SUPERPAVE® Compaction

BRIAN J. COREE AND KERA VANDERHORST

SUPERPAVE® has revolutionized the technology of asphalt mixture design and analysis. A significant element of this change has been the transition from impact compaction (Marshall) to that of gyratory compaction. The SUPERPAVE® Gyratory Compactor (SGC) has been developed from the Texas Gyratory Machine and the French Laboratoire des Ponts et Chaussees (LCPC) gyratory protocol. It is believed that the resulting mixtures more closely resemble those that have been compacted in normal construction practice. By recording the sample height throughout the compaction process, an entire history of compaction may be developed, in contrast to the traditional Marshall impact compaction process, wherein only the final compacted state of the mixture may be examined. There is, however, a fallacy in the method recommended by SUPERPAVE®: the resulting "compaction curve" cannot be considered to be fully representative of the compaction history of an "in-service" mixture. This is addressed in this paper. The SUPERPAVE® mixture expert task group (ETG) has recognized the concerns of state highway agencies and contractors and recommended that further strength tests be performed for Level 1 mixtures. The current direction for this additional testing is primarily focused on detecting unstable, or rut-susceptible, mixtures. The leading contenders for this type of testing are the many and various flavors of rut-testers: the Hamburg Rut-Tester, the Georgia Loaded-Wheel Tester, the Asphalt Analyzer, etc. These all require the use of added equipment and, in most cases, different sample compaction techniques. The authors propose a testing procedure using the SGC that is simple, direct and inexpensive. Key words: SUPERPAVE®, SGC, compaction, plasticity, rutting.

INTRODUCTION

A significant component of the SUPERPAVE® Volumetric (erstwhile Level 1) mix design protocol relies on the compaction procedure. This procedure uses the SUPERPAVE® Gyratory Compactor (SGC) which imparts a constant vertical pressure of 600kPa to the sample while rotating (or gyrating) the sample with an eccentricity of 1.25° from the vertical axis. It is claimed that this method of compaction results in a material that more closely resembles that on the road in terms of particle alignment and density (*1*). This laboratory compaction process proceeds through three landmarks: N_{init} which corresponds to the state of the mixture as the breakdown roller makes its first few passes; N_{des} representing the anticipated state of density in the mixture after 3 to 5 years of service; and N_{max} which represents a "factor-of-safety" condition should the traffic projections be seriously underestimated or the climate hotter than anticipated. The bulk specific gravity of the sample, G_{mb}, is measured after complete compaction to N_{max} gyrations. With this parameter and a knowledge of the maximum theoretical specific gravity of the mixture, G_{mm}, the volumetric parameters of the mixture (Va, VMA and VFA) are "back-calculated" for any degree of compaction ($0 < N_{gyr} < N_{max}$).

Center for Transportation Research and Education, Iowa State University, 484 Town Engineering, Ames, Iowa 50011.

SUPERPAVE® GYRATORY COMPACTION

The SUPERPAVE® compaction process was designed so that it "...would realistically compact trial mix specimens to densities achieved under actual pavement climate and loading conditions," and further "... that potential tender mixture behavior and similar compaction problems could be identified" (*1*). The first of these statements implies that the resulting compaction curve (% G_{mm} vs log(N)) will accurately represent the state of the mixture at any point in the anticipated life of the mixture, i.e., during construction and subsequently under traffic. Certainly the densities achieved by SGC compaction, measured on cooled samples, may more closely represent those measured on samples obtained from in-service pavement, although the recommended magnitudes of N_{des} may require "fine-tuning" (*3*). However, does the information presented on the SUPERPAVE® compaction curve (Figure 1) truly represent the state of the mixture during the laboratory compaction process?

During construction, the temperature of the mixture is typically in the range 80°C to 200°C. The greater part of the compaction is achieved while the mixture is in excess of 115°C. Under operating conditions under traffic, the mixture temperature may range (typically for Iowa) in the range -28°C to 58°C (as indicated by the grade of the binder, PG 58-28). In the laboratory, mixtures are compacted at an equi-viscous temperature ($T_{compaction}$) approximating a viscosity of 0.28 Pa.s throughout the compaction process. Thus the laboratory compaction procedure is reasonably representative of the construction compaction conditions, but not of in-service conditions. To what extent is this significant?

The compaction curve is being examined to determine to what extent it can be used as a surrogate "mixture suitability" test. Bahia (*4*) and others (*5*) are examining the properties of this curve. Bahia has in fact separated out the construction and trafficking components (differentiated at 92% G_{mm} or 8% air voids) and draws conclusions as to the suitability of the mixtures, separately for the construction and trafficked phases.

The authors accept the assumption that the state of the mixture during construction compaction is represented by the laboratory compaction curve up to a density of about 92% G_{mm}. Nonetheless, it should not be forgotten that this curve is developed based on sample height, and then back-calculated to provide the analytic density parameters; however, the trafficking, or in-service portion (% G_{mm} > 92%) reflects a condition of artificially elevated temperature during laboratory compaction. If it is assumed that at N_{des} the compaction is computed at 96% G_{mm}, the tacit assumption is that there are 4% air voids in the mixture. This is taken to be true at a temperature of 25°C or approximately in the cooled sample, but cannot hold at the elevated temperatures during compaction.

The compaction curve is typically a straight line, perhaps curving over to a more horizontal relationship beyond N_{des}. In Figure 1, the four conventional compaction curves (P_b = 4.2, 4.7, 5.2 and 5.7%) are essentially linear. Note, however, that the line representing the

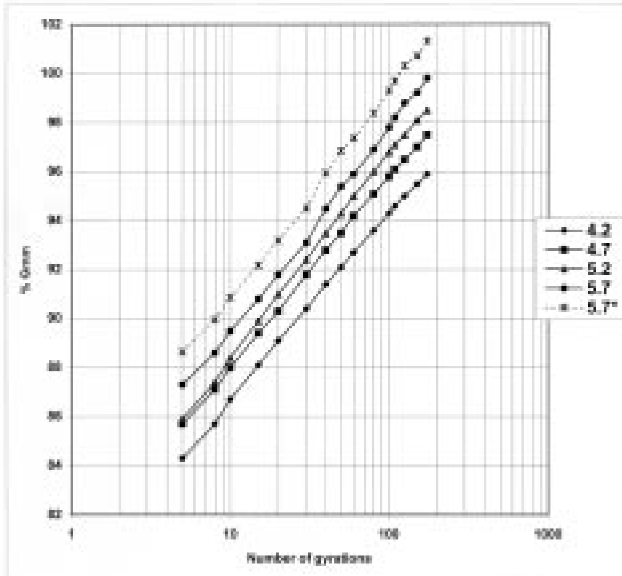

FIGURE 1 Typical SGC compaction curves (*1*).

"true" volumetrics (in this case at a $T_{compaction}$= 155°C) at P_b = 5.7 (noted as 5.7*) exceeds 100% G_{mm} at N_{max}! Even at N_{des} , the actual voids are 0.3% V_a and 97.8% VFA. These indicate that at this elevated temperature, the volume of the voidless mixture is greater than that of the mixture at 25°C when the bulk specific gravity was measured.

However, since the compaction curve is developed at elevated temperatures (~155°C), the volume of the binder during compaction is much greater than that assumed in the calculation of the G_{mm}. At a standard temperature of 25°C, the specific gravity of the binder may be assumed to be of the order of 1.020, *while at 155°C, the same material might have a specific gravity of only 0.933*, which is significantly different. In the design example given on pages 105-108 of reference (*1*), the compaction curves at different binder contents are all reasonably linear and compute to give air voids at N_{des} in the range 5.5% @ 4.2% P_b to 1.9% at 5.7% P_b and the voids filled parameter from 65% to 89% over the same binder range. Whereas during the compaction process, the actual air void contents at N_{des} can be computed to range from 4.5% at 4.2% P_b to 0.6% at 5.7% P_b and voids filled from 71% to 96%. This paints a very different picture that is not reflected by the compaction curve. The actual mixture condition during laboratory compaction (at 4.7% binder content) is V_a= 2.9%, VFA= 81% as opposed to the conventionally computed 4% and 74% respectively. A mixture with 2.9% air voids and voids filled of 81% might well be considered marginal, if not unstable, *but this potential instability is not reflected in the compaction curve*, and the picture only gets worse as the binder content increases (Figure 1). A summary of the reported and actual volumetric conditions for the example given are shown in Table 1.

TABLE 1 Reported Versus Actual Volumetrics of Example Mixture at N_{des}

Binder Content, P_b%	Reported Values V_a	VFA	VMA	Actual Values V_a	VFA
4.2	5.5	59.3	13.4	4.5	70.7
4.7	3.9	70.1	13.2	2.9	80.8
5.2	3.0	77.9	13.4	1.8	88.3
5.7	1.9	86.2	13.6	0.6	96.1

Rutting Plasticity

It is frequently assumed (*6,7*) that rutting plasticity, or permanent vertical strain, at N repetitions of load, e^p_N, can be characterized from the initial permanent strain, e^p_1, and the slope of the $\log(e^p_N)$ vs log(N) plot, in accordance with the following relationship:

$$\varepsilon^p_N = \varepsilon_1{}^p N^s \text{ or } \log(\varepsilon^p_N) = \log(\varepsilon_1{}^p) + S.\log(N)$$

It is not possible, however, to obtain neither a linear log-log relationship nor even a linear semi-log relationship using the recommended SGC. Thus, the SGC data does not conform to the rutting models adopted or investigated by SUPERPAVE® (*6, 7*).

The inability of the SGC compaction curve to highlight plastic instability is attributed to the fact that the mixture is so effectively contained within the relatively infinitely rigid walls of the mold and the equally rigid top and bottom platens that the type of lateral plastic flow observed in rutting pavement is totally prevented, even though the actual state of the mixture may be wholly plastic during laboratory compaction (e.g. at 5.7% P_b , V_a= 0.6% and VFA = 96.1%.)

CAN THE SGC BE USED TO EVALUATE PLASTIC INSTABILITY?

Given the above statements, can the SGC be used to evaluate plastic instability? The answer is yes, but with some qualification. Alternate equipment (the Hamburg Rut-Tester, the Georgia Loaded-Wheel Tester, the Asphalt Analyzer, etc.) allow lateral plastic flow to develop under the load by running tire-like loads over compacted slabs of asphalt, thereby more closely simulating actual performance in the pavement. More theoretical material models must be used in conjunction with the Superpave Shear Tester (SST) to measure "fundamental" mixture response parameters in order to yield more accurate rutting models. To therefore use the SGC, a means must be found to permit the same type and degree of plastic response in the mixture sample. The authors propose the method described below. This method is under current development and pilot-testing at this time and it is recognized that much work remains to more closely define operational standards and performance-related criteria.

Under current operational procedures, an "optimum" binder content is defined by using the method recommended under the SUPERPAVE® Volumetric design protocol. The resulting candidate mixture is further tested for resistance to stripping by AASHTO T-283. It is proposed that an extra batch (or batches) be made up at this stage and tested as follows:

- Each sample is compacted in the usual fashion (at $T_{compaction}$, 600kPa and 30rpm) to 92% G_{mm}, based on data already obtained; thereby representing compaction during construction at appropriate pressures and temperatures.

- The mold, complete with sample, is placed in a controlled oven, and brought to an operational temperature. This temperature is currently proposed as the high temperature used in the appropriate PG grading, i.e. the average 7-day maximum temperature at a depth of 20mm in the pavement. Preliminary testing has shown that it takes approximately 12 hours to achieve a state of thermal uniformity throughout the sample.
- The mold and sample are replaced into the SGC, but instead of the full 150mm dia. (nom.) top platen, a modified top platen with a reduced contact area (typically 100mm dia.) and about 25mm deep is placed between the sample and the top platen. The pressure may be adjusted to simulate different design tire pressures, for example, instead of the 600kPa on the full 150mm dia. top platen (87psi), indicated pressures of 307kPa (100psi on the reduced contact area) or 368kPa (120psi) may be used. This then simulates a *project specific traffic compaction scenario*, while allowing an annular gap of 25mm (nom.) around the axial loading plate for plasticity to develop.
- Compaction (at $T_{compaction} = T_{average\ 7\text{-}day\ maximum\ pavement\ temperature}$ and 30rpm) is continued (currently for 250 gyrations). The sample height is recorded continuously. Since the sample is no longer uniform in height or density, comparison to G_{mm} is not appropriate.
- Normalize the sample height to percent vertical strain (ε = 100 x [(height at N=1) - (height at N)]/ (height at N=1).
- Plot log(vertical strain) versus log(N): it will be observed that this relationship is essentially linear.
- By linear regression, obtain the values of the intercept, $\varepsilon^p{}_1$, and slope, S. These correspond to the SUPERPAVE® rutting model parameters and can be used in the same manner to predict rutting.

Preliminary Test Results

A preliminary set of tests has been performed using this protocol on an arbitrary aggregate gradation. This pilot study was undertaken in order to check that (a) the method itself did not compromise the equipment by testing mixtures at 58°C which are much stiffer than those tested at 155°C, and (b) that the resulting log(vertical strain) vs log(N) would be indeed be linear in accordance with the SUPERPAVE® prediction models.

Mixtures were made up at 4.0, 4.5, 5.0, 5.5 and 6.0% binder contents. The asphalt binder was a "generic" AC-10 available in the laboratory. In order to expedite the pilot study, the specific gravities of the blended aggregates were not determined, consequently the VMA and VFA parameters derived below are based on aggregate effective specific gravity, and are thus biased. The conventional volumetrics at N_{max}= 150 are summarized in Table 2.

Each mixture was tested according to the protocol outlined above. The log(vertical strain) vs log(N) results were plotted and examined. From N > 10, the relationships were closely linear and are shown in Figure 2 and therefore meet the general expectations of the SUPERPAVE® rutting model. A further plot of the vertical strain against binder content, P_b, at various levels of traffic (or N) is shown in Figure 3, in which it is clearly demonstrated that the mixtures become significantly more plastic at binder contents in excess of 5.0% at all levels of trafficking (or N). This plot is wholly complementary to results reported by Monismith and Vallerga on a similar study in 1956 (*9*).

TABLE 2 Sample Volumetrics Summarized

Binder Content, P_b%	V_a%	VMA %	VFA %	N(@ 92% G_{mm}
4.0	4.2	15.3	72.8	45
4.5	2.9	15.1	80.6	29
5.0	1.4	15.2	91.0	16
5.5	1.0	16.1	93.6	11
6.0	0.1	16.7	99.1	7

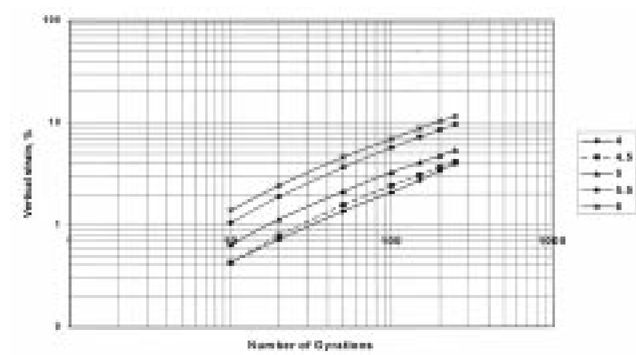

FIGURE 2 Strain development in proposed protocol.

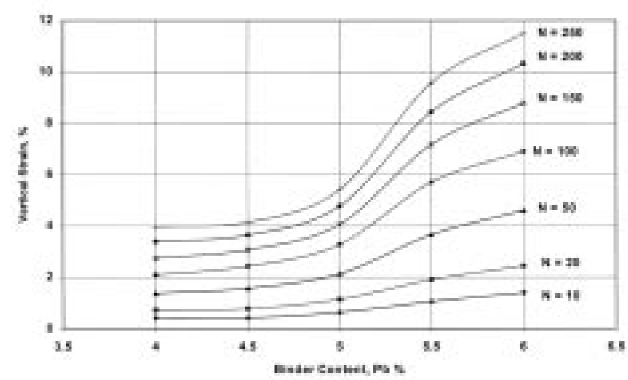

FIGURE 3 Observed strain development by binder content.

Conventional SGC Protocol Revisited

At this point, it was realized that trying to obtain a linear log(vertical strain) vs log(N) plot from the conventional SGC compaction curve (to N_{max} at $T_{compaction}$) was not necessarily appropriate. The initial state of these mixtures is not, in fact, known. It is likely that the richer mixtures will self-compact more than drier mixtures due to charging the mold even before loading begins. Using the recorded compaction information, the strains were recomputed using the heights at 92% G_{mm} as the reference height. The results are shown in the log-log plot in Figure 4, in which it is seen that potentially linear trends are being modified at higher levels of compaction such that strains become almost asymptotic to a horizontal (con-

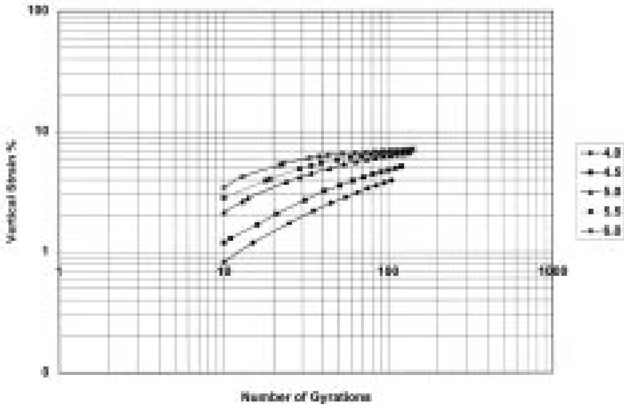

FIGURE 4 Constrained strain in SGC.

stant) value between 7 and 8%. This fresh observation lends credence to the earlier assumption that the extreme rigidity and confinement provided by the mold walls and loading platens is preventing the development of lateral plastic flow.

CONCLUSIONS

The conventional SGC compaction curve cannot be used to identify rutting plasticity in asphalt mixtures. Truly unstable conditions may indeed occur during laboratory compaction and are not so identified.

A modified protocol is proposed by which plastic instability can be readily measured and identified. This method can also yield the parameters required by the SUPERPAVE® rutting model.

Further development and refinement of the method is needed before definitive statements cat be made as to its utility in practice, in particular, validation of the method against mixtures of known rutting sensitivity will be required.

FURTHER WORK

Further testing of both laboratory and real mixtures will be undertaken to refine the operating parameters of this protocol. Real mixtures with known rutting performance (both the good and the bad) will be tested to validate the method and, hopefully, to define performance-related criteria of acceptability.

The geometry of the testing set-up lends itself to a more complete analysis of the states of stress and strain during the test. This may provide a more "rigorous" validation of the testing environment. The strain vs loading results obtained so far appear to conform to some of the concepts of mixture rheology, and may be amenable to a more focused analytical model of rutting instability in asphalt mixtures.

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