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ABSTRACT

The need for accurate, consistent volumetric measurements of hot mix asphalt (HMA) has become increasingly important in the past few years. This change has come about because more and more states are utilizing volumetrics to design the HMA mixtures and then to evaluate them during construction. Since volumetrics are now widely used for quality assurance, it has become a major concern for both the state and the contractor to measure these properties with accuracy and reliability. Minor changes in volumetric properties may be the difference in whether a contractor receives full pay or reduced pay for produced mixtures.

It is believed that differences in how mixtures are handled and tested have played a role in discrepancies between government agency and contractor test results. The objective of this study was to evaluate the effects of re-heating and compaction temperatures on the volumetric properties of HMA mixtures. These effects were studied with two experiments. In the first experiment, mix was compacted after 0, 3 and 20 hours storage. In the second experiment, mix was compacted at three different temperatures; standard target compaction temperature for the grade of asphalt cement in the mixture, target-14°C and target+14°C. These two conditions generally vary from laboratory to laboratory and are believed to cause changes in mixture properties. Fine and coarse graded mixtures comprised of granite and sandstone aggregate with PG64 and PG76 binder were compacted with the Superpave Gyratory Compactor (SGC) and their volumetric properties measured.

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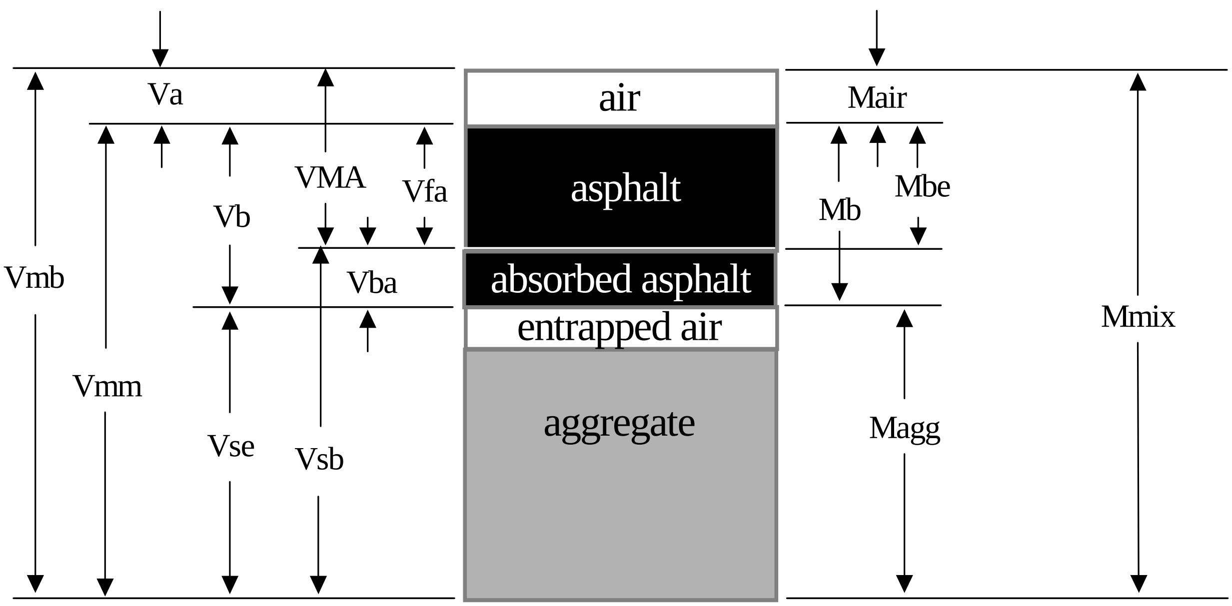
INTRODUCTION

In the hot mix asphalt (HMA) construction industry, the need for accurate, consistent volumetric measurements has recently become more important. Since more states are relying on volumetric properties to both design the mixture and then to evaluate the final product during the construction phase, the need for reliable test results has become a necessity. Volumetrics are being widely used to determine the pay a contractor will receive for constructed HMA.

It is believed by some that discrepancies between agency and contractor test results may be partially related to re-heating mixture samples that have cooled below compaction temperatures. Also, when re-heating mixtures, the compaction temperature, if not closely monitored, could be inaccurate and thus cause more deviation. The effect of these two issues needs to be looked at more closely to determine if they significantly affect sample volumetrics.

Hot Mix Asphalt Volumetrics

There are three volumetric properties most commonly measured to evaluate the physical characteristics of HMA (*1*): voids in total mix (VTM), voids in mineral aggregate (VMA), and voids filled with asphalt cement (VFA). These mixture properties are explained in Figure 1 and defined as follows:



VMA = Volume of voids in mineral aggregate
V_{mb} = Bulk volume of compacted mix
V_{mm} = Voidless volume of paving mix
V_{fa} = Volume of voids filled with asphalt
V_a = Volume of air voids
V_b = Volume of asphalt binder
V_{ba} = Volume of absorbed asphalt binder
V_{sb} = Volume of mineral aggregate (by bulk specific gravity)
V_{se} = Volume of mineral aggregate (by effective specific gravity)

M_{mix} = Total mass of asphalt mixture
M_b = Mass of asphalt binder
M_{be} = Mass of effective aggregate binder
M_{agg} = Mass of aggregate
M_{air} = Mass of air = 0

Figure 1. Components of a Compacted HMA Specimen (*2*)

<u>Voids in Total Mix (VTM)</u> - The total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as a percent of the volume of the compacted paving mixture.

<u>Voids in the Mineral Aggregate (VMA)</u> - The volume of intergranular void space between the aggregate particles of a compacted paving mixture that includes the air voids and asphalt cement not absorbed into the aggregates.

<u>Voids Filled with Asphalt Cement (VFA)</u> - The volume of the VMA, expressed as a percentage, that is filled with asphalt cement.

These properties are measured during mix design and production of HMA.

BACKGROUND

In quality control and quality assurance methods the different ways in which mixtures are handled prior to testing is believed to play a role in the variability between governmental agency and contractor measured properties. One common reason given for these differences has been the effect of re-heating the HMA mixture prior to laboratory compaction. There are two reasons for re-heating of the mixture. One reason for re-heating the mixture is a result of transporting the sample to the laboratory for testing, while the second occurs when either referee or verification samples must be tested. Referee samples are taken and set aside for possible testing when case discrepancies occur between contractor and agency results. These samples will have cooled for hours or even days. In order to compact these mixtures they must be re-heated to compaction temperatures. The method used to reach that temperature is believed to have an effect on the properties of the mixtures. Some states have established standard procedures for this process in an attempt to reduce variability, however problems and discrepancies may still occur. Methods of re-heating used by three state DOTs are provided below.

Alabama Method (<u>3</u>):
Where feasible, both the contractor and the government agency perform testing on site at the plant producing the mixture. However, in some cases the agency or the contractor may transport their samples over some distance to another laboratory. When this occurs the distance traveled might be far enough to allow the mixture to cool sufficiently to require re-heating prior to compacting samples. Samples are typically tested at the contractors plant site, however, this can not always be done. Although the samples are packed in insulated containers to minimize heat loss, the travel time may be 1 to 2 hours or longer. When this happens, the mixture may require re-heating to achieve the proper test temperature. A referee system is also sometimes used which requires re-heating. Referee samples are sometimes stored for as long as one week before they are tested.

North Carolina Method (<u>4</u>, <u>5</u>):
In North Carolina, 150 pounds of mix is sampled from a truck and split into four quarters. Half of the material is taken by the contractor while the other half goes to the state. These two portions are then split again by each party with half tested and the other half retained for re-testing if discrepancies result. The contractor's samples are tested onsite while the state usually transports their samples to another location for testing. The distance traveled typically takes from 30 to 45 minutes, which allows cooling that usually requires re-heating to achieve a workable condition. The contractor as well as the state retain material from their samples in case differences occur. These retained samples require re-heating to a workable temperature for splitting and additional heating to compaction temperature.

Colorado Method (6):
Quality Control issues are handled in Colorado with procedures similar to most other states, i.e., both the state and the contractor measure mixture properties. The samples taken by the state for payment purposes are referred to as regional samples. These samples are taken, along with the contractors samples, at the paver. They are transported to either a regional lab or to a mobile lab as dictated by travel distances. In these instances, travel times up to two hours will likely require re-heating. Since the contractor's sample is taken at the paver, some re-heating might also be necessary. Other samples that are taken periodically are for the state central laboratory to verify test results from regional laboratories. The samples often are stored for days before they are tested.

Previous Re-Heating Work

Not much has been done in the way of researching the effect of re-heating on HMA properties. Only one source could be located that made mention of this issue and how it may or may not affect results. An analysis (7) was done on collected QC/QA data in the state of Alabama for Superpave Mixes. The objective of the study was to compare variability and accuracy in achieving target production values for Marshall and Superpave mixes. Part of the study looked at the possible effect of re-heating on air void percentages (VTM). Contractors compacted samples at plant sites, but mix for ALDOT samples required transport to division laboratories where re-heating was required prior to compaction. The mean air void percentage of over 600 contractor measurements and over 300 ALDOT measurements, shown in Table 1, differed by only 0.01 percent. This difference is insignificant. However, there were several other uncontrolled variables associated with the statistics and more direct comparisons are needed to definitively establish the influence of re-heating.

Table 1. Comparison of Contractor and ALDOT Voids for 1997 Superpave Projects (7)

Agency	No. of Measurements	Mean Air Voids (%)	Stan. Deviation (%)
Contractor	605	3.92	0.99
ALDOT	325	3.93	1.05

Compaction Temperature Variability

When mixtures are re-heated for compaction, another issue develops that may affect the final properties of compacted samples. This issue is control of the test temperature. Only one of the three above states, Colorado, mentions a standard procedure for re-heating (6). North Carolina defines only the temperature to produce a workable condition for quartering (4). If samples are not controlled carefully during re-heating, they could either be accidently overheated or held at an elevated temperature longer than necessary. These problems could often occur without the use of standard re-heating procedures. Either of these situations could affect the final mixture properties. Also, if care is not taken, the temperature at which the mixture is compacted might be either higher or lower than the target compaction temperature. If no standard procedure is followed for re-heating nor for selecting compaction temperature, the chance that discrepancies will occur between contractor and agency test results is high.

Temperature and Compactability
Because of asphalt cement viscosity changes with temperature, mix compaction temperature is important. However, one study performed at the University of Wisconsin-Madison, NCHRP 9-10 (8), showed surprising data that indicated little change in density with change in compaction temperature. Samples were compacted at temperatures from 155°C to 80°C and measured to determine VTM, VMA, and VFA percentages. Table 2 shows the limited data that was

developed. This data showed that although the asphalt cement viscosity changed by three orders of magnitude between 80°C and 155°C, compaction temperature had little to no effect on volumetric properties of the compacted samples. Because there was some concern with the methods which were used in the pilot study, a second evaluation was carried out. This time other modes of laboratory compaction were utilized along with the SGC. In this second study, similar mixture samples were compacted on four different compactors utilizing three different compaction temperatures. These test temperatures were 160°C, 115°C, and 80°C. The results of this work, as illustrated in Figure 2, showed that all four compactors differed in terms of sensitivity to temperature, with the SGC being the least sensitive. It was also mentioned in this report that some had expressed concern that the SGC applied too much compactive effort (8). If this information is correct, then the allowable range of compaction temperatures may be broader for the SGC than is currently specified.

Table 2. Volumetric Properties of Mixtures Re-Compacted with the SGC at Decreasing Temperatures (@N_{design}) (8)

Temperature, °C	Air Voids, %	VMA, %	VFA, %
Coarse Gradation, Limestone			
155	4.3	14.5	70.3
145	5.1	15.2	66.3
130	4.5	14.6	69.5
115	4.7	14.8	68.5
80	4.8	14.9	67.7
Fine Gradation, Crushed Gravel			
155	4.2	14.9	72.1
145	3.7	14.5	74.6
130	4.0	14.7	73.1
115	3.6	14.4	74.9
100	3.7	14.5	74.6
80	4.2	14.9	71.9

OBJECTIVES

The objectives of this study were to evaluate the effects of both re-heating and compaction temperature on volumetric properties of HMA mixtures. The primary focus was to determine how storage (cooling) and re-heating of the mixture to its respective compaction temperature affected volumetric properties. Also, as a secondary focus, the effect of inaccurate compaction temperatures was studied to determine if lack of temperature control might increase the chances of mixture property variability. All mixtures were compacted with the Superpave Gyratory Compactor (SGC) with a consistent compactive effort of 100 gyrations. After compaction, mixture volumetric properties were determined.

SCOPE

This study consisted of compacting various mixtures at three temperatures with the same compactive effort to determine their volumetric properties. In order to consider a range of mixtures, two aggregate sources, two gradations, and two grades of asphalt cement were utilized.

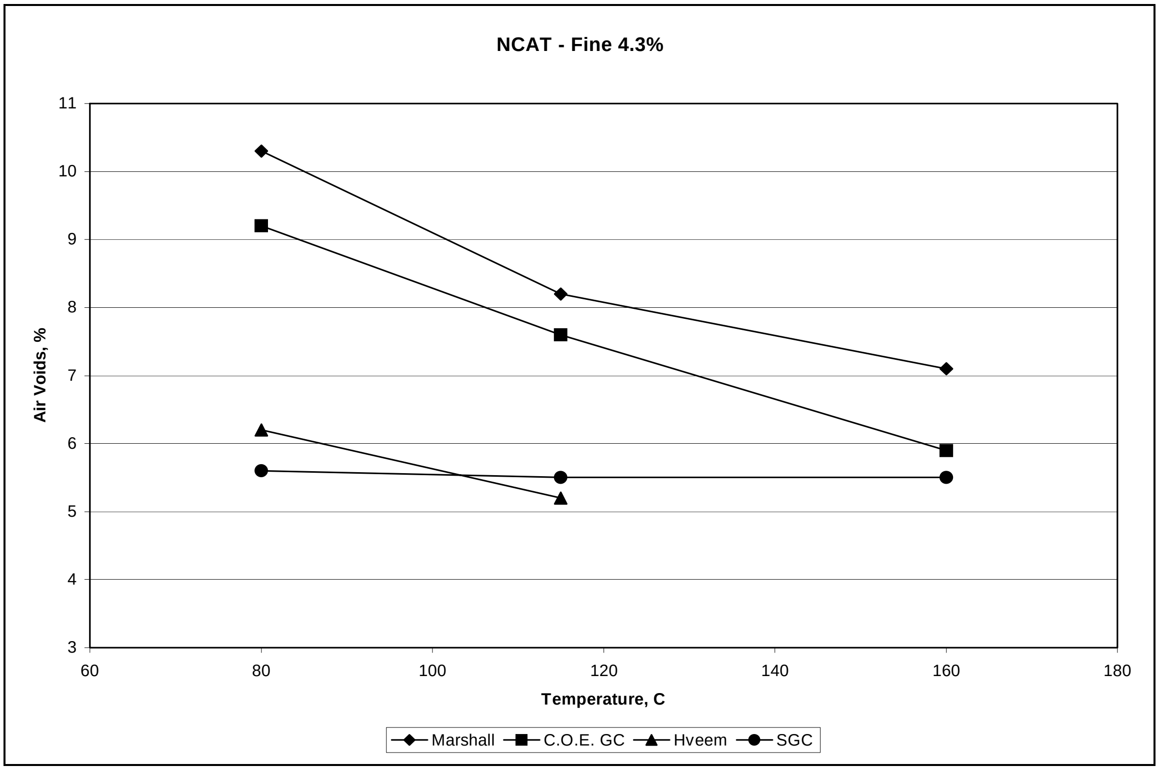


Figure 2. Effect of Temperature on Air Voids Measured after Compaction Using Different Compaction Methods for HMA Containing a Fine Crushed Gravel Mixture (7)

The aggregate sources differed in moisture absorption percentages, one high and the other low. The two gradations were a coarse-graded and a fine-graded Superpave gradation. Two grades of asphalt cement were a PG64-22 and a PG76-22. Three storage times (0, 3 and 20 hours) were used throughout the study. Storage time refers to the additional time a mixture was allowed to sit at room temperature (approximately 25°C) after an initial four-hour aging.

In addition, the effect of compaction temperature was studied by compacting identical samples at three different compaction temperatures. The temperatures used in this phase of the study were the standard compaction temperature for the specific asphalt grade being tested and the standard compaction temperature ±14°C. These temperatures were 135, 149 and 163°C for the PG64-22 binder and 149, 163 and 177°C for the PG76-22 binder to simulate compaction temperatures that are too high and too low.

TEST PLAN

The overall work plan for this study consisted of five tasks. In general, the work involved compacting different mixtures first by utilizing various storage times and then at different compaction temperatures. These compacted samples were then tested to measure their volumetric properties. Volumetric properties were next compared to determine if processing and testing variables had any significant effects. However, before any mixtures could be tested, asphalt contents were selected to give 4.0 percent air voids when compacted with 100 gyrations of the SGC. Each phase is discussed in detail in the following sections. Figure 3 shows the overall test plan that was followed.

Development of Mix Designs

The first step in the test plan was to develop mix designs for each of the mixtures. The two aggregate types, two asphalt cements, and two gradations created eight different mixture combinations. Three point designs were performed to determine asphalt contents that provided 4.0 percent air voids (VTM) in each of the eight mixtures.

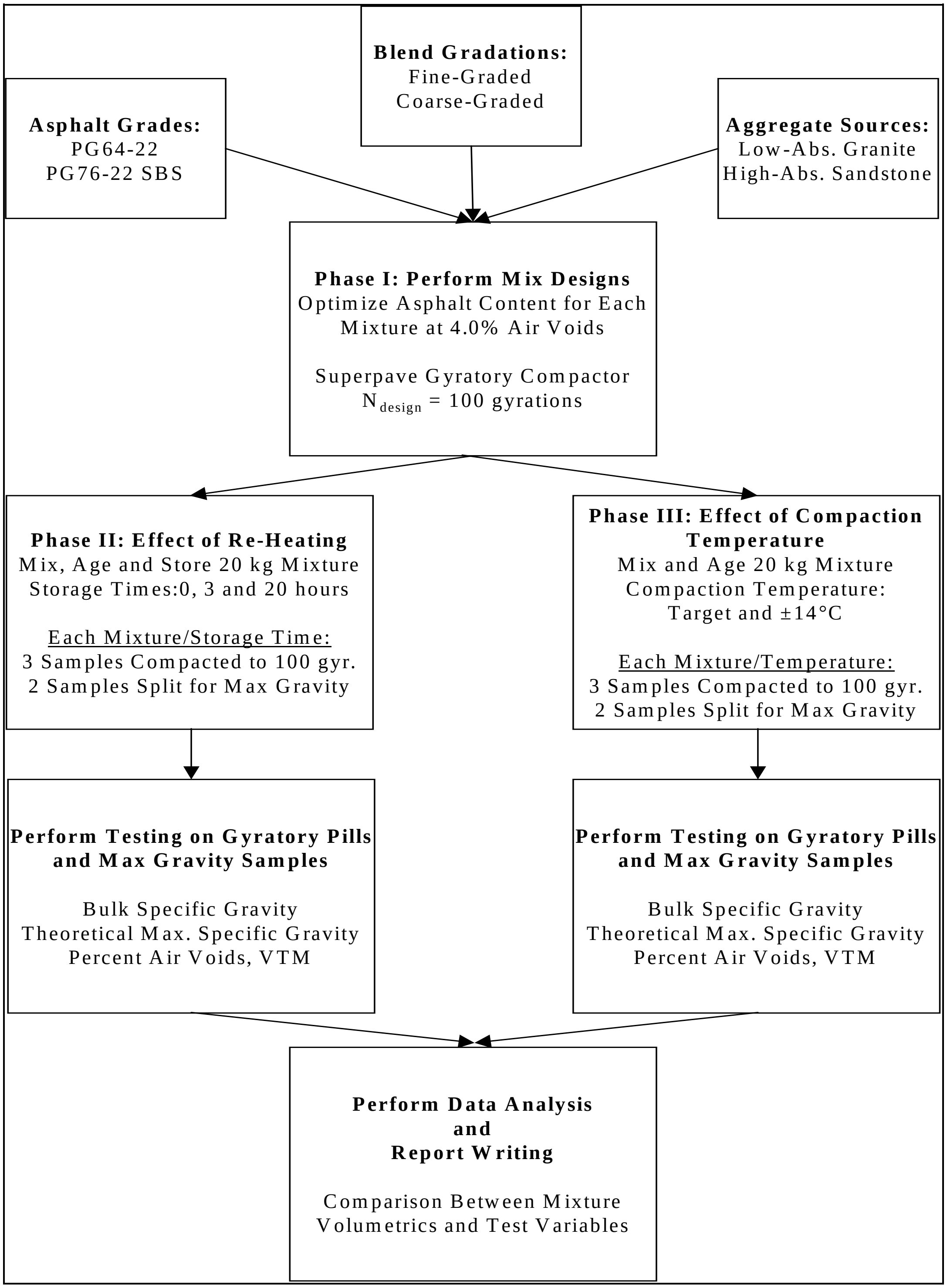


Figure 3. Flow Chart of Project Test Plan

Mixing and Short-Term Aging

Because 20,000 gram samples were required for evaluating storage time and compaction temperature, equivalent size samples were used in the design phase. For each mixture combination, three 20,000 gram samples were prepared, each at different asphalt cement contents. Once mixed, each of the large samples was placed in a pan for short term oven aging, as required by Superpave mix design procedures (AASHTO PP-2-99). All samples were placed in a forced-draft oven for four hours at 135°C to simulate production aging. Because of the need for a large pan size, the surface area requirement was not met. The AASHTO specification calls for a 21kg/m^2 mass to pan area ratio while these large pans with 20,000 gram samples had a mass to surface area of approximately 53kg/m^2.

Quartering Test Samples

Once the 20,000 gram sample had completed its four hour short-term age, it was pulled from the oven and rapidly quartered into four approximately equal portions. Out of each of three of the portions, 4800 gram samples were weighed out while two 1200 gram samples were taken from the fourth portion. The 4800 gram samples were compacted on the gyratory and the two 1200 gram samples were used to determine maximum mixture specific gravity. Once weighed into a pan, all test samples were then placed into another forced-draft oven and heated to the specific compaction temperature for the grade of asphalt cement in the mixture. The time needed to heat to compaction temperature after quartering was 20 to 30 minutes. The samples were closely monitored to minimize the time exposed to excess temperatures.

Superpave Gyratory Compaction

When the 4800 gram samples reached compaction temperature, they were compacted with 100 gyrations in the Superpave gyratory compactor. This gyration level is the compactive effort for 3.0-30 million ESALs. After compaction, samples were cooled overnight before being tested. The 1200 gram samples were also pulled from the oven once they reached compaction temperature and left to cool prior to maximum specific gravity testing.

Optimum Asphalt Content Determination

The gyratory compacted samples were tested according to AASHTO T-166 to determine bulk specific gravity. The 1200 gram samples were tested according to AASHTO T-209 to determine their theoretical maximum specific gravity. Since there were three sets of maximum gravity samples, each at different asphalt cement contents, the effective specific gravity of the aggregate was determined for each asphalt content and then averaged. This average effective gravity was used to back calculate maximum specific gravities for each asphalt cement content used in the design. With these two values, the bulk and maximum gravities, the air voids (VTM) in each sample were determined. The three samples for a given blend combination were prepared at different asphalt cement contents to bracket the target of 4.0 percent air voids. The optimum asphalt content was determined from these results.

Effect of Storage Plus Re-Heating

In this portion of the study, the effect of re-heating on HMA volumetrics was evaluated. The goal of this part of the study was to simulate what happens to mixtures during QC/QA work on paving projects. When samples are taken, some are split down to testing size and tested immediately, others may be either transported to another laboratory for quartering and testing or stored for possible testing on a later date. Therefore, in this phase sample storage times were varied prior to compaction.

Storage Times

The storage time refers to the amount of time that each mixture was allowed to cool at room temperature after its initial four hour short-term aging process prior to heating to compaction temperature. Storage times of 0, 3 and 20 hours were used. The zero (0) storage time means that no cooling time was allowed between aging and heating to compaction temperature. These samples might represent samples that are typically quartered and tested immediately after sampling. The three hour samples represent samples that are transported to another laboratory before quartering and testing. The twenty hour samples might represent referee or verification samples that may be tested after several days of storage. The 3 and 20 hour samples were left in their aging pans, but covered with aluminum foil during the storage phase.

Quartering and Re-Heating of Samples
The zero storage time samples were pulled from the oven after the four hour short-term age, split into three 4800 gram gyratory and two 1200 gram maximum gravity test samples, and placed into another oven for heating to compaction temperature. The 3 and 20 hour storage time samples had cooled and had to be re-heated to achieve a workable condition for quartering. These samples were placed into the aging oven in the large aging pans. They were covered with aluminum foil during the re-heating stage so as to minimize oxidation of the mixture. Obviously, the 3 hour samples had not cooled completely to room temperature, and did not require as long to re-heat. The re-heating times used for the 3 and 20 hour samples were 2 and 4 hours, respectively. Once workable, these samples were quartered and placed into another oven for heating to compaction temperature. Once in the compaction oven, all test samples took approximately 30 minutes to achieve compaction temperature.

Gyratory Compaction and Testing
After gyratory test samples reached compaction temperature, they were compacted in the Superpave gyratory with 100 gyrations. They were allowed to cool overnight before measuring their bulk specific gravities. For each combination of aggregate type, asphalt cement grade, blend gradation, and storage time, three samples were compacted. Along with these three gyratory samples, two maximum gravity samples were tested. The average maximum gravity value determined from testing was used to calculate the percent air voids for each compacted specimen. Also, VMA and VFA calculations were performed. Thus, for each of the eight material combinations, nine samples were compacted (3 at 3 different storage times).

Effect of Compaction Temperature

In the third part of the study the effect of compaction temperature was evaluated. During QC/QA testing, inaccurate control of compaction temperature could very well occur. It has always been assumed that the compacted density of HMA is very dependent upon the temperature. As was shown in Figure 2, the percentage of air voids achieved by the Marshall hammer decreased from approximately 10.3 to 7.1 when increasing the compaction temperature from 80 to 160°C. This figure also showed that compaction with the SGC is less sensitive to temperature than with Marshall hammers. Therefore, the compaction temperature of these laboratory prepared mixes was varied to determine whether or not poor control would significantly increase the variability of volumetric properties.

Three 20,000 gram samples were prepared for each of the eight mixture combinations. Once mixed, these samples were aged for the standard four hours at 135°C, removed from the aging oven and split into three 4800 gram and two 1200 gram samples. The samples were then immediately heated to compaction temperature and compacted.

The three compaction temperatures used were the target temperature for that specific binder grade and ±14°C. The maximum gravity test samples were also heated to the standard compaction temperature prior to testing. For each of the eight mixture combinations, three sets of three gyratory test samples, differing only by compaction temperature, were prepared. The six maximum gravity test samples for each mixture were averaged and used for volumetric calculations.

TEST RESULTS

Data Presentation (Coding System)

In order to delineate the different mixtures used in the project a coding system was developed. The coding system used for both graphical and tabular presentations throughout the paper is shown in an example as follows:

LOW-64-F

where,

LOW = Aggregate Type (Absorption Characteristic)
64 = Binder Type (Superpave Performance Grade)
F = Blend Type (Gradation: Fine or Coarse Graded)

Mix Design Results

Table 3 shows asphalt contents for 4 percent air voids, as well as corresponding VMA and VFA, for the eight different mixture combinations. The data in Table 3 shows that although the percentages of VMA in the sandstone mixtures (the high absorptive mixes) are considerably lower, the optimum asphalt contents are higher than those of the granite mixtures. This is primarily a result of the absorptive nature of the sandstone requiring more asphalt cement. Thus, the percentages of VFA are also lower for the sandstone mixtures.

Table 3. Optimum Mixture Properties for Eight Research Mixtures

Optimum Mixture Properties			
Mixture Type	**Asphalt Content for 4.0% VTM**	**VMA, %**	**VFA, %**
LOW-64-F	4.5	14.0	71.0
LOW-64-C	5.1	15.2	75.0
LOW-76-F	4.5	14.3	72.5
LOW-76-C	4.9	14.9	72.5
HIGH-64-F	5.6	10.6	63.0
HIGH-64-C	5.3	10.8	62.0
HIGH-76-F	5.5	10.6	63.0
HIGH-76-C	5.2	10.6	62.0

Effect of Re-Heating Data

In the re-heating phase of the study, samples of each of the eight mixture combinations were compacted with the SGC after being subjected to different storage times. Each sample was exposed to the same amount of short-term aging prior to storage, and compacted at the same temperature using the same number of gyrations. The storage time, as stated previously, refers to the amount of time that a sample is removed from the short-term aging oven and allowed to cool at room temperature before being quartered into test samples for compaction. The storage times evaluated were 0, 3, and 20 hours. Since the samples were allowed to cool, re-heating was a necessity to achieve a workable condition for quartering. Also, after quartering, the test samples had to continue to be heated to reach compaction temperature. The temperature used in this phase was the target temperature for the specific grade of asphalt cement being used. Volumetric property averages are shown in Tables 4-6 for each storage time evaluated.

Table 4 shows the average percentage of air voids (VTM) for storage time utilized for each mixture type evaluated. The 0 storage time basically represents a reproduction of the optimum mixtures as generated by the original mix designs. Although 4.0 percent VTM was targeted in the mix design phase, the 0 storage time values are slightly different, however, this small difference had no significant effect. Since production mixtures typically vary from their target VTM, these void levels were considered acceptable.

Table 4. Average Percent Air Voids vs. Storage Time

Average VTM vs. Storage Time				
Mixture Type	**Asphalt Content,%**	**Storage = 0 hr (VTM)**	**Storage = 3 hr (VTM)**	**Storage = 20 hr (VTM)**
LOW-64-F	4.5	4.8	4.7	4.6
LOW-64-C	5.1	3.5	3.8	4.2
LOW-76-F	4.5	4.4	3.8	4.3
LOW-76-C	4.9	3.7	3.0	3.7
HIGH-64-F	5.6	4.9	5.4	5.1
HIGH-64-C	5.3	5.0	4.8	4.7
HIGH-76-F	5.5	4.0	3.5	4.4
HIGH-76-C	5.2	3.7	3.6	4.0

Average VMA percentages are given in Table 5 for each storage time. The values for the four low-absorption granite mixtures are fairly normal for Superpave mixes, however, the high-absorption sandstone mixtures have low VMA values that are typically unacceptable. This low percentage was not intended, but does give a representation of the effects of storage times on low-VMA mixtures. Again, the 0 storage times represent the baseline mixture while the 3 and 20 hour samples represent re-heating.

Lastly, the percentage of voids filled with asphalt, VFA, versus storage time is shown for each mixture combination in Table 6. Since VFA is calculated using both VTM and VMA, it can be expected that any effect seen in values of voids and/or VMA will also show differences in VFA. Since all eight mixtures had approximately equal VTM percentages and four of the eight had much lower VMA percentages, it would be expected that those mixes with lower VMA will also have lower VFA values.

Table 5. Average Percent Voids in the Mineral Aggregate vs. Storage Time

Average VMA vs. Storage Time				
Mixture Type	**Asphalt Content,%**	**Storage = 0 hr (VMA)**	**Storage = 3 hr (VMA)**	**Storage = 20 hr (VMA)**
LOW-64-F	4.5	14.8	14.7	14.7
LOW-64-C	5.1	14.9	14.8	15.3
LOW-76-F	4.5	14.7	14.0	14.4
LOW-76-C	4.9	14.5	14.0	14.6
HIGH-64-F	5.6	11.2	11.5	11.5
HIGH-64-C	5.3	11.6	11.3	11.4
HIGH-76-F	5.5	10.6	10.7	11.1
HIGH-76-C	5.2	10.6	10.3	10.7

Table 6. Average Percent Voids Filled with Asphalt vs. Storage Time

Average VFA vs. Storage Time				
Mixture Type	**Asphalt Content,%**	**Storage = 0 hr (VFA)**	**Storage = 3 hr (VFA)**	**Storage = 20 hr (VFA)**
LOW-64-F	4.5	67.3	68.2	68.9
LOW-64-C	5.1	76.4	74.5	72.9
LOW-76-F	4.5	70.1	72.6	70.0
LOW-76-C	4.9	74.3	78.5	74.6
HIGH-64-F	5.6	56.3	53.3	55.5
HIGH-64-C	5.3	56.9	58.1	58.5
HIGH-76-F	5.5	62.6	67.2	60.6
HIGH-76-C	5.2	65.4	64.6	63.0

Effect of Compaction Temperature Data

In the compaction temperature evaluation, samples of each of the eight mixture types were compacted with the same number of gyrations on the SGC but at three different temperatures. This evaluation was performed to determine the effect of compaction temperature variation on volumetric property differences. For each of the eight research mixtures three samples were prepared at the optimum asphalt content. These three samples were aged for four hours, split into three gyratory test samples each and compacted utilizing three different temperatures. Thus, nine samples were compacted for each of the eight research mixtures, three for each of three compaction temperatures. The temperatures used in this phase were the target temperature for the grade of asphalt cement used in the research mixture as well as the target temperature ±14°C. Average volumetric properties are shown in Tables 7-9 for each of the mixture types.

As with the re-heating phase of the study, it was again shown in Table 7 that although the target VTM was 4.0 percent for each of the mixtures, the measured values for the test mixes did not always fall right on the target. Regardless, the air void percentages varied less than 1.0 percent from the target. Since the focus of the study was to determine the effect of temperature variation of volumetric properties, it was felt that no asphalt content adjustment was necessary. The air void range acquired is adequate to measure differences caused by temperature.

Tables 8 and 9 show the results for VMA and VFA.

The goal of this phase of the work was to determine the effect of the compaction temperature on the volumetric properties of each mixture type. The results show that there were very little differences in the VMA and VFA for the various compaction temperatures.

Table 7. Average Percent Air Voids vs. Compaction Temperature

Average VTM vs. Compaction Temperature				
Mixture Type	**Asphalt Content,%**	**Target Temp. -14° C (VTM)**	**Target Temp. (VTM)**	**Target Temp. +14° C (VTM)**
LOW-64-F	4.5	4.1	4.2	4.0
LOW-64-C	5.1	3.3	3.2	3.1
LOW-76-F	4.5	3.4	3.5	3.2
LOW-76-C	4.9	4.1	4.1	3.9
HIGH-64-F	5.6	4.4	4.3	4.2
HIGH-64-C	5.3	5.0	4.5	4.4
HIGH-76-F	5.5	4.0	4.0	4.1
HIGH-76-C	5.2	4.0	3.8	3.9

Table 8. Average Percent Voids in the Mineral Aggregate vs. Compaction Temperature

Average VMA vs. Compaction Temperature				
Mixture Type	**Asphalt Content,%**	**Target Temp. -14° C (VMA)**	**Target Temp. (VMA)**	**Target Temp. +14° C (VMA)**
LOW-64-F	4.5	14.3	14.4	14.2
LOW-64-C	5.1	14.6	14.4	14.3
LOW-76-F	4.5	13.8	13.9	13.6
LOW-76-C	4.9	14.9	15.0	14.7
HIGH-64-F	5.6	11.2	11.1	11.0
HIGH-64-C	5.3	11.3	10.9	10.7
HIGH-76-F	5.5	10.7	10.7	10.7
HIGH-76-C	5.2	10.8	10.6	10.7

Table 9. Average Percent Voids Filled with Asphalt vs. Compaction Temperature

Average VFA vs. Compaction Temperature				
Mixture Type	**Asphalt Content,%**	**Target Temp. -14° C (VFA)**	**Target Temp. (VFA)**	**Target Temp. +14° C (VFA)**
LOW-64-F	4.5	71.5	70.8	71.8
LOW-64-C	5.1	77.2	78.2	78.7
LOW-76-F	4.5	75.7	74.7	76.4
LOW-76-C	4.9	72.5	72.4	73.7
HIGH-64-F	5.6	60.7	61.2	61.9
HIGH-64-C	5.3	56.0	58.5	59.5
HIGH-76-F	5.5	62.4	62.3	61.9
HIGH-76-C	5.2	62.6	64.0	63.3

DATA ANALYSIS

The goal of this study was to determine whether re-heating of HMA or compaction temperature variability could lead to differences in HMA volumetric properties. In order to determine if any significant differences could occur, the student's t-test.

Effect of Storage Plus Re-Heating

In the re-heating phase of the study, three different storage times were utilized which referred to the amount of time each test mixture was allowed to cool at room temperature before being re-heated to the standard compaction temperature. The three times evaluated were 0, 3 and 20 hours. Since the 0 storage time represented mixtures that did not experience re-heating, the two t-test comparisons made for each mixture combination were first between 0 and 3 hours and then between 0 and 20 hours. Each of the student t-test procedures performed are summarized in Tables 10, 11 and 12.

Student's T-Test for VTM Comparisons

When looking at each of the eight individual mixtures, six out of the eight had a significant difference in either the 0 to 3 hour comparison, the 0 to 20 hour comparison, or both comparisons. However, some of these statistically significant differences do not show any practical differences. For instance, the LOW-64-F mixture had VTM means of 4.8, 4.7 and 4.6 at 0, 3 and 20 hours, respectively. These were determined to be statistically different but there is no practical difference.

By grouping the mixtures based on either their aggregate type, asphalt grade or blend gradation, only one of the six groups, PG76 mixtures, showed significant differences. Also, as before, this difference is quite small. Additionally, this difference was only seen between the 0 and 3 hour storage times and not the 0 and 20 hour. When analyzing all the mixtures together, no significant difference could be seen in either storage time comparison.

Table 10. Results of Student's T-Test for Storage Time Comparisons of VTM

Mixture Type	Mean VTM's			0 to 3 Hour Comparison			0 to 20 Hour Comparison		
	0 hrs	3 hrs	20 hrs	$t_{statistic}$	$t_{critical}$	Significant Difference	$t_{statistic}$	$t_{critical}$	Significant Difference
LOW-64-F	4.8	4.7	4.6	3.536	2.776	YES	3.578	2.776	YES
LOW-64-C	3.5	3.8	4.2	1.460	2.776	NO	3.780	2.776	YES
LOW-76-F	4.4	3.8	4.3	3.511	2.776	YES	2.000	2.776	NO
LOW-76-C	3.7	3.0	3.7	11.000	2.776	YES	1.414	2.776	NO
HIGH-64-F	4.9	5.3	5.1	4.221	2.776	YES	1.789	2.776	NO
HIGH-64-C	5.0	4.7	4.7	1.180	2.776	NO	1.441	2.776	NO
HIGH-76-F	4.0	3.5	4.4	8.660	2.776	YES	3.051	2.776	YES
HIGH-76-C	3.7	3.7	4.0	0.000	2.776	NO	0.795	2.776	NO
LOW Mixtures	4.1	3.8	4.2	1.283	2.074	NO	0.350	2.074	NO
HIGH Mixtures	4.4	4.3	4.5	0.254	2.074	NO	0.670	2.074	NO
PG64 Mixtures	4.6	4.6	4.6	0.262	2.074	NO	0.423	2.074	NO
PG76 Mixtures	4.0	3.5	4.1	3.176	2.074	YES	0.892	2.074	NO
Fine Mixtures	4.5	4.3	4.6	0.789	2.074	NO	0.497	2.074	NO
Coarse Mixtures	4.0	3.8	4.1	0.707	2.074	NO	0.641	2.074	NO
All Mixtures	4.3	4.1	4.4	0.982	2.013	NO	0.725	2.013	NO

Table 11. Results of Student's T-Test for Storage Time Comparisons of VMA

Mixture Type	Mean VMA's			0 to 3 Hour Comparison			0 to 20 Hour Comparison		
	0 hrs	**3 hrs**	**20 hrs**	**$t_{statistic}$**	**$t_{critical}$**	**Significant Difference**	**$t_{statistic}$**	**$t_{critical}$**	**Significant Difference**
LOW-64-F	14.7	14.7	14.7	0.000	2.776	NO	0.500	2.776	NO
LOW-64-C	14.9	14.8	15.3	0.671	2.776	NO	2.353	2.776	NO
LOW-76-F	14.7	14.0	14.5	20.000	2.776	YES	4.243	2.776	YES
LOW-76-C	14.5	14.0	14.6	10.607	2.776	YES	0.707	2.776	NO
HIGH-64-F	11.2	11.4	11.5	2.412	2.776	NO	2.500	2.776	NO
HIGH-64-C	11.6	11.3	11.4	1.180	2.776	NO	1.323	2.776	NO
HIGH-76-F	10.6	10.7	11.2	1.000	2.776	NO	4.276	2.776	YES
HIGH-76-C	10.6	10.3	10.7	1.387	2.776	NO	0.187	2.776	NO
LOW Mixtures	14.7	14.4	14.8	2.444	2.074	YES	0.423	2.074	NO
HIGH Mixtures	11.0	10.9	11.2	0.326	2.074	NO	0.958	2.074	NO
PG64 Mixtures	13.1	13.1	13.2	0.034	2.074	NO	0.154	2.074	NO
PG76 Mixtures	12.6	12.2	12.7	0.445	2.074	NO	0.133	2.074	NO
Fine Mixtures	12.8	12.7	13.0	0.108	2.074	NO	0.209	2.074	NO
Coarse Mixtures	12.9	12.6	13.0	0.375	2.074	NO	0.081	2.074	NO
All Mixtures	12.9	12.7	13.0	0.353	2.013	NO	0.205	2.013	NO

Table 12. Results of Student's T-Test for Storage Time Comparisons of VFA

Mixture Type	Mean VFA's			0 to 3 Hour Comparison			0 to 20 Hour Comparison		
	0 hrs	3 hrs	20 hrs	$t_{statistic}$	$t_{critical}$	Significant Difference	$t_{statistic}$	$t_{critical}$	Significant Difference
LOW-64-F	67.3	68.2	68.9	2.606	2.776	NO	5.742	2.776	YES
LOW-64-C	76.4	74.5	72.9	2.267	2.776	NO	3.876	2.776	YES
LOW-76-F	70.2	72.6	70.1	15.430	2.776	YES	0.530	2.776	NO
LOW-76-C	74.3	78.5	74.6	14.289	2.776	YES	1.280	2.776	NO
HIGH-64-F	56.3	53.3	55.5	5.325	2.776	YES	1.151	2.776	NO
HIGH-64-C	56.9	58.1	58.5	0.921	2.776	NO	1.466	2.776	NO
HIGH-76-F	62.6	67.2	60.6	9.568	2.776	YES	2.888	2.776	YES
HIGH-76-C	65.4	64.6	63.0	0.500	2.776	NO	1.003	2.776	NO
LOW Mixtures	72.0	73.5	71.6	0.908	2.074	NO	0.338	2.074	NO
HIGH Mixtures	60.3	60.8	59.4	0.226	2.074	NO	0.592	2.074	NO
PG64 Mixtures	64.2	63.5	63.9	0.204	2.074	NO	0.088	2.074	NO
PG76 Mixtures	68.1	70.7	67.1	1.220	2.074	NO	0.476	2.074	NO
Fine Mixtures	64.1	65.3	63.8	0.447	2.074	NO	0.148	2.074	NO
Coarse Mixtures	68.2	68.9	67.3	0.198	2.074	NO	0.315	2.074	NO
All Mixtures	66.2	67.1	65.5	0.427	2.013	NO	0.334	2.074	NO

Student's T-Test for VMA Comparisons
In comparing VMA differences for each individual mixture, three of the eight had significant differences between the mean values at 0, 3 and 20 hours of storage. Only one of the three mixtures, LOW-76-F, had significant differences between both the 0 and 3 hour comparison as well as the 0 and 20 hour comparison. However, the difference seen between the 0 and 20 hour times was small. The other two mixtures, LOW-76-C and HIGH-76-F, showed significant differences in only one of the two comparisons performed, 0 to 3 hours and 0 to 20 hours, respectively.

When grouping the mixtures based on aggregate type, asphalt grade, or gradation only one of the six groups showed significance, LOW mixtures. However, the difference between the VMA values in this comparison was 0.3 percent which is again less than the ±0.4 percent tolerance range. When grouped together, all mixtures were shown to have no significant difference in VMA values in either the 0 to 3 hour comparison or the 0 to 20 hour comparison.

Student's T-Test for VFA Comparisons
When analyzing effects on VFA properties, six of the eight individual mixtures had significant differences in either one or both of the comparisons performed. Only one of the six mixtures, HIGH-76-F, showed significance in both comparisons made.

When grouped by aggregate type, asphalt grade, or blend gradation, no significance was seen with any of the six groups in either the 0 to 3 hour comparison or the 0 to 20 hour comparison. This was also the case for the two comparisons made on the mixtures as a whole, all mixtures.

Effect of Compaction Temperature

In the compaction temperature phase of the study, three different temperatures were targeted prior to compacting samples. Unlike the re-heating phase of the study, none of these samples were allowed to cool for any length of time prior to compaction. The goal of this phase was to determine what, if any, effect variability in compaction temperature made on volumetric properties of HMA. The three temperatures evaluated were; the standard target compaction temperature for the specific grade of asphalt cement in the mixture, target temperature -14° C, and target temperature +14°C. The standard targets used were 149°C for the PG64-22 binder and 163°C for the PG76-22. The two t-test comparisons made for each mixture combination were first between target and target-14°C and then between target and target+14°C. Details of the Student T-Test procedures performed and are summarized in Tables 13, 14 and 15.

Student's T-Test for VTM, VMA and VFA Comparisons
The data in Table 13 shows that (for neither individual mixtures or groups of mixtures) there is no significant difference seen between VTM properties of samples compacted at either -14°C below target or +14°C above target compaction temperatures. Just as with the VTM data, Tables 14 and 15 show no significant differences in VMA or VFA for any of the mixture types.

Table 13. Results of Student's T-Test for Compaction Temperature Comparisons of VTM

Mixture Type	Mean VTM's			Target -14°C to Target Comparison			Target to Target +14°C Comparison		
	Target -14°C	Target	Target +14°C	$t_{statistic}$	$t_{critical}$	Significant Difference	$t_{statistic}$	$t_{critical}$	Significant Difference
LOW-64-F	4.1	4.2	4.0	0.658	2.776	NO	0.714	2.776	NO
LOW-64-C	3.3	3.2	3.1	0.406	2.776	NO	0.313	2.776	NO
LOW-76-F	3.4	3.5	3.2	0.632	2.776	NO	0.891	2.776	NO
LOW-76-C	4.1	4.1	3.9	0.000	2.776	NO	1.569	2.776	NO
HIGH-64-F	4.4	4.3	4.2	0.394	2.776	NO	0.281	2.776	NO
HIGH-64-C	5.0	4.5	4.4	1.896	2.776	NO	0.530	2.776	NO
HIGH-76-F	4.0	4.0	4.1	0.000	2.776	NO	0.612	2.776	NO
HIGH-76-C	4.0	3.8	3.9	0.562	2.776	NO	0.197	2.776	NO
LOW Mixtures	3.7	3.8	3.5	0.121	2.074	NO	0.968	2.074	NO
HIGH Mixtures	4.4	4.2	4.2	1.016	2.074	NO	0.041	2.074	NO
PG64 Mixtures	4.2	4.0	3.9	0.551	2.074	NO	0.521	2.074	NO
PG76 Mixtures	3.9	3.9	3.8	0.110	2.074	NO	0.396	2.074	NO
Fine Mixtures	4.0	4.0	3.9	0.187	2.074	NO	0.601	2.074	NO
Coarse Mixtures	4.1	3.9	3.8	0.753	2.074	NO	0.367	2.074	NO
All Mixtures	4.0	4.0	3.8	0.529	2.013	NO	0.661	2.013	NO

Table 14. Results of Student's T-Test for Compaction Temperature Comparisons of VMA

Mixture Type	Mean VMA's			Target -14°C to Target Comparison			Target to Target +14°C Comparison		
	Target -14°C	Target	Target +14°C	$t_{statistic}$	$t_{critical}$	Significant Difference	$t_{statistic}$	$t_{critical}$	Significant Difference
LOW-64-F	14.3	14.4	14.2	0.548	2.776	NO	0.714	2.776	NO
LOW-64-C	14.6	14.4	14.3	0.455	2.776	NO	0.234	2.776	NO
LOW-76-F	13.8	13.9	13.6	0.487	2.776	NO	0.755	2.776	NO
LOW-76-C	14.9	15.0	14.7	0.196	2.776	NO	1.835	2.776	NO
HIGH-64-F	11.2	11.1	11.0	0.221	2.776	NO	0.318	2.776	NO
HIGH-64-C	11.3	10.9	10.7	2.229	2.776	NO	0.574	2.776	NO
HIGH-76-F	10.7	10.7	10.7	0.277	2.776	NO	0.229	2.776	NO
HIGH-76-C	10.8	10.6	10.7	0.588	2.776	NO	0.218	2.776	NO
LOW Mixtures	14.4	14.4	14.2	0.082	2.074	NO	0.933	2.074	NO
HIGH Mixtures	11.0	10.8	10.8	1.096	2.074	NO	0.139	2.074	NO
PG64 Mixtures	12.8	12.7	12.6	0.200	2.074	NO	0.170	2.074	NO
PG76 Mixtures	12.5	12.5	12.4	0.010	2.074	NO	0.104	2.074	NO
Fine Mixtures	12.5	12.5	12.4	0.061	2.074	NO	0.170	2.074	NO
Coarse Mixtures	12.9	12.7	12.6	0.231	2.074	NO	0.108	2.074	NO
All Mixtures	12.7	12.6	12.5	0.142	2.013	NO	0.195	2.013	NO

Table 15. Results of Student's T-Test for Compaction Temperature Comparisons of VFA

Mixture Type	Mean VFA's			Target -14°C to Target Comparison			Target to Target +14°C Comparison		
	Target -14°C	Target	Target +14°C	$t_{statistic}$	$t_{critical}$	Significant Difference	$t_{statistic}$	$t_{critical}$	Significant Difference
LOW-64-F	71.5	70.8	71.8	0.678	2.776	NO	0.849	2.776	NO
LOW-64-C	77.2	78.2	78.7	0.432	2.776	NO	0.263	2.776	NO
LOW-76-F	75.7	74.7	76.4	0.741	2.776	NO	0.840	2.776	NO
LOW-76-C	72.5	72.4	73.7	0.155	2.776	NO	1.563	2.776	NO
HIGH-64-F	60.7	61.2	61.9	0.276	2.776	NO	0.306	2.776	NO
HIGH-64-C	56.0	58.5	59.5	2.074	2.776	NO	0.526	2.776	NO
HIGH-76-F	62.4	62.3	61.9	0.085	2.776	NO	0.440	2.776	NO
HIGH-76-C	62.6	64.0	63.3	0.614	2.776	NO	0.155	2.776	NO
LOW Mixtures	74.2	74.0	75.1	0.151	2.074	NO	0.836	2.074	NO
HIGH Mixtures	60.4	61.5	61.7	0.894	2.074	NO	0.106	2.074	NO
PG64 Mixtures	66.4	67.2	68.0	0.235	2.074	NO	0.233	2.074	NO
PG76 Mixtures	68.3	68.4	68.8	0.030	2.074	NO	0.170	2.074	NO
Fine Mixtures	67.6	67.3	68.0	0.112	2.074	NO	0.270	2.074	NO
Coarse Mixtures	67.1	68.3	68.8	0.345	2.074	NO	0.155	2.074	NO
All Mixtures	67.3	67.8	68.4	0.214	2.013	NO	0.294	2.013	NO

CONCLUSIONS

Within the limits imposed in this study (three and 20 hours storage time plus re-heating), storage time plus re-heating had no significant effects on the volumetrics of samples compacted with 100 gyrations of the Superpave gyratory compactor. This indicates that having to re-heat the mix prior to compaction has no effect on volumetrics. Only two binder types were evaluated, others may show an effect.

This study also showed that increasing or decreasing the compaction temperature by 14°C also had no effect on volumetrics. Other studies have shown similar results.

It is believed that the reason re-heating and modifying the compaction temperature had no significant effect was due to the fact that the Superpave gyratory compactor is really a constant strain compactor. The gyration angle is set at 1.25° and this is basically applied regardless of mix stiffness. So as the mix gets stiffer the load required to achieve the 1.25° angle is simply increased. In effect, mixes at lower temperatures are compacted with higher compaction effort since the strain is the same and the load is higher.

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