Effect of Compaction Temperature on Rubberized Asphalt Mixes

Soon-Jae Lee, Serji N. Amirkhanian, Carl Thodesen,
Khaldoun Shatanawi

Department of Civil Engineering,
Clemson University, USA

soonjae93@gmail.com
kcdoc@clemson.edu
tcarl@clemson.edu
kshatna@clemson.edu

ABSTRACT. *In general, the binder in asphalt rubber mixtures is stiffer than that in a conventional binder; therefore, the need for a higher compaction temperature. The compaction temperature for conventional mixes in the laboratory is defined as the range of temperatures where the unaged asphalt binder has a kinematic viscosity of 280±30mm^2/s. With respect to rubberized mixes, the compaction temperature should be determined carefully because the viscosity affects the compactability of the mixes. This study was initiated to investigate the effect of compaction temperature on several rubber-modified mixes. For this, four Superpave mix designs (9.5mm) for four asphalt binders (control, 10% and 15% rubber modified, and 3% SBS-modified binders) were conducted to determine optimum asphalt contents (OAC). A total of 160 specimens were fabricated using Superpave gyratory compactor at four compaction temperatures (116, 135, 154, and 173°C). The binders were short-term aged for 2 hours at the mixture compaction temperatures using rolling thin film oven (RTFO) prior to the binder tests. Evaluation of the mixtures and the binders included the following testing procedures: Volumetric properties (as-compacted, horizontally cut, and vertically cut specimens), rotational viscometer, and dynamic shear rheometer (DSR). The results from this study showed that the compaction temperatures used in this study significantly affected the volumetric properties of the rubberized mixtures, unlike conventional mixtures with virgin and SBS-modified binders.*

KEYWORDS: *compaction temperature, rubberized mixtures, volumetric properties*

1. Introduction

1.1. *Background*

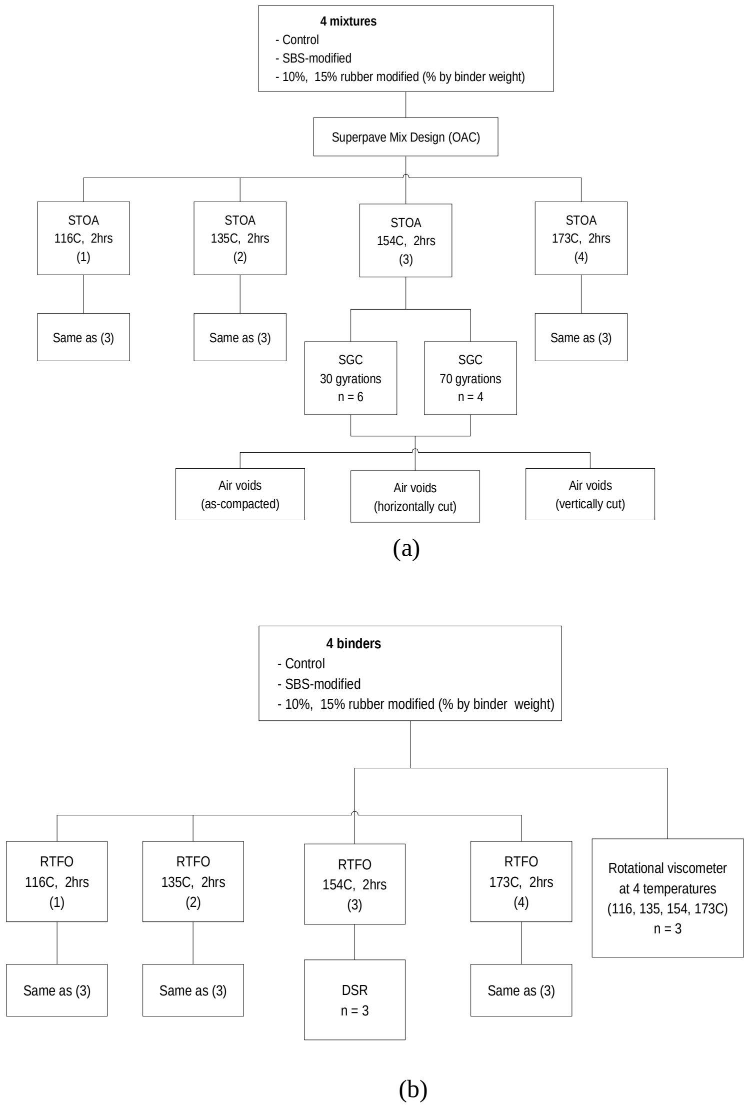
Compaction is the process by which the volume of air in an asphalt mixture is reduced through the application of external forces. The expulsion of air enables the mix to occupy a smaller space thereby increasing the unit weight or density of the mix. Compaction is an essential factor in the design and subsequent production of asphalt mixtures.

The compaction temperature influences workability, which is related to the achieved density of the mixture. The compaction temperature recommended in the current Superpave procedures for asphalt mixtures is defined as the range of temperatures where an unaged asphalt binder has a kinematic viscosity of $280\pm30\text{mm}^2/\text{s}$. This requirement was based on experience with unmodified asphalt binders. In general, the binder in modified mixtures is stiffer than that in conventional mixtures; therefore, the need for a higher compaction temperature. However, previous studies (Azari et al. 2003, Bahia 2000, Stuart 2000) on the effect of compaction temperature on the volumetric properties of asphalt mixtures showed that specimens could have the same volumetric properties over a very wide range of compaction temperature. Stuart (2000) also suggested that a wide compaction temperature range (119 to 159°C) could be used for modified mixtures with the limestone-Novophalt binder.

With respect to rubberized asphalt mixtures, the compaction temperature should be determined carefully because the viscosity and amount of the asphalt rubber binder affect the compactability of the mixtures. Based on experience in the field, rubberized asphalt mixtures are compacted at a higher temperature than conventional mixtures (Amirkhanian and Corley 2004). Still, the effect of compaction temperature on rubberized asphalt mixtures is considered to be somewhat unclear because the physical and chemical properties of the mixtures as a function of the compaction temperature are not well understood.

1.2. *Objective and scope*

This study investigated the effect of compaction temperature on the properties of rubberized asphalt mixtures. Four mixtures with control PG 64-22, 3% SBS-modified PG 76-22, 10% rubber-modified, and 15% rubber-modified binders were designed using Supepave specifications (Superpave 2001). The mixtures were compacted at 116, 135, 154, and 173°C temperatures. Several properties of these mixtures, including air voids of the as-compacted, horizontally cut, and vertically cut specimens, binder stiffness at compaction temperatures, and $G^*/\sin\delta$ of binders after short-term aging at compaction temperatures were evaluated. Figure 1 shows a flow chart of the experimental design procedure used in this study.



OAC: Optimum Asphalt Content   STOA: Short-term Oven Aging
RTFO: Rolling Thin Film Oven   SGC: Superpave Gyratory Compactor

Figure 1. *Flow chart of experimental design procedures for evaluating the effect of compaction temperature on (a) four asphalt mixtures and (b) four asphalt binders*

2. Experimental program

2.1. *Materials*

Four binders (control PG 64-22, 3% SBS-modified PG 76-22, 10% rubber-modified, and 15% rubber-modified binders) were used in this study. The control and 3% SBS-modified binders were collected from one source. Rubber-modified binders were made by adding a specified amount of ambient rubber (-40 mesh) to the control binder, mixing with a stirrer (700 rpm) at 177°C for 30 minutes (Shen et al. 2005). This mixing condition matches the field practices used in South Carolina to produce field mixtures. The properties of all the binders are listed in Table 1.

One granite aggregate source was used for preparing samples. Hydrated lime, which was used as an anti-strip additive, was added at a rate of 1% by dry mass of aggregate.

Table 1. *Properties of four binders*

Aging states	Test properties	Control PG 64-22	SBS-modified PG 76-22	10% rubber modified	15% rubber modified
Unaged binder	Viscosity @135^{o}C (Pa-s)	0.430	1.475	1.226	2.308
	G*/sin(delta)@64 ^{o}C (kPa)	1.279	-	2.974	-
	G*/sin(delta)@76 ^{o}C (kPa)	-	1.338	0.742	1.294
RTFO aged residue	G*/sin(delta)@64 ^{o}C (kPa)	2.810	-	-	-
	G*/sin(delta)@76 ^{o}C (kPa)	-	2.508	2.060	2.990
RTFO + PAV aged residue	G*sin(delta)@25 ^{o}C (kPa)	4074	-	-	-
	G*sin(delta)@31 ^{o}C (kPa)	-	2129	4480	-
	Stiffness @-12 ^{o}C (MPa)	217	212	243	-
	m-value @-12 ^{o}C	0.307	0.310	0.330	-

2.2. *Superpave Mix Designs*

A nominal maximum size 9.5mm Superpave mixture was used for the mix design in this study. The procedures described in AASHTO T 312 regarding the preparation of HMA specimens were followed. All mixtures used an identical structure of aggregate to distinguish the influence of the binders. A gradation of mixtures used in this study is illustrated in Figure 2. Optimum asphalt contents were obtained and used to produce specimens at 4 different compaction temperatures.

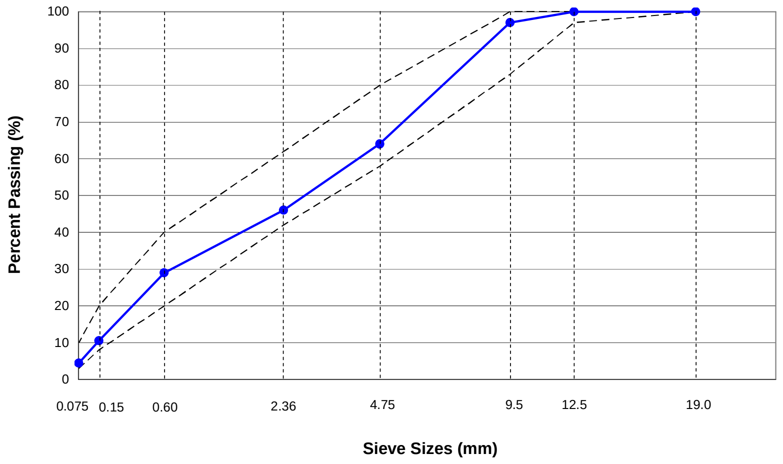


Figure 2. *Gradation chart of 9.5mm mixture*

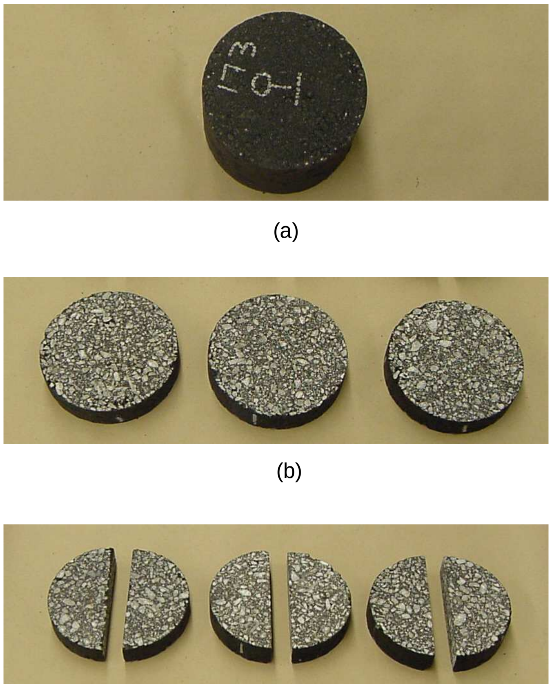
2.3. *Compaction as a function of temperature*

The mixing of the aggregates with the asphalt binders was conducted at 155°C. The loose asphalt-aggregate mixtures were oven aged at the compaction temperatures for 2 hours prior to the compaction. The four compaction temperatures used were 116, 135, 154, and 173°C. This range was selected based on the temperatures (135 and 154°C) which are commonly used as short-term oven aging temperatures in the laboratory to simulate binder aging and absorption during the construction of HMA pavements.

The specimens were fabricated to the two target air void contents of 7±1% and 4±1% using 30 and 70 gyrations of Superpave gyratory compactor, respectively. Each specimen was 150 mm in diameter and 100±2 mm in height. A total of 160 specimens (4 binders × 4 compaction temperatures × 2 gyration levels × 6 (for 30 gyrations) or 4 repetitions (for 70 gyrations)) were prepared and tested.

2.4. *Volumetric Properties*

After the air voids were measured, four specimens from each set (10 specimens) were 3-slice cut horizontally and two of the four specimens were cut vertically as shown in Figure 3. The specimens were cut using diamond tipped saw blades. The volumetric properties of cut specimens were measured.



(a)

(b)

(c)

Figure 3. *(a) as-compacted, (b) horizontally cut, and (c) vertically cut specimens*

2.5. *Rotational Viscometer*

Superpave binder specifications include a maximum viscosity requirement (3 Pa·s) for an unaged binder. In this study, rotational viscosity test (AASHTO T 316) was conducted at 4 different test temperatures (116, 135, 154, and 173°C) to verify the viscosity change as a function of temperature.

2.6. *Dynamic Shear Rheometer*

To evaluate the effect of short-term oven aging (STOA) at compaction temperatures on the binders, $G^*/\sin\delta$ of the binders was measured using the dynamic shear rheometer (DSR) test (AASHTO T 315). The test was conducted at 64°C with the binders being short-term aged for 2 hours at 116, 135, 154, and 173°C using a rolling thin film oven test (RTFOT) prior to the testing.

2.7. *Analyses Methods*

Statistical analysis was conducted using analysis of variance (ANOVA) of Statistical Analysis System (SAS). The primary variables included the effects of the binder types (control, SBS-modified, 10% rubber modified, and 15% rubber modified binders), the compaction temperatures (116, 135, 154 and 173°C) and the specimen sections (top, middle and base of specimen).

3. Results and discussions

3.1. *Superpave mix designs*

Table 2 shows the optimum asphalt content (OAC), maximum specific gravity (MSG) and bulk specific gravity (BSG) data of the mix designs with four different binders. The optimum asphalt contents were found to be 4.6, 4.7, 6.0 and 6.2% for the mixtures with control, SBS-modified, 10% rubber modified, and 15% rubber modified binders, respectively. Previous research has indicated that, in general, the OAC for the CRM mixtures are approximately 1% higher than that obtained for mixtures using no CRM. The higher OAC for mixtures using the CRM binder is attributed to the thicker film of the CRM binder coating the aggregates due to the presence of the rubber particles (Shen et al. 2006).

Table 2. *Results of Superpave mixture designs*

Properties	Mixtures			
	Control	SBS-modified	10% rubber modified	15% rubber modified
OAC (%)	4.6	4.7	6.0	6.2
MSG	2.438	2.433	2.387	2.375
BSG	2.331	2.336	2.291	2.269

OAC: Optimum Asphalt Content
MSG: Maximum Specific Gravity
BSG: Bulk Specific Gravity

3.2. *Air voids as a function of the compaction temperature*

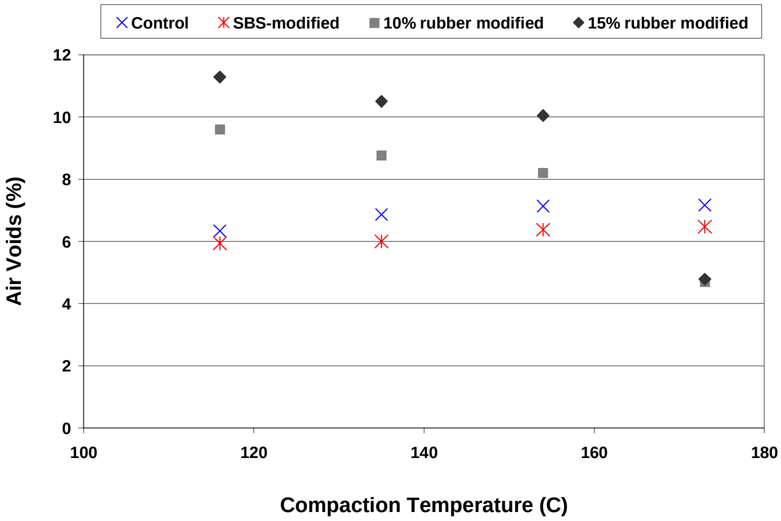
3.2.1 The as-compacted specimens

The air void contents of 160 specimens fabricated at 4 compaction temperatures were calculated. Figure 4 shows the air void contents of the as-compacted specimens as a function of the compaction temperature. In general, specimens made with control or SBS-modified binders could have almost the same volumetric properties over a very wide range of compaction temperatures (116 to 173°C). This means that it is possible to satisfy the two target air void contents of 7±1% and 4±1% using 30 and 70 gyration levels; respectively, of Superpave gyratory compactor at all compaction temperatures used in this study. However, in the case of rubber-modified mixtures, the air void content significantly decreased with increasing the compaction temperature. The range of compaction temperatures to satisfy both the target air voids of 7±1% and 4±1% was 140 to 166°C and 154 to 160°C for 10% and 15% rubber-modified mixtures, respectively.

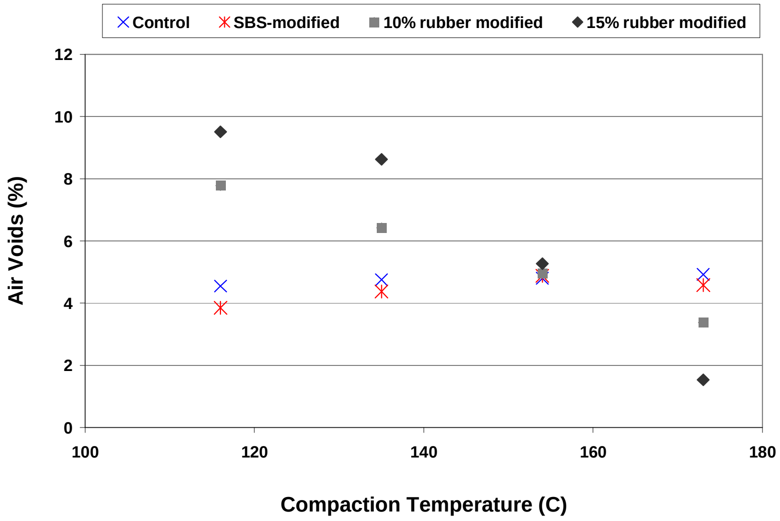
Using one-way analysis of variance, the statistical significance of the change in the air voids with the increase in compaction temperature was examined (Table 3). The data indicate that air void contents of rubber-modified mixtures are affected significantly by compaction temperature (Table 3). Similar to the previous research (Bahia 2000 and Stuart 2000), there was no significant difference, at $\alpha=0.05$ level, among the air void contents of four compaction temperatures in both control and SBS-modified mixtures.

3.2.2 The horizontally cut specimens

To examine the homogeneity of air void contents throughout each specimen, four specimens from each set were randomly selected and 3-slice cut horizontally (Figure 3), and the air void content of each slice was measured (Table 4). The results indicated that the middle section of all specimens had the lowest air void content compared to the top or base sections of specimens. The result is thought to be associated with two smooth surfaces of the middle section, while the top and base sections have a smooth surface and a rough surface. Before measuring air void contents of horizontally cut specimens, it was predicted that the air void of top section may be less than that of base section. In Table 4, it is difficult to find this trend (the air void of top section < the air void of base section) in control or SBS-modified mixture. With respect to the rubber-modified mixtures, a general trend can be observed that the air void difference between top and base sections is dependent on the air void content. In most cases of rubberized mixtures, the air void of top section was lower than that of base section when the air void was relatively high. On the other hand, a relatively low air void resulted in the higher air void for the top section.



(a)



(b)

Figure 4. *Change in air void contents as a function of compaction temperature with (a) 30 gyration level and (b) 70 gyration level of SGC*

Table 3. *Statistical analysis results for air void gradient of as-compacted specimens (α = 0.05)*

<table>
<tr><th rowspan="2">Air void</th><th colspan="16">Mixtures</th></tr>
<tr><th colspan="4">Control</th><th colspan="4">SBS-modified</th><th colspan="4">10% rubber modified</th><th colspan="4">15% rubber modified</th></tr>
<tr><td rowspan="2">All</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td>A</td><td>A</td><td>A</td><td>A</td><td>A</td><td>A</td><td>A</td><td>A</td><td>A</td><td>B</td><td>B</td><td>C</td><td>A</td><td>A</td><td>A</td><td>B</td></tr>
<tr><td rowspan="3">30 gyrations</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
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<tr><td></td><td colspan="2">B B B</td><td></td></tr>
<tr><td rowspan="3">70 gyrations</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
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<tr><td></td><td colspan="2">B B B</td><td></td></tr>
</table>

1: 116°C (Compaction temperature)
2: 135°C
3: 154°C
4: 173°C

Air voids of compaction temperatures with the same letter are not significantly different.

3.2.3 The vertically cut specimens

The side-by-side halves were also compared in terms of differences in air void contents. One-way and two-way analyses of variance of the air void data measured from the side-by-side specimens indicated that the difference in the air void content is not significant at the 5% level for all mixtures.

3.3. *Binder viscosity as a function of the compaction temperature*

Figure 5 shows the change in viscosity of four asphalt binders as the test temperature increases from 116 to 173°C. As expected, the higher test temperature lead to a decrease in the high temperature viscosity of the binders tested. At 116°C, the viscosity of 3% SBS-modified binder was approximately 5 times higher than that of control binder, but mixtures with SBS-modified or control binders showed almost the same volumetric properties at the compaction temperature (Figure 4). The reason might be that the SGC exerts a high level of compaction energy. In another study (Stuart 2000), the results indicated that the SGC will compact specimens to nearly the same density unless the workability is changed drastically. However, this trend was not consistent for mixtures with rubber-modified binders. Because of the presence of rubber particles, the viscosity and amount of the asphalt rubber binder are considered to affect the compactability of the mixtures.

Table 4. *Air voids of horizontally cut specimens*

	Control (PG 64-22)								**SBS-modified (PG 76-22)**							
	116 °C		135 °C		154 °C		173 °C		116 °C		135 °C		154 °C		173 °C	
T	6.2	∧	7.5	∧	8.7	∨	8.3	∨	6.3	∨	7.0	∨	7.6	∨	7.8	=
M	4.6		5.6		6.0		5.9		4.3		4.4		4.9		5.6	
B	6.9		8.6		7.7		8.0		6.2		6.4		6.4		7.8	
T	7.6	∧	7.8	∧	6.9	=	6.9	∧	7.2	∨	7.3	∨	7.0	∧	7.0	∨
M	5.4		5.6		5.1		5.4		5.0		5.0		5.3		4.9	
B	8.6		8.0		6.9		7.5		6.7		6.7		7.1		6.8	
T	6.1	∧	5.9	∨	6.3	∨	5.9	∨	4.5	∧	5.9	∨	5.2	∨	5.2	∧
M	3.4		3.8		4.8		3.6		2.6		3.4		2.8		3.3	
B	6.3		5.3		6.1		5.7		5.1		5.0		4.6		5.3	
T	5.6	∨	5.6	∨	6.3	∨	5.8	∨	4.7	∨	5.4	∨	6.6	∨	5.3	∨
M	3.3		3.6		4.3		3.4		2.7		3.1		4.4		3.3	
B	5.3		5.4		5.7		5.3		4.5		4.8		6.2		4.6	

Table 4. *Continued*

	10% rubber modified								**15% rubber modified**							
	116 °C		135 °C		154 °C		173 °C		116 °C		135 °C		154 °C		173 °C	
T	9.8	∧	8.0	∧	9.5	∧	5.6	∨	11.8	∧	8.0	∧	9.1	∧	6.4	∨
M	8.5		6.8		8.3		3.3		11.3		8.5		8.0		4.1	
B	10.2		8.4		9.8		5.0		12.5		10.9		10.4		5.3	
T	8.8	∧	9.5	∧	6.5	∨	6.5	∨	10.3	∧	10.9	∧	10.9	∧	5.3	∨
M	7.6		8.4		4.0		4.7		9.6		9.7		10.7		2.7	
B	9.3		9.8		5.8		6.4		11.0		11.4		11.8		4.2	
T	9.3	∧	6.6	∧	6.4	∨	5.0	∨	10.5	∧	9.5	∧	6.6	∨	3.1	∨
M	8.4		5.0		4.4		2.6		10.6		8.4		4.4		0.1	
B	10.6		6.7		6.1		4.5		11.4		10.6		6.0		2.2	
T	7.5	∧	6.6	∧	7.7	∧	3.2	∨	7.2	∧	7.3	∧	8.1	∧	2.9	∨
M	7.1		5.3		7.0		0.6		6.2		6.3		7.9		0.1	
B	8.6		7.2		8.1		2.5		8.7		8.1		9.2		1.9	

T : Top of specimen M : Middle of specimen B : Base of specimen

∨ : Air void of top is greater than air void of base
= : Air void of top is same as air void of base
∧ : Air void of top is less than air void of base

3.4. *Binder properties after short-term aging at compaction temperature*

Figure 6 shows the relationship between G*/sin δ value at 64°C and RTFO aging temperature for four asphalt binders. The G*/sin δ value significantly increased as short-term aging temperature increased from one temperature to the next temperature. Since binder properties measured in this study were too sensitive to the aging temperature, it was difficult to find any relationship between the volumetric properties of mixture and the properties of the asphalt binder in the mixture at the compaction temperature.

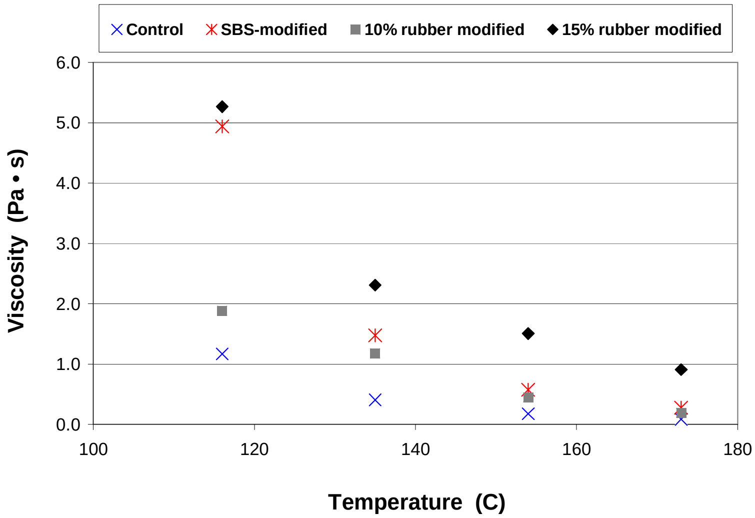

Figure 5. *Change in viscosity of asphalt binder with temperature*

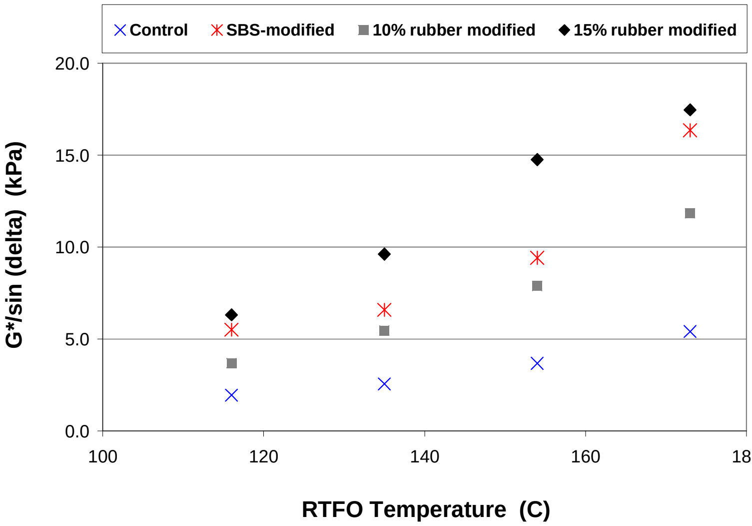

Figure 6. *Change in G*/sin δ of asphalt binder with change in aging temperature (test temperature = 64°C)*

4. Summary and conclusions

(1) For the specimens compacted using the SGC, the difference in the air void contents as a function of the compaction temperatures was found to be insignificant for the control and SBS-modified mixtures. The specimens, for the mixture used in this study, could have the same volumetric properties at a very wide range of compaction temperatures from 116 to 173°C.

(2) The air void contents of the mixtures with rubberized binders decreased as compaction temperature increased from one temperature to the next consecutive temperature. From statistical analysis, it was shown that the compaction temperature significantly affected the total air void contents of the mixtures.

(3) In general, the specimens of rubberized mixtures which were 3-slice cut horizontally showed that the air void content of the top section was less than that of the base section when the total air void content was relatively high.

(4) The differences in the air void contents of the specimens which were cut vertically were not statistically significant regardless of mix type.

(5) Binder properties after subjecting to short-term aging at the compaction temperature were too sensitive to the aging temperature, and it can be concluded that the binder properties are not considered to be associated with the volumetric properties of the mixtures at the compaction temperatures.

(6) It is recommended to conduct another study with a higher rubber percentage than 15% and various crumb rubber sizes, and evaluate the mechanical properties of rubberized mixtures to correlate with the volumetric properties of the mixtures at different compaction temperatures.

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