*6*) on pavement density. Traffic load was measured in ESALs for this experiment.

SHRP, a $150-million research program authorized by the U.S. Congress (1988–1993), provided funds to produce new asphalt binder and mix design specifications to improve pavement performance. The design life of pavements is usually 20 years. Typically, if a pavement is not placed with the optimum AC content and gradation, it could show extensive damage after a few years of traffic. Current methods of asphalt mix design must be improved.

Ideally, a pavement must have the ability to resist vertical and shear forces that are applied by traffic. Indeed that is the basis for mix design criteria today. Factors such as aggregate size, shape, orientation, gradation, and asphalt content may cause premature failure in pavement.

The most widely accepted definition of optimum AC content is "... the highest asphalt content that can be used without having so much that it prevents the pavement from developing strength from the applied loads" (*8*). The loads referred to are traffic. Pavement density is a function of traffic and climate (temperature) (*8*). For pavements to be designed correctly, traffic and climate must be simulated in the laboratory for the mix design. Rational traffic simulation has been lacking in current practice.

The heart of all mixture design methods is the laboratory compaction method. From the Hubbard Field Method of mix design to the SHRP SUPERPAVE method, attempts have been made to select a compaction device that achieves a density similar to that of the actual pavement.

This paper documents development of laboratory gyratory compaction criteria for use in the SUPERPAVE mix design system. Data from in-service pavements were used to determine an appropriate gyratory compaction protocol. Results are presented as well as the method for use in SUPERPAVE.

BACKGROUND

Historically, there have been three compaction methods that have been used in routine asphalt concrete mixture design—impact compaction, kneading compaction, and gyratory compaction.

Impact Compaction

Impact compaction is the oldest method of laboratory compaction. In the 1920s, Hubbard and Field used a Proctor hammer, borrowed from the geotechnical field, to compact asphalt mixtures (*1*).

In the 1930s, Marshall began developing the Marshall method of mixture design. Impact compaction from the Hubbard field method was adopted, except that the compactor face was made equal to the mold diameter. Subsequently, the Marshall method was adopted for highway design. The number of blows applied to each face of the specimen (35, 50, and 75 blows) was tied to general traffic levels. Higher energy levels (blows) were used for higher traffic levels. Unfortunately, different densities, because of the variability in Marshall hammers (mechanical, rotating, and manual hammers), will result when these compaction blows are applied (*9*).

Some variation of Marshall mixture design has been adopted by 75 percent of the highway agencies; it is the predominant method of mix design used today (*1*). However, in simulating field compaction properties the Marshall hammer ranked third out of five compactors tested in the AAMAS study (*10*).

Kneading Compaction

Independent of the Marshall mix design development, Hveem developed a mix design method in the 1930s and 1940s. The compaction method Hveem selected is referred to as kneading compaction. Kneading compaction applies force through a roughly triangular-shaped foot that covers only a portion of the specimen face. Tamps are applied uniformly on the specimen face to achieve compaction.

The objective of kneading compaction, like other compaction methods, is to achieve specimen density that matches postconstruction mixture density under traffic. Mixtures applied to high volume traffic are subjected to more and higher pressure tamps.

Kneading compaction has been adopted by several states in the western United States, where the Hveem mix design is commonly used. Outside this region, kneading compaction is not common practice.

Gyratory Compaction

Gyratory compaction was developed in the 1930s in Texas (*11*). The process involves applying a vertical load while gyrating the mold in a back-and-forth motion. Gyratory compaction, like California kneading compaction, produces a kneading action on the specimen. The kneading action is caused by gyrating the specimen through a horizontal angle. The angle of gyration of various compactors ranges from 1.00 to 6.00.

Gyratory compaction, as it developed in Texas, is used in a few states but has not gained wide acceptance. Compaction using gyratory action has been further developed and applied by the Army Corps of Engineers as well as the Central Laboratory for Bridges and Roads (LCPC) in France (*12,13*).

In a recent study of the AAMAS (*10*), sponsored by NCHRP, which preceded SHRP, the Texas gyratory shear compactor proved to simulate field compaction, when compared to other compactors (*10*), Five compaction devices were compared. They are listed in descending order beginning with those that best simulated field cores in various engineering properties.

- Texas gyratory shear compactor,
- California kneading compactor,
- Mobile steel wheel simulator,
- Arizona vibratory kneading compactor, and
- Marshall mechanical hammer.

In the 1940s, the U.S. Army Corps of Engineers began to develop a compactor by applying the principle of gyratory movement. The goal was to develop a new method of asphalt mix design for service under extreme traffic conditions (*14*). Development of the compactor continued though the 1950s, and by the early 1960s its use had been demonstrated (*15*). However, the gyratory testing machine gained little acceptance as a routine mix design tool. Outside the Corps of Engineers it has been used primarily as a research tool.

In the late 1950s, a delegation from France visited the United States and studied the Texas gyratory method (G. Huber, unpublished data). The LCPC evaluated parameters affecting gyratory compaction; in 1972 it finalized a gyratory protocol. Angle of gyration, speed of rotation, and vertical pressure were the three major variables studied. In the French application of gyratory compaction, the compactor is used to simulate density at the end of construction instead of during service. Today, gyratory compaction is used routinely in France for part of the mix design process. More recently, gyratory compaction has been introduced in several countries, including Sweden, Switzerland, and Australia. The SHRP protocol for gyratory compaction is a workable compromise between various approaches to gyratory compaction, such as the French LCPC, U.S. Army Corps of Engineers, and Texas methods.

Selection of SHRP Compaction Protocol

The gyratory and Hveem methods of asphalt mix design generate higher densities than a mix design using the Marshall hammer (*16*). The reason for the higher densities is the kneading action each method produces. The kneading action simulates field particle orientation of the aggregate better than Marshall compaction does. One of the primary reasons for using a gyratory compactor is its ability to reproduce the high densities that are encountered in the field (*17*). McRae and Foster suggest that the "gyratory compactor is producing specimens with stress-strain properties comparable to those of the actual pavement" (*17*).

A decision was made to evaluate a Texas-type gyratory compaction for application in the SUPERPAVE program on the basis of compaction studies that predated SHRP. In particular, the NCHRP study as part of AAMAS as well as other studies within SHRP were to be used in this evaluation.

SHRP decided to evaluate gyratory compaction as the potential method of compaction for the SUPERPAVE mixture design system. Work by LCPC provided insights into compaction characteristics of mixtures but did not establish a relationship between gyratory compaction and pavement density at the end of its service life. The purpose of this study is to establish that relationship.

EXPERIMENT BACKGROUND

The study, *Gyratory Compaction Characteristics: Relation to Service Densities of Asphalt Mixtures,* was conducted by the Asphalt Institute. It defined N_{Design} as the compactive effort (number of gyrations at a specific pressure) at which the air void level is measured for volumetric design. In other studies, such as experiments on the Army Corps of Engineers' gyratory testing machine or the Texas gyratory, gyration pressure had been varied as a function of tire pressure and traffic levels (*17,18*). It was decided that the SHRP compaction protocol would maintain a constant gyration pressure and a specified number of gyrations to define two levels of compaction: (a) construction compaction [92 percent of maximum theoretical specific gravity (MSG)] and (b) traffic compaction (96 percent of MSG), as shown in Figure 1. Also, gyrations at 89 and 98 percent densities were defined as threshold limits for an acceptable mix. Percent compaction is defined as the ratio of bulk specific gravity (BSG) to MSG.

Design specifications of the SHRP Gyratory Compactor are as follows:

- Angle of gyration, 1.00 degree;
- Speed, 30 rpm;
- Vertical pressure, 0.6 MPa (87 psi); and
- 100-mm (3.94-in.) and 150-mm (5.91-in.) diameter molds.

The purpose of the experiment was to determine the number of gyrations (N_{Design}) required to represent various traffic levels in different climates. Thus, gyrations (N_X) must relate to traffic levels (E_X). This is compatible with information reported in the literature, which indicates that the asphalt layer under traffic increases in density linearly with the logarithm of the number of traffic passes until it reaches its ultimate density (*7*).

The main concern of those conducting the experiment was relating gyrations to traffic. Initial air voids of GPS sites were unknown, historical traffic was a guess, and the original materials were unavailable. Some assumptions had to be made, increasing the variability and margin of error of the experiment. Such is the challenge SHRP faces with large-scale experimental plans.

A more desirable process would have been a "controlled" field experiment to determine N_{Design} as a function of traffic level, tire pressure, and pavement structure. However, such a project was not feasible within the limited time and resources available. It was decided that the use of uncontrolled GPS sites might provide a reasonable determination of N_{Design}, as long as a number of sites were used to average out the error caused by individual project variations. Scatter in the data was expected to be significant.

The final objective of the experiment was to provide the ability to produce compaction curves for various mix gradations at different asphalt cement contents (percent AC). When N_{Design} is entered into the compaction curves, this will allow the pavement design to have the optimum mix gradation at the optimum percent AC for a desired level of traffic in a specific climate. Thus, we can fulfill the SHRP objective of being able to produce rut-resistant mixtures with adequate durability (*19*).

Two gyration levels were studied: (a) gyrations (N_{Const}) representing compaction (C_{Const}) resulting from initial pavement construction and (b) gyrations (N_{Design}) representing compaction (C_{Design}) from current traffic in the wheel path. N_{Const} is the gyration that represents field compaction at the end of construction as the result of rolling. Neither C_{Const} densities nor out-of-wheel-path densities were available. The out-of-wheel-path data would not have provided usable densities, because the out-of-wheel-path pavement areas densify to some degree from wandering traffic. The only data available were from cores that were in the wheel path. The construction compaction was assumed to be 92 percent of the max-

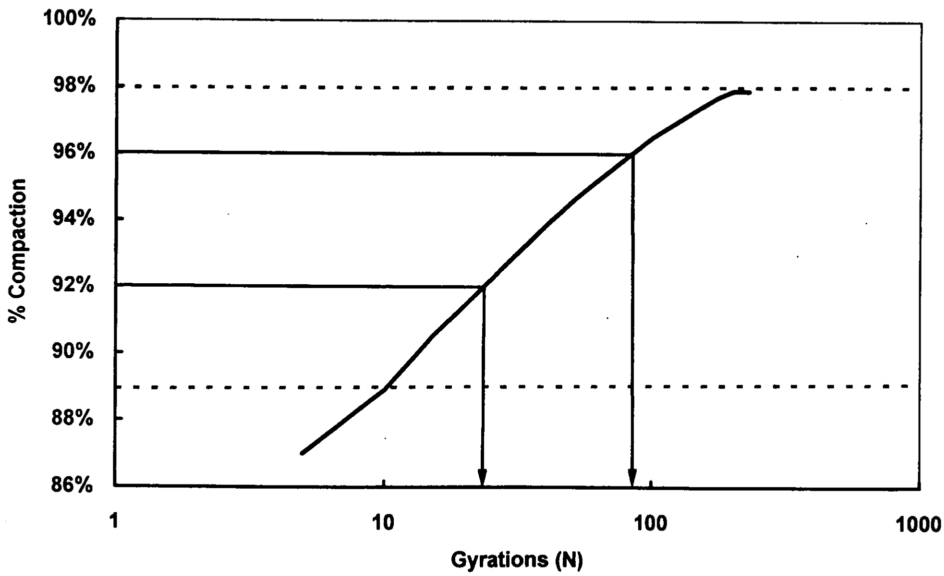

FIGURE 1 Schematic to define construction and traffic compaction.

imum specific gravity, and an assumption was made in order to complete the design curves. Without this assumption, there would have been no data available at zero ESALs (i.e., postconstruction information). The 92 percent of MSG is a reasonable assumption, because these pavements most likely were designed to have an in-place density of 92 percent of solid density, and 8 percent air voids (*8,20*).

N_{Design} EXPERIMENT

The experiment was conducted following these steps:

- Select site of cores,
- Collect cores and core data (layer description, gradation, density, percent AC, BSG, MSG) from the SHRP Material Reference Library (MRL),
- Separate core layers and lifts,
- Measure BSG of each layer and lift,
- Extract asphalt binder and salvage aggregate,
- Compact specimens using salvaged aggregate,
- Measure the BSG and MSG of each compacted specimen,
- Plot densification data,
- Tabulate N_{Const} and N_{Design} for each site,
- Complete statistical analysis, and
- Determine design gyrations (N_{Design}).

The experiment involved extracting the aged asphalt, and then remixing the salvaged aggregate with AC-20 grade asphalt cement and compacting it to achieve compaction curves. The original testing matrix included asphalt concrete cores representing three ages, three climates, three traffic levels, and upper and lower layers. This required 27 pavement sites with 54 mixtures. The goal was to provide sufficient data that would represent the majority of roads that are traveled today and reduce potential error in the analysis. Later, it was decided that only old pavements, older than 12 years, would be used. Pavements at old sites already would be densified to their ultimate density, because most pavements reach their ultimate density after the third summer's traffic (*8*). Table 1 indicates 18 pavement sites in the testing matrix, only 15 of which were available. There are only single sites for hot climates. The 305-mm (12-in.) diameter cores were collected from various SHRP road test sections and stored in the MRL until needed for testing purposes.

Cores from pavements with more than 12 years of traffic exposure represent pavements that have densified to their design percent air voids [100 percent − percent Compaction (percent C_X)]. One assumption made in this experiment is that pavements were designed to have final air voids of 3 to 5 percent and the pavements were placed at 7 to 9 percent air voids. This is a reasonable assumption because most pavements are required to have these densities. Some pavements have higher or lower air voids than 7 to 9 percent at construction. Overall, 7 to 9 percent air voids at construction is a reasonable air-void range (*8,20*).

When the cores and core data were received from the MRL, they were verified and marked for cutting. The BSG of each layer and lift to be compacted was measured in accordance with ASTM-D2726-90 and compared with BSG from SHRP core information gathered from various independent contractors. The asphalt binder was extracted from the layers and lifts by the quantitative extraction of bituminous paving mixtures method (ASTM-D2172). Extraction provided the recovered aggregate and indicated the required asphalt cement content (percent AC) needed for remixing. All the aggregate was recovered, including the dust fraction that was removed from the extraction solvent by centrifuge.

Next, the salvaged aggregate was remixed with fresh asphalt binder at the amount percent AC, as determined from the extraction. The laboratory standard asphalt cement (AC-20) was used for mixing all specimens. Because the viscosity of asphalt is directly related to temperature, all the specimens were prepared according to the proper mixing and compacting temperatures as specified by the asphalt grade (*21*).

The most critical time of the bitumen life is the time it is exposed to high temperatures at the hot-mix plant (*22*). Thus, the asphalt concrete mixture was allowed to cure for 4 hr at 135°C in loose form. SHRP determined that this served as the short-term aging process that simulates curing from the plant mixing of asphalt concrete. The mixture was then loaded into a preheated mold for compaction. The size of mold depended upon the nominal maximum aggregate size of the mixture; nominal maximum aggregate size being defined as one sieve size larger than the first sieve to retain more than 10 percent. The 100-mm mold was used for 19.0-mm (¾-in.) and less nominal mixtures, whereas the 150-mm mold was used for greater than 19.0-mm (¾-in.) nominal mixtures. The mold was then placed into an SHRP gyratory compactor, and the vertical ram was lowered into the mold. As the specimen gyrated, specimen heights were recorded at 5, 10, 15, 20, 30, 40, 50, 60, 80, 100, 125, 150, 175, 200, and 230 gyrations. Even though the mix density of most probably occurred at a lower gyration than 230, this end gyration ensures complete densification of the mix. Finally, the specimen was extracted from the mold and allowed to cool overnight. Afterwards, BSG and MSG of each compacted specimen were measured.

Compaction data were then entered into a spreadsheet that produced densification curves for two specimens of the same selected layers and lifts. The two densification curves were averaged and used for further analysis.

The next step was to determine the number of gyrations that corresponded to the in-place density at the time of coring and at the time of construction. The measured density, expressed as percent maximum theoretical density (C_X), of the cores was matched to the compaction data and the corresponding number of gyrations (N_X) was noted. For density at the time of construction, no measured data were available; therefore, an assumption of 92 percent MSG was made. Thus, the construction densities (92 percent) were also entered into the compaction curves to produce the corresponding gyration (N_{Const}).

TABLE 1 Core Site Selection Matrix

TEMPERATURE		HOT			WARM			COOL		
TRAFFIC		Low	Medium	High	Low	Medium	High	Low	Medium	High
CORES	Original	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Replicate				✓	✓	✓	✓	✓	✓

The corresponding field gyrations (N_X) and construction gyrations (N_{Const}), which achieved the required field and construction densities during laboratory compaction, produced two data points (N_X and N_{Const}) for each specimen's layer and lift. Hence, 30 data points (2 data points × 15 cores) were produced for the upper layers. There was only one upper layer from each core used in the analysis. The upper layers [less than or equal to 102-mm (4-in.) from the surface] analyzed were the uppermost layers tested.

Analysis

It was hypothesized that there was some relation between gyrations (N_X) and traffic (E_X). It has been shown in this experiment that a linear relation exists between percent compaction (C_X) and the logarithmic function of gyrations (Log N_X). It has also been shown that a linear relation exists between percent compaction (C_X) and the logarithmic function of traffic (Log E_X) (*5*). Therefore, a linear relation should exist between the logarithmic function of gyrations (Log N_X) and the logarithmic function of traffic (Log E_X).

Determination of the Design Gyrations (N_{Design})

Three lines were regressed through the data points at a confidence level of 95 percent. This produced curves for the three climates (hot, warm, and cool). By using these design curves, one can enter the graph with a known traffic level and specific climate and obtain the corresponding design gyration (N_{Design}).

Figure 2 shows a plot of these design curves. It should be noted that the experiment includes design traffic up to 3.2 × 10^7 ESALs. Thus, as represented on the graph, values greater than 3.2 × 10^7 ESALs were extrapolated.

For the above model to be used in SUPERPAVE, the temperature zones (hot, warm, and cool), which were determined from monthly mean maximum air temperature (°F), had to be converted to weekly mean maximum air temperature (°C).

Next, these temperatures in weekly mean maximum air temperature (°C) were plotted against the design gyrations at designated traffic levels. The design traffic levels to be used in SUPERPAVE are defined in Table 2. The design gyrations (N_{Design}) to represent each of these ESAL limits, which will correspond to a design air voids of 4 percent, are compiled in Figure 3.

One now has the ability to use the design gyrations (N_{Design}), obtained from the design curve, Figure 3, to acquire the design 4 percent compaction (C_x) from compaction curves of future mixes. For instance, to design a mixture for Traffic Level 4 and a weekly mean maximum air temperature of 39°C, the N_{Design} would be 103 gyrations. To achieve the optimum aggregate blend and asphalt content for this mix design, the designer simply would enter the design gyration (N_{Design}), representing design traffic, into the compaction curve of the new mix design to obtain the final percent compaction (C_x) of that mix (target is 96 percent MSG).

CONCLUSIONS AND RECOMMENDATIONS

The purpose of the N_{Design} experiment was to determine the number of gyrations (N_{Design}) required to represent mixture densification that will occur under various traffic levels in different high-temperature climates. Thus, gyrations (N_X) must relate to traffic levels (E_X). This

TABLE 2 SUPERPAVE Traffic Levels

Traffic Level	ESAL Limits	Design %Air Voids
1	<3x10^5	4
2	<1x10^6	4
3	<3x10^6	4
4	<1x10^7	4
5	<3x10^7	4
6	<1x10^8	4
7	<3x10^8	4

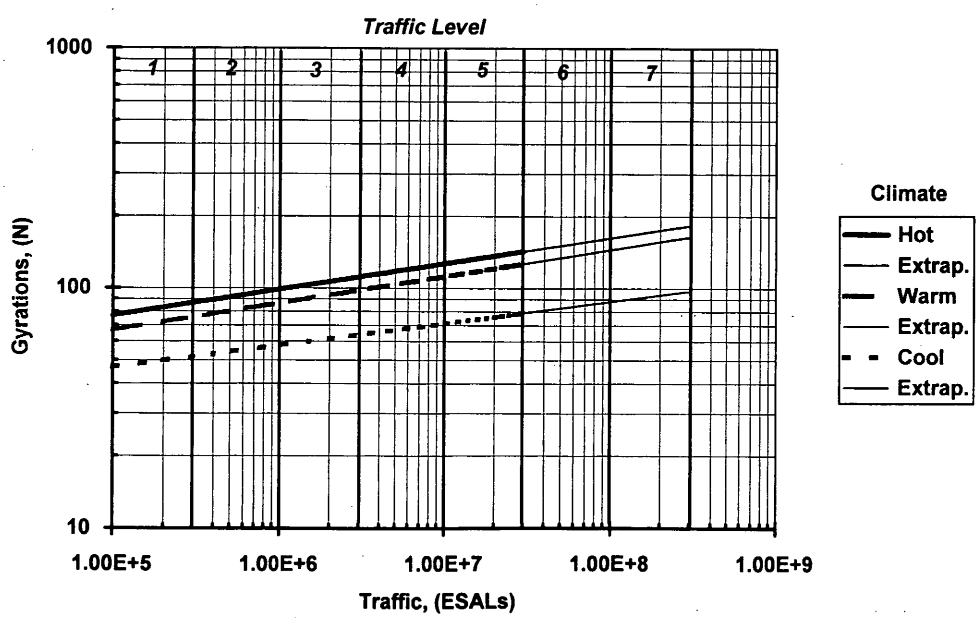

FIGURE 2 Design gyrations versus traffic.

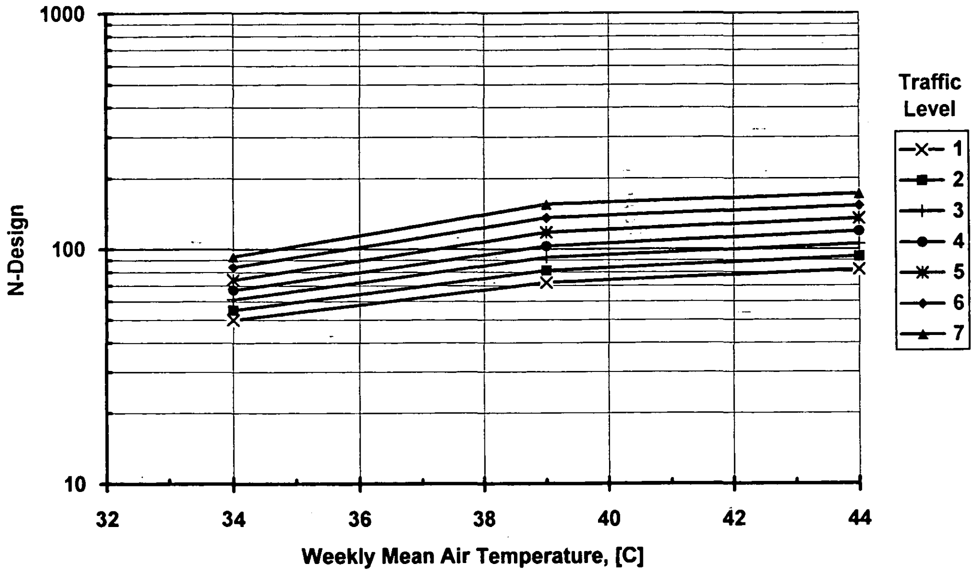

FIGURE 3 Design gyrations.

relationship was proven to exist. This relationship provides a method of choosing a mix design to have the blended aggregate gradation and percent asphalt binder matched to a desired traffic level in a specific climate.

Data for sites with hot climates were limited because there were no replicate specimens. However, design gyrations graph (Figure 3) could be reasonably plotted because the hot-climate design curve requires more gyrations than the cool-climate design curve at the same level of traffic.

The number of gyrations representing construction density (no traffic) is called N_{Const}. N_{Const} was calculated to be 22, 18, and 16 for hot, warm, and cool climates, respectively. Although reasonable, the numbers were based on the assumption that the construction compaction (C_{Const}) of the tested pavements was 92 percent of the maximum specific gravity. N_{Const} will produce a target density that should be generated during initial construction.

The relationship between number of gyrations and traffic would not have been possible if a construction compaction ($C_{Const} = 92.0$ percent) had not been assumed. Even though the relation is an assumption, which has been proven reasonable, the results may be in error because the traffic data were separated by a large margin. For example, data points were located at 0.001 kESALs (1 ESAL). The rest of the data was located at 600 to 28,713 kESALs. There were no data available for the gap from 0 to 600 kESALs. Hence, error introduced as a result of this gap in traffic data may affect the exact gyration-traffic relation.

The results of the N_{Design} experiment are acceptable at this early stage in the development of the SHRP gyratory compactor. The linear relation of the logarithmic function of gyrations (Log N_X) versus the logarithmic function of traffic (Log E_X) was proven to exist, although, more research is required to increase the precision of the gyration versus traffic model. The SHRP gyratory compactor was used in the mix design of various new SHRP road test sections. Thus, more data will be available soon to check and adjust SHRP gyratory compactor design gyrations (N_{Design}). Certainly, more research needs to be completed to increase the precision of N_{Design}.

In the authors' preliminary studies with a modified Texas 6-in. gyratory compactor, specimens similar to SHRP gyratory specimens have been made (M. Anderson, unpublished data). Therefore, it may be possible for the Texas 6-in. gyratory compactor, with its similarities to the SHRP gyratory, to be modified into a SHRP gyratory compactor.

Degradation of the aggregate, as in any type of compaction method, is a concern that needs to be addressed. Degradation must be simulated in laboratory compaction because aggregate degradation occurs naturally in the field. Laboratory impact compaction causes too much degradation, cracking, and exposing the aggregate faces. However, it has been found that gyratory compaction, which produces proper orientation of the aggregate and has low initial pressures, closely simulates the degradation found in field compaction (*11*).

More research is needed to monitor the long-term pavement performance of experimental pavements that are currently being designed with this new methodology. For example, the long term pavement performance program, designed to generate a large data base in the next 20 years, is being managed by FHWA. Compaction models developed for the FHWA study should be calibrated as soon as long-term pavement performance data become available.

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DISCUSSION

John I. McRae
CEO Engineering Developments Co., Inc.

This SHRP procedure using a fixed pressure of 0.6 MPa (87 psi) fails to consider the requirement of an increase in density and reduction in bitumen as traffic load increases. Increasing density by increasing the number of cycles of kneading at the same vertical pressure can be empirically related to traffic, but when contact pressures exceed the pressure used in the test, the method will reach its limitations and become out of phase with the ultimate density. Out-of-phase compaction tests are the primary reason for the rutting failures experienced to date.

A rational method of compaction should introduce the tire contact pressure and compact to an equilibrium condition, that is, effect a balance between the applied load and internal resistance. Based upon the Army Corps of Engineers' experience, this has been defined as a rate of densification of 1 lb/ft^3/100 revolutions.

Another tenet of mix design is to accept the maximum permissible bitumen content as that at the peak of the bitumen content versus unit weight aggregate-only curve (minimum VMA).

Figure 4 illustrates a gyratory testing machine (GTM) mix design test using the plot of unit weight aggregate only versus bitumen content, along with the associated gyratory stability index (GSI), GTM shear modulus (*Gg*), and GTM compression modulus (*Eg*).

The authors are to be commended for their extensive literature review. The following articles offer related material:

> From the preceding discussions, it is evident that a procedure that is not dependent upon voids would be desirable. The flexible Pavement Laboratory of the Corps of Engineers has recognized this and is now studying a mix design procedure based on a very direct approach to the problem. Specifically, an attempt is being made to develop a laboratory compaction procedure which will simulate prototype compaction not only as to compactive effort but also as to compactive action and thus allow direct selection of the optimum condition independent of specific gravity and voids considerations.
>
> The compaction phenomenon, when properly controlled, is by its very nature the most direct indicator of optimum asphalt content since what is generally desired in a pavement is a mix that is fully compacted and at a desired equilibrium condition under the imposed traffic. . . .
>
> In the current program, the Flexible Pavement Laboratory is developing a kneading-type laboratory compactor based on the "Texas Gyratory" principle. Field data of density versus asphalt content, mainly from test sections built for other specific purposes, are being collected which will be used as a basis for establishing a laboratory procedure to duplicate the field compaction asphalt-density curve. It is believed that this test method will make it possible to select the optimum bitumen content independent of voids consideration (*1*).

> In an effort to develop improved procedures for the design and control of hot-mix bituminous pavements, the Waterways Experiment Station developed the gyratory testing machine, a laboratory compaction and

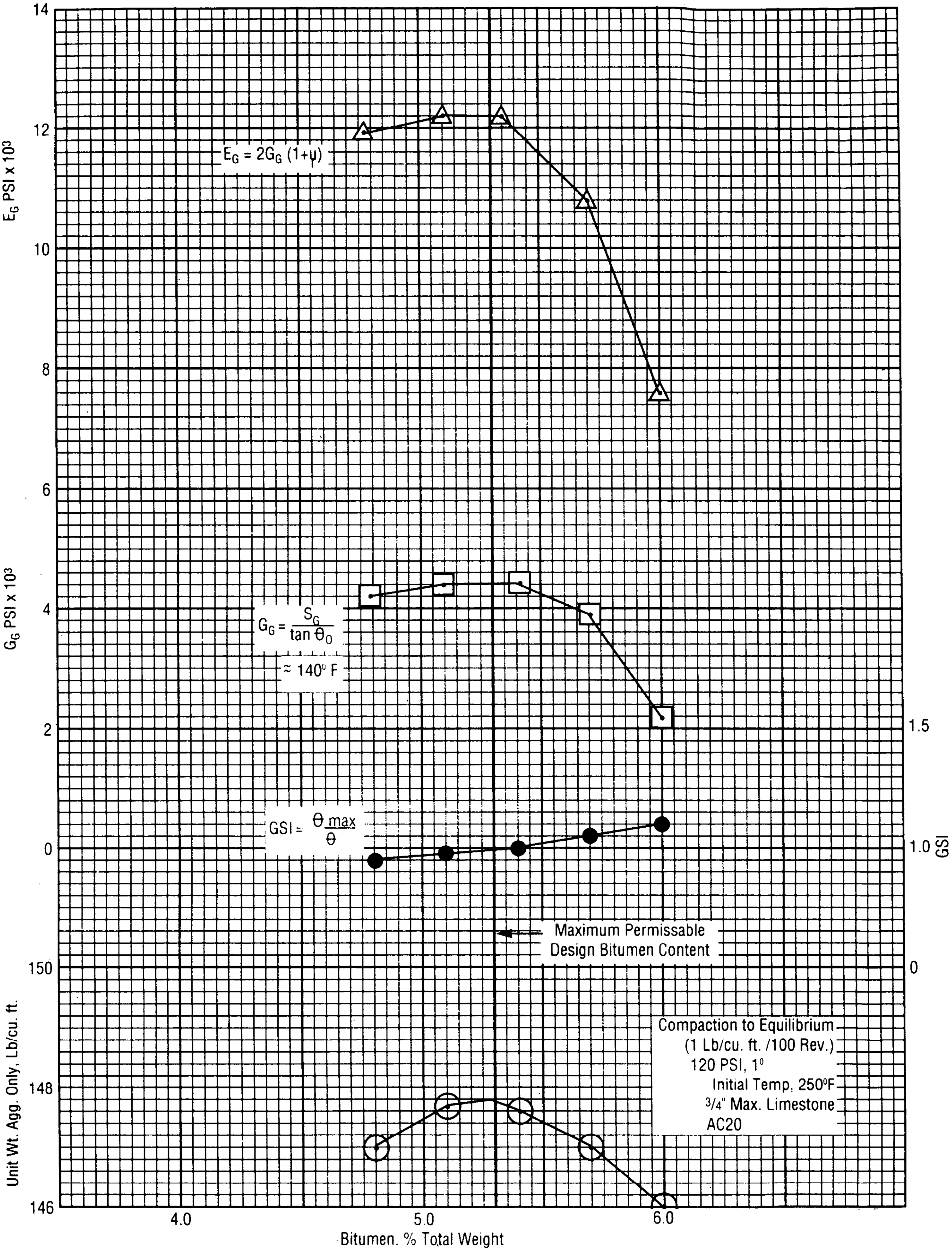

FIGURE 4 **Gyratory testing machine mix design test.**

> testing device believed capable of (*a*) producing high densities equal to those that develop under channelized traffic of heavy wheel loads; (*b*) producing specimens with stressstrain characteristics similar to those of actual pavement sample of equal density and bitumen content; (*c*) predicting the number of load applications a paving mixture can withstand before failure; (*d*) predicting the design bitumen content independently of voids criteria; and (*e*) providing a more positive and faster plant-control test. Extensive laboratory and field tests proved the principle of the gyratory testing machine to be sound and its predictions to be more accurate than those of other previously established test methods (*2*).

The U.S. Army Corps of Engineers' GTM (ASTM D 3387) was evaluated along with the Texas Shear Compactor (ASTM D 4013), which was modified to produce the SHRP (Rainhart) gyratory compactor pictured in Figure 2 of the paper under discussion. The following excerpts from the study apply:

> The Corps of Engineers gyratory testing machine (GTM) was used to study the effects of traffic densification. The GTM is the only device that can monitor the mixtures's behavior during the densification process. Using the other compaction devices, test specimens must be initially compacted and then tested separately (p. 122).
>
> The Corps of Engineers GTM provides an indication of this shearing resistance of asphaltic concrete mixtures. Those mixtures included in this study that are known to be susceptible to shoving and lateral distortion were identified as such with the GTM. Thus use of the GTM is recommended in the AAMAS procedure (p. 166).
>
> Thus it is suggested that additional projects be added or coordinated effort between the states be used to evaluate a more diverse range of mixtures (p. 179).
>
> Gyratory shear strength or the use of the Corps of Engineers GTM was found to provide a reasonable evaluation of asphaltic concrete mixtures that were known to be "sensitive" mixtures or mixtures that are susceptible to a reduction in shear strength with traffic. However, this parameter is not used in any mechanistic model nor is it commonly used to evaluate mixtures. Thus additional mixtures should be evaluated and designed with the GTM and then monitored to gain the critical performance data to validate its results (*3*).

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Authors' Closure

We would like to reemphasize the point made in the paper that the SHRP gyratory compactor is not a testing device but is a laboratory compaction device. Mr. McRae raises several points concerning laboratory compaction. The first regards vertical pressure and load.

1. *Vertical pressure and load.* The SHRP gyratory compactor uses a vertical pressure of 0.6 MPa, the same used by LCPC in development of the French gyratory compactor. The pressure is similar to though somewhat lower than highway tire pressures. Ad hoc testing has indicated that SHRP gyratory densification curves, although sensitive to vertical pressure, are highly sensitive to angle of gyration. Additional research would be necessary to confirm use of the SHRP gyratory for airport applications, where tire pressures are three to five times those of highway vehicles.

Mr. McRae's suggestion that compaction continue to an equilibrium condition is an interesting idea, but the definition of equilibrium is unclear. The parameter he proposed, 1 lb/ft^3/100 gyrations, is an empirical value related to mixtures at an air base, under aircraft tires using the gyratory testing machine. The gyratory testing machine can not be compared with the SHRP gyratory compactor.

The densification curve of a mixture under gyratory compaction is very sensitive to angle of gyration. SHRP requires the angle to be specified within a tolerance of ± 0.02 degrees. Mr. McRae's data indicate the angle of the gyratory testing machine varies by as much as 0.10 degrees during specimen compaction—five times the tolerance allowed by SHRP. Furthermore, the angle does not remain constant during specimen compaction. Hence, the variable angle of the gyratory testing machine produces confounded densification curves that cannot be compared with SHRP gyratory compactor data.

2. *Selection of asphalt binder at minimum voids in mineral aggregate.* As Mr. McRae noted, one of the tenets of mixture design is to select asphalt content near the minimum VMA for specimens produced with a compactor that has been calibrated to the application. Figure 5 illustrates the relationship of air voids, voids in mineral aggregate, voids filled with asphalt, and specimen density with asphalt content for a 19-mm nominal, maximum size mixture. This mixture was designed using the SHRP gyratory compactor and was subsequently constructed on Interstate 43 outside Milwaukee, Wisconsin, in August 1992. The mixture has shown excellent performance to date.

Volumetric property data for the I 43 mixture shown in Figure 5 is typical for a SHRP designed mixture. The design asphalt content, 4.8 percent, was selected at 4.0 percent air voids, slightly less than the asphalt content that produces the minimum VMA. Hence, the SHRP gyratory meets this basic tenet of mix design.

3. *Selected Quotes from Literature.* Mr. McRae quotes from three sources. The first paper (I) is a discussion of specific gravity measurement methods and calculation of air voids. The quoted portion of the paper is an opinion of the author based on his belief that air voids inside porous aggregates should be considered part of the specified air-void content. The scientific community has found no evidence to support this opinion and has adopted as standard practice the definition of air voids outside asphalt-coated aggregate particles.

The AAMAS report evaluated the gyratory test machine and recommended it for the AAMAS method of mixture design, with a caveat: because insufficient data exist regarding mixtures designed with the gyratory testing machine, additional pavements must be designed, built, and monitored to provide validation of the machine.

The AAMAS method of mix design was a precursor to the SHRP method; it was intended to set the stage and act as a pilot program. Various portions of the SHRP research plans, including determination of a laboratory compactor, were designed based on results of the AAMAS study. Hence, the gyratory test machine and its limitations were considered by SHRP.

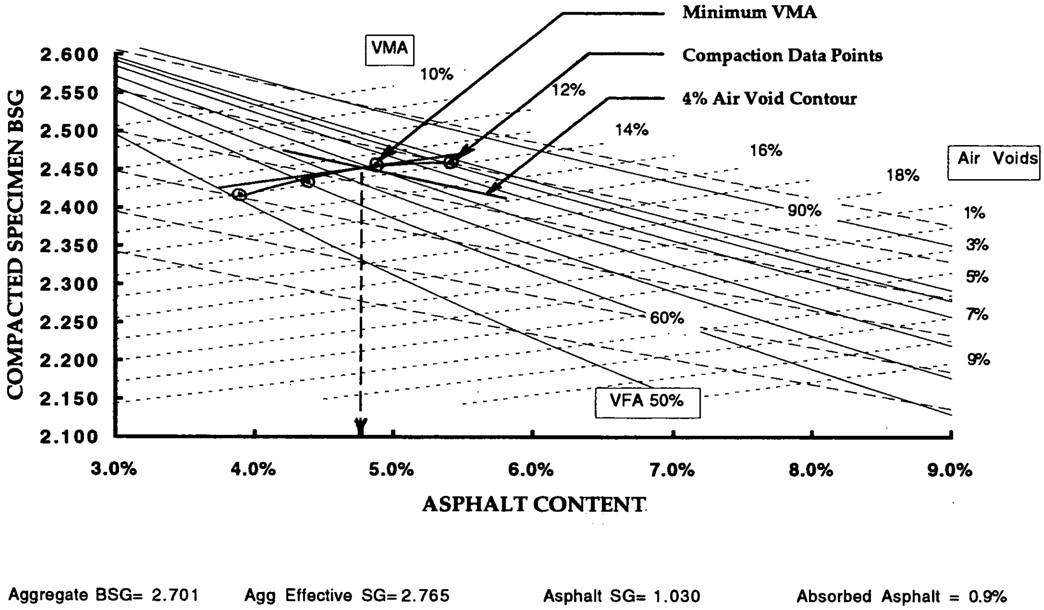

FIGURE 5 Relationship of air voids, VMA, and voids filled with asphalt for Interstate 43 (19-mm nominal maximum size mixture).

Mr. McRae's discussion focuses on promoting the Army Corps of Engineers' gyratory testing machine. The authors believe the SHRP gyratory compactor, complete with validation including the study reported in this paper, is the device that best meets the requirements for a laboratory compactor within the context of the SHRP SUPERPAVE mixture design system.

This paper represents the views and opinions of the authors and not necessarily SHRP, Asphalt Institute, or University of Kentucky.

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