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# EFFECT OF AGGREGATE GRADATION, AGING, AND COMPACTION ENERGY ON SWELLING CHARACTERISTICS OF RUBBER MODIFIED ASPHALTS MIXTURES

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**Abstract:** Use of ground tire rubber (GTR) in asphalt has been experienced for decades. There has been extensive research on rubber modified asphalts and many pavements have been built using this material. In general, use of rubber in asphalt has been shown to be beneficial both from environmental point of view (landfill saving) and field performance (reduction in rutting and increase in fatigue resistance). A challenge faced with the use of rubber modified asphalts for certain types of aggregate gradation is the swelling of rubber particles, and the rebound of the material after compaction. This phenomenon is more severe in the dry process (when rubber is first blended with the aggregate); however, it does also pose a challenge in the wet process (when rubber is first blended with asphalt). Such behavior affects mechanical properties of the mix, and results in reduction of density in the field. A laboratory experiment was undertaken to quantify the level of this swelling and to determine the magnitude of specimen swelling as affected by the aging level and compaction energy when the wet process is utilized. Specimens were prepared under short-term and long-term aging processes and compaction was conducted using a gyratory compactor at different energy levels. The experiment was also conducted in a way to determine the gradation effect, and to separate the effect of rubber swelling on specimen rebound from the effect of compaction energy on this rebound. It was found that the rebound and swelling are highly affected by the aggregate gradation, with denser gradations resulting in higher swell. The study also indicated that extended aging reduces the specimen swelling significantly. Similarly, higher rebound was observed under higher compaction energy. Finally, the mix swelling and rebound were correlated with the rubber modified binder characteristics through multiple stress creep and recovery (MSCR). The findings of this study are significant in assisting the mix designer with a tool for better control of the mix behavior and reduction of swelling both in the laboratory and in the field.

## 1 INTRODUCTION

Millions of used vehicle tires are disposed each year and this number keeps increasing due to growing demand of vehicles and traffic. Discarded tires pose a severe environmental problem in the United States. Normally, discarded tires are reused, resold, retreated, or landfilled. Among possible uses of scrap tires, only two methods have shown potential for the greatest benefit: use as combustion fuel and crumb rubber modifier (CRM) for paving industry (Heitzman 1992). CRM use in asphalt paving has a relatively long history and its first use goes back 1840 (Heitzman 1992). However, a rational approach for use did not come into play until McDonald introduced the wet process in 1960s.

Mixing crumb rubber with virgin asphalt binder results in the improved performance of blended binder. One challenge faced with CRM binder, however, is the swelling of rubber particles when blended with asphalt binder, and the rebound of the compacted specimens. Swelling is a diffusion – not a chemical – process that results from the liquid moving into the internal matrix of the polymer (Stroup-Gardiner et al. 1993). This phenomenon affects mechanical properties of asphalt mixes and potentially results in reduction of density in the field. When asphalt binder and crumb rubber particles are blended together, the aromatic components of the asphalt binder get absorbed into the polymer chains in crumb rubber particles to form a gel-like material. Such absorption results in swelling of the rubber particles to two to three times their original volume (Heitzman 1992). The interaction is affected by a number of variables such as the temperature at which the blending-reaction occurs, the length of time the temperature remains elevated, the type and amount of mechanical mixing energy, the surface size and texture of the crumb rubber, and the aromatic component contents of the asphalt binder (Heitzman 1992). The swelling causes an enormous increase in the mass viscosity of the system due to reduced free space between the swollen rubber particles (Heitzman 1992), as compared with neat asphalt or asphalt with un-swollen rubber early in the interaction process.

Airey et al. studied the absorption of light fraction of asphalt binder into crumb rubber particles using a basket drainage method (Airey et al. 2003). They examined the chemical composition and rheological properties of residual binder as well as swelling of the rubber particle. Overall, rubber mass increases with the increase of interaction time, but increasing rate decreases with the increase of interaction time, regardless of binder source. Their test results indicated the rate of adsorption is directly related to the viscosity as well as the chemical composition of the bitumen, and the total amount of absorption is controlled by the nature of the crumb rubber, such as grinding process and contents. Peralta et al. studied the influence of binder type on the rubber morphology (Peralta et al. 2010). The authors used the basket drainage method to recover the swelled rubber and residual binder, then calculated their density against interaction time. Based on their calculations, the density of rubber first decreases then increases with the increase of interaction time. They authors believed that a large quantity of air and moisture among the rubber particles expand their volume thus reducing the rubber density at the beginning of the interaction, then air and moisture are replaced by liquid bitumen, causing density of rubber to increase.

Although a number of studies are available on the swell of CRM binder, few can be found on the subject of rebound of compacted CRM asphalt specimens. Therefore, a laboratory experiment was undertaken to quantify the level of rebounding in asphalt mixes after compaction, and to determine if the magnitude of specimen rebounding was affected by the aging level, compaction energy, and gradation when using wet process. Dimension (height and diameter) changes were logged after certain time intervals post compaction to determine the rebound ratio of compacted specimens. Finally, the mix rebound was correlated with the CRM binder characteristics through the results of multiple stress creep and recovery (MSCR) binder test.

## 2 RESEARCH OBJECTIVES AND SCOPE

The main objective of this study was to investigate the effect of aging, compaction energy, and gradation on the rebound of compacted CRM asphalt mixes using the wet process. This was accomplished by measuring the volume change on compacted CRM specimens. CRM specimens were manufactured using different gradations, and they were exposed to a range of compaction energies and different aging conditions. Additionally, changes in specimen dimension after compaction of CRM asphalt specimens were compared with changes in specimens manufactured with only virgin binder. The MSCR test results on CRM binder were also evaluated to correlate properties of aged binders with the rebounding of compacted specimens.

## 3 MATERIAL AND EXPERIMENTAL PROGRAM

### 3.1 3.1 Materials

The dolomite/limestone aggregate used in this study came from a local source, with 55 percent coarse aggregate (retained on #4 sieve), and 45 percent fine aggregate (passing #4 sieve). Apart from one 9.5-millimeter dense gradation, two additional gap gradations were also included. All specimens and binder samples were prepared using a PG58-28 binder and one source of crumb rubber passing #30 mesh. All gradations are shown in Fig. 1.

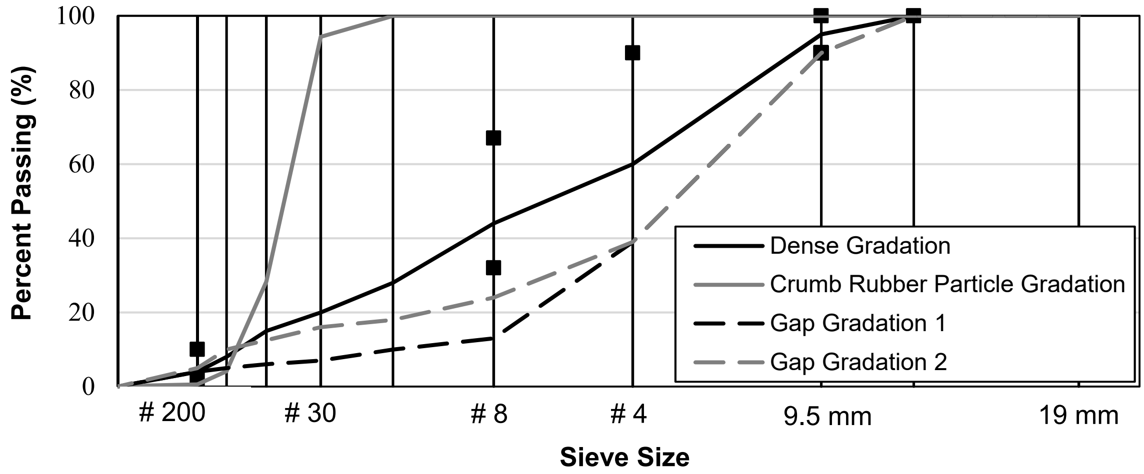



Figure 1: Aggregate gradation and crumb rubber particle gradation

The following procedure was followed to prepare CRM binder:

1. Heat PG58-28 virgin binder at 150℃ for 60 minutes.
2. Continue heating virgin binder in a temperature-controlled container until it stabilizes at 165℃.
3. Add crumb rubber into the heated virgin binder gradually and within a period of five minutes. Blending occurs at 3000 RPM while CRM is added. The amount of added CRM will be 15 percent of the total mass (mass of binder plus mass of CRM).
4. Agitate the CRM binder for an hour at a reduced shear rate of 700 RPM after all rubber particles are added.
5. The blended CRM binder is cooled to room temperature.
6. When it is time to use the modified binder, it must be heated at 150℃ for one and a half hours.

The temperature of the blending container was maintained at 170 ℃ for the entire shear blending process. The CRM binder was used no later than one day after manufacturing. Finally, all specimens were mixed and compacted at 150℃.

## 3.2 Mix Design

A dense graded Superpave 9.5 millimeter mix design (case 1) was used throughout the study with design binder contents of 5.2 percent and 5.7 percent for virgin binder and CRM binder, respectively. When performing mix design with CRM binder, virgin aggregate gradation was adjusted to make room for the added crumb rubber particles. The adjusted gradation with crumb rubber has the same gradation as the virgin aggregate gradation. As a part of the study to evaluate the impact of gradation, six different cases were considered as presented in Table 1.

Table 1 Different Cases for Mix Considered for This Study

| Case No. | Binder | Gradation | Binder Content, % |
|---|---|---|---|
| 1 | Virgin | Dense | 5.2 |
| 2 | CRM | Dense with adjustment for rubber | 5.7 |
| 3 | CRM | Dense as Case 2 | 5.2 |
| 4 | CRM | Dense, as Case 1 | 5.2 |
| 5 | CRM | Gap Gradation 1 | 7.0 |

| | | | |
|---|---|---|---|
| 6 | CRM | Gap Gradation 2 | 6.2 |

## 3.3 Test Program

### 3.3.1 General Scope

The laboratory program was established to capture the effect of aging, gradation, and compaction level on the specimens. After mixing, specimens were placed into two groups. Specimens of Group I were short-term aged (STOA) in loose condition (not compacted) for two hours at 150℃. Specimens of Group II were not only short-term aged but also long-term aged (LTOA) in loose condition at 85℃ for 120 hours. Afterwards, they were re-heated at 150℃ for two hours before compaction. Specimens were compacted at three energy levels: 70, 90, and 110 gyrations.

### 3.3.2 Swell Measurements

The change of diameter and height were logged 0, 10, 60, 120, 240, 1200 minutes after compaction. The diameter and height data at 0 minutes were obtained from the data collected by the software of the Superpave Gyratory Compactor (SGC). This data was used to calculate the initial volume of specimens. Data from the remaining the time intervals was measured using two digital calipers (Fig. 2), averaging three measurements. The expansion ratio was calculated as the ratio of volume at a certain time after compaction over the initial volume.

(a) (b)

Figure 2: Measuring diameter (a) and height (b) after compaction

Since swell and rebound occurs right after release of pressure, immediate measurement of air void of specimens before swelling begins is difficult. Thus, a unique method was used to calculate the initial and final air void (AV) of compacted CRM specimens. First, a volume correction factor between ideal cylinder (calculated using height readings from the SGC) and actual specimen volume (measured through AASHTO T 166) was established. The correction factor offsets the irregularities observed on the surface of the asphalt specimens. It is air void dependent and was established using data from specimens made with no rubber as such specimens have negligible volume change with time after compaction. Next, the initial volume (before pressure relief) of CRM specimens was back-calculated using the correction factor and height readings of the corresponding CRM specimens. Here, initial volume refers to the actual volume of the specimen at the completion of compaction and before release of pressure. This initial volume was then used to calculated the initial bulk specific gravity ($G_{mb}$) and additionally, initial air void. The initial air void was further compared with the actual air void (with swell), measured 20 hours after compaction.

### 3.3.3 Evaluating Effect of Modified Binder Characteristics

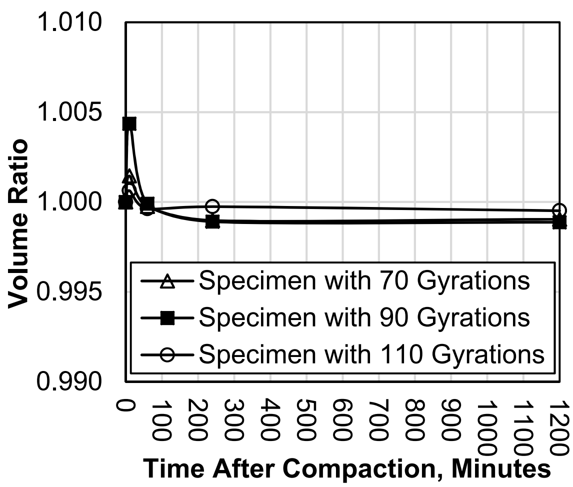
It is evident that swelling of compacted specimens containing rubber modified asphalt is influenced by properties of the asphalt binder after modification. Specifically, it is reasonable to believe that stiffness and elastic recovery characteristics of the rubber modified asphalt play a role in this respect. Therefore, our testing program included determination of the magnitude of stiffness and recovery of modified binders after short-term and long-term aging. For this purpose, the Multiple Stress Creep Recovery (MSCR) test (AASHTO 2014) was utilized. The test determines the percent recovery and non-recoverable creep compliance of asphalt binders. The percent recovery value is intended to provide a means for determining the elastic response and stress dependency of the modified asphalt binders, while the non-recoverable creep compliance is an indicator of the resistance of an asphalt binder to permanent deformation. For this study, short-term aging was achieved through rolling thin-film oven (RTFO) and long-term aging through pressure aging vessel (PAV). The aged CRM binders were tested using the MSCR protocol at 72℃ under two stress levels, 0.1 and 3.2 kPa. One exception to the protocol was setting the gap between plates in the dynamic shear rheometer. The standard requires this setting at one millimeter. However, considering the upper size of rubber particles (0.6 millimeter), the gap was set at two millimeters to accommodate the size of crumb rubber particles and maintain a ratio of at least three between the particle size and the plate gap.

# 4 RESULTS AND ANALYSIS

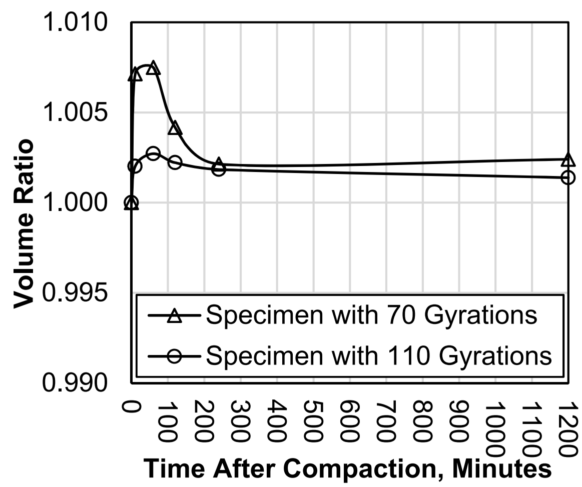
## 4.1 Volume Change Comparison

### 4.1.1 Effect of Aging and Compaction Energy

The volume change of specimens with different aging conditions and compaction energies are shown in Fig. 3 for dense graded mixes. Plots include results from specimens with different aging conditions and compaction energies. The first figure (3a) is for STOA virgin mix and is added as a reference for comparison with CRM mixes. This is a dense graded mix made with PG58-28 binder without any crumb rubber.




(a)

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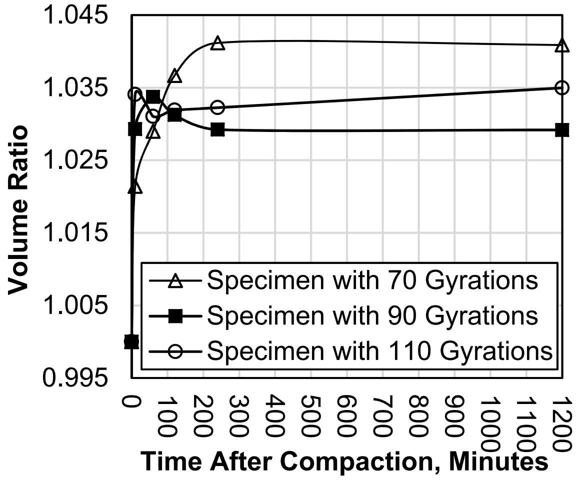


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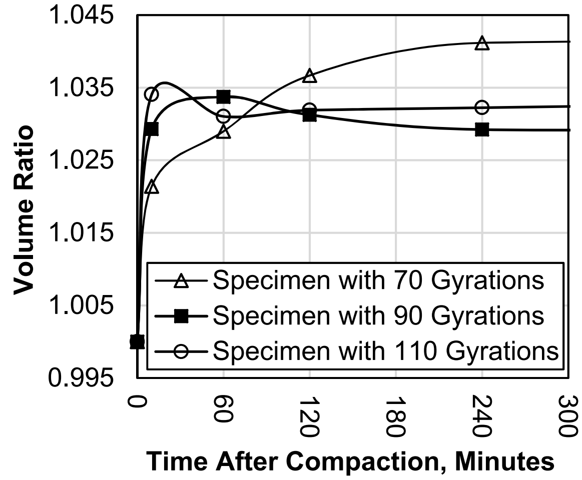


(d)

Figure 3: Expansion ratio comparison, (a) STOA virgin mix, (b) LTOA CRM mix, (c) STOA CRM mix, and (d) STOA CRM mix in detail

Regardless of compaction energy, there was no significant volume change for STOA virgin mix (Fig. 3a), except for slight volume increase (less than 0.5 percent) right after compaction. However, after two hours cooling at room temperature, this slight increase in volume vanished and the volume did not change until the end of the measuring cycle. The final volume ratio was almost one, indicating no change in volume with time, after compaction, Similar to the STOA virgin mix, volume change of LTOA CRM mix (Fig. 3b) was not significant. There was also a slight increase in volume right after compaction, but the change of volume vanished after specimen temperature dropped. The final volume increase of LTOA CRM mix was less than 0.3 percent regardless of compaction energy.

Contrary to the virgin mix and the long-term aged mix, the increase in volume for STOA CRM mix was significant. There was a three to four percent increase in volume within a short time after compaction (Fig. 3c). This is an important observation indicating that CRM mixes in dense gradation expand significantly after compaction, and that long-term conditioning of the mixes significantly reduces the potential for expansion.

Finally, there will be the effect of compaction level. Fig. 3c indicates that the specimen with the lowest level of compaction (70 gyrations) has a higher level of rebound compared with the specimen with the highest compaction energy (110 gyrations). The specimen with the median compaction level (90 gyrations) exhibited the lowest expansion level. To understand this behavior, one has to consider the compactability of the mix, and how the compaction path of the mix follows as the number of gyrations increases. Fig. 4 presents the compaction patterns for these three compaction levels using the exact same mix. One could see that, for this specific mix, after 60 gyrations, the change in height is minimal (less than one millimeter per 10 gyrations) for all three specimens. Any further compaction effort beyond this point is not contributing to compaction; rather it is probably simply degrading the mix. This phenomenon is probably the reason for the observed behavior in the magnitude of the rebound for different compaction levels.

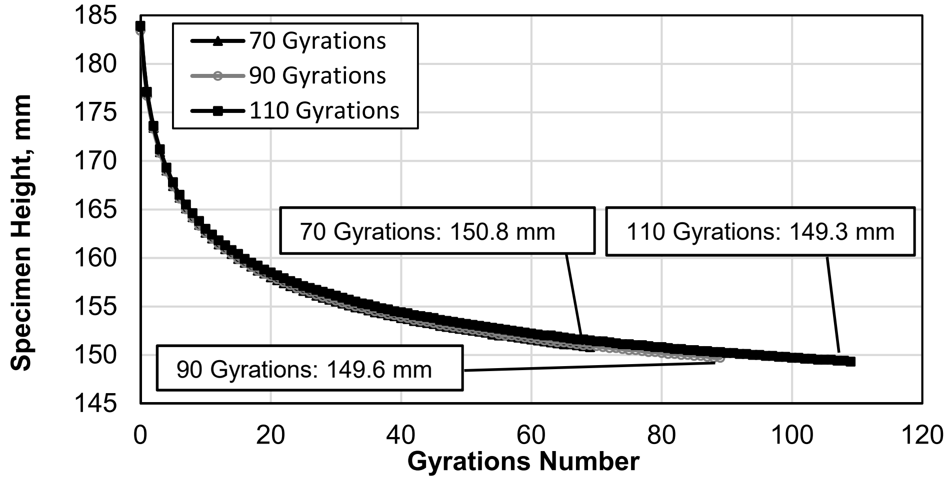


Figure 4: Compaction pattern of STOA CRM mix with three compaction energy levels

Based on the observations discussed above, it is clear that LTOA CRM binder mix has similar rebound characteristics as STOA virgin binder mix, while STOA CRM mix has very different rebound properties after compaction.

### 4.1.2 Effect of Gradation Change

It was mentioned previously that two gap graded mixes were included in the study to determine the impact of the gradation change on volume expansion after compaction. The results are shown in Fig. 5. All specimens were prepared with the same binder and rubber contents, short-term aged, and compacted at 70 gyrations. Although gap-graded aggregate 2 has a slightly denser gradation compared to gap-graded aggregate 1, both share a similar final volume increase of roughly two percent. This expansion is half the volume increase of the dense gradation. It is obvious that the significant expansion observed in dense graded mixes could be highly reduced by generating a gap in the gradation. This observation is expected as a gap-graded mix provides more space for rubber particles. This increased void space allows the rubber particles to be exposed to lower level of “squeezing pressure” during compaction and hence lower rebound after compaction. It can also be seen that once sufficient gap is generated (see gap-graded 2); further increase in void space (see gap-graded 1) would not result in reducing the volume expansion any further.

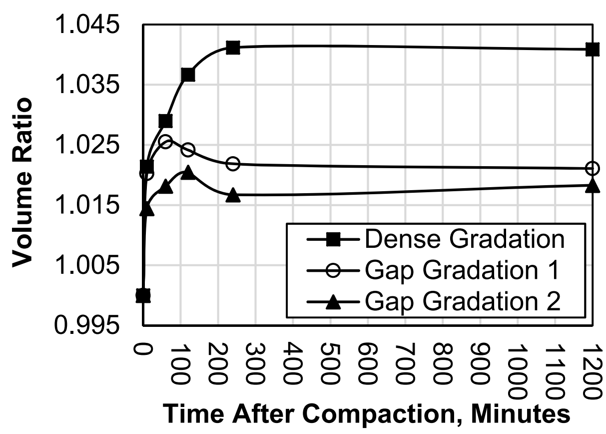


Figure 5: Effect of gradation on volume ratio changes

## 4.2 Air Void Change Comparison

The significance of volume expansion in CRM mixes is finally reflected in its impact on the pavement density and air void. Hence, it is important to quantify the impact of this expansion on air void. The corresponding air void change of mixes discussed in section 4.1 is shown in Fig. 6. Only partial results are shown here due to space limitation, but similar trends can be observed for the data not shown. Regardless of compaction energy, only slight decrease in air void level can be observed for STOA virgin mix after specimens had been compacted for 20 hours (Fig. 6a). Additionally, the effect of compaction energy is as expected, i.e. higher compaction level leads to lower air voids. LTOA CRM mix showed similar characteristics to STOA virgin mix, with a slight increase in air void for the specimen compacted with 70 gyrations (Fig. 6b). However, significant air void change is observed for short-term aged CRM mixes (Fig. 6c).

For all specimens, regardless of gyration level, the air void increased significantly 20 hours after compaction. Calculations put this void increase as 50 percent over the initial air void, indicating a considerable level of rebound 20 hours after compaction. It is also worth noticing that for STOA mixes, the air void of specimens under 90 gyrations is almost identical to that under 110 gyrations. This observation is further indication of a threshold value for compaction energy beyond which no further increase in density is achieved. This phenomenon also ties into the concept of “locking point” in compaction. Locking point refers to the point in compaction process where aggregate particles “lock” together, and additional gyrations (i.e. more compaction energy) does not contribute to further densification, rather it begins to degrade the aggregate (Prowell and Brown 2007, Honbeck 2008).

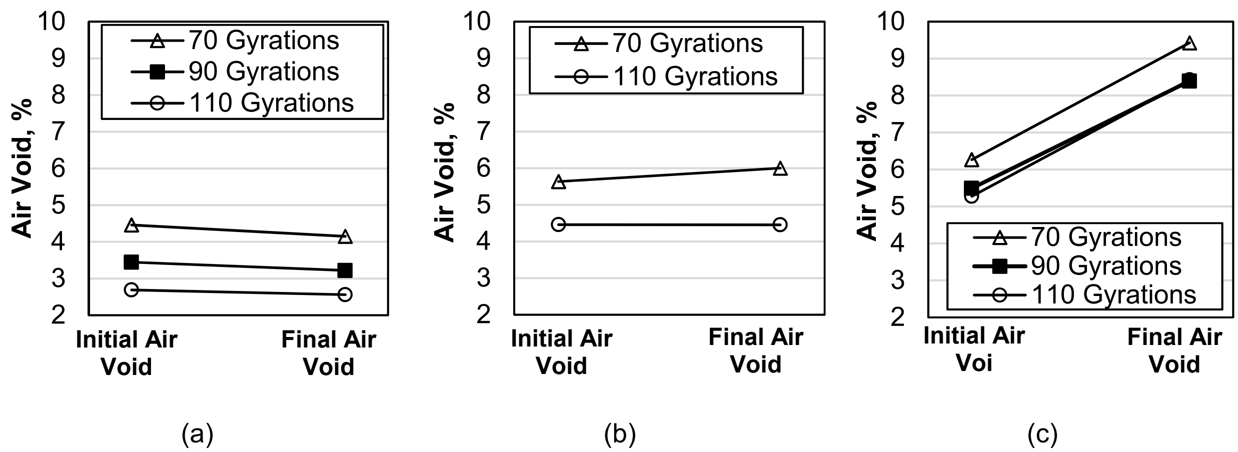


Figure 6: Air void change, (a) STOA virgin mix, (b) LTOA CRM mix, and (c) STOA CRM mix

To further investigate the effect of gradation and compaction energy on the rebound behavior of CRM mixtures, a second phase of study was conducted in which two groups of specimens were prepared using different batch weights but compacted to the same height. For each corresponding specimen of Group 1, an additional mass of 150 grams was added to the batch weight to make the specimens of Group 2. Since all specimens were compacted to a fixed height of 150 millimeter, the additional mass of Group 2 specimens required higher number of gyrations to result in the same height as specimens of Group 1. Obviously, higher mass of Group 2 resulted in lower initial air void as shown in Fig. 7. Within each group, two cases are considered: Case 2 with 5.7% binder based as designed, and Case 3 with 5.2% binder content. Case 1, previously discussed, was with virgin binder (No CRM) and not included in this part of the study. Even though the batch weights within each group are the same, initial air level varies due to different gradations and different theoretical maximum specific gravity ($G_{mm}$). It must be noted that all specimens were CRM modified and all were short-term oven aged. As discussed previously, the expansion was found to be significant only for CRM mixes exposed to short-term aging.

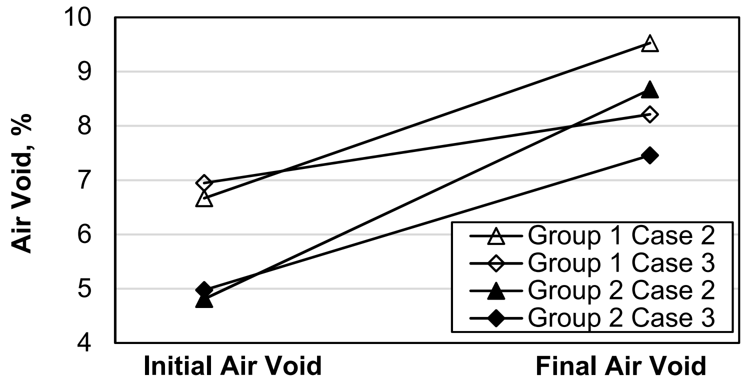


Figure 7: Air void change of different cases,

Note: Group 2 Specimens were made with 150 grams more material compared with Group 1,

Case 2: CRM mix with 5.7 % binder

Case 3: CRM mix with 5.2% binder

There are several observations worth noticing as reflected in Fig. 7. As expected for STOA CRM mixes, all specimens show significant rebound 20 hours after compaction regardless of the initial air void level. More interestingly, the specimens of Group 2 (i.e. with higher mass at the same height) show significantly higher rebound compared with specimens of Group 1. This is true for both types of gradations presented in Fig. 7. Table 2 presents a quantitative comparison of the expansion level for both cases. Group 1 specimens starting at higher air void compared with Group 2 had an air void increase of 43 percent and 18 percent for cases 2 and 3. Group 2 specimens showed approximately 80, 50 percent increase in air void for the corresponding cases. It is reasonable to believe that higher rebound of Group 2 specimens is the result of elastic rubber feeling higher pressure under compaction in the case of Group 2. It is also important to note that within each group, the specimens with higher binder content (i.e. Case 2) had a higher rebound compared with specimens with lower binder content (i.e. Case 3).

Table 2: Expansion level comparison between cases

| Group | Case | Initial Air Void, % | Final Air Void, % | Percent Increase in Air Void, % |
|---|---|---|---|---|
| 1 (lower mass, same height) | Case 2 | 6.67 | 9.53 | 43 |
| 2 (higher mass, same height) | Case 2 | 4.81 | 8.67 | 80 |
| | | | | |
| 1 (lower mass, same height) | Case 3 | 6.95 | 8.21 | 18 |
| 2 (higher mass, same height) | Case 3 | 4.98 | 7.46 | 50 |

### 4.3 Correlation between Specimen Rebound and Properties of Modified Binder

The MSCR binder test results are shown in Fig. 8. The percent recovery value (Fig. 8a) determines the elastic response of modified asphalt binders, while the non-recoverable creep compliance (Fig. 8b) is an indicator of the resistance to permanent deformation under repeated load.

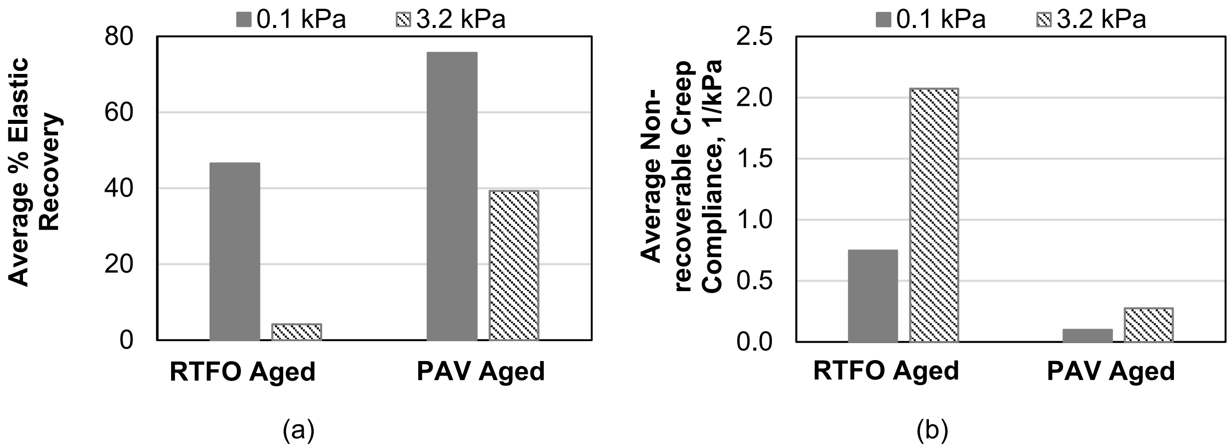


Figure 8: MSCR results of CRM binder, (a) average percent recovery and (b) average non-recoverable creep compliance

The elastic response of CRM binder was improved significantly from 47 percent to 76 percent at 0.1 kPa stress level and from 4 percent to 39 percent at 3.2 kPa stress level, after the binder had been long-term aged. Correspondingly, non-recoverable creep compliance of CRM binder also decreased tremendously after long-term aging.

There are two results worth noting as reflected in Fig. 8: 1) the STOA binder has higher compliance compared to the LTOA binder, 2) the STOA binder exhibits significantly lower recovery compared to the LTOA binder. Both observations are expected as long-term aged binder is obviously stiffer than the short-term aged binder. Furthermore, as the binder gets long-term aged, it pulls away from viscous behavior and moves more towards elastic behavior compared to short-term aged binder due to significant loss of volatiles and oxidation.

At the first look, the higher recovery of the LTOA binder seems contrary to the CRM mix behavior, as LTOA mix exhibited significantly lower swell compared with the STOA mix. However, one should not ignore the high impact of the binder stiffness on the rebound magnitude. While LTOA binder has considerably higher recovery, it is also much stiffer than STOA binder, hence under the same compaction energy (gyrations), it deforms very little compared to STOA binder. As a result, once compaction is complete and pressure is released, the LTOA mix rebounds very little. In other words, the original squeeze for LTOA CRM binder is very small to begin with. Hence, the rebound is small in spite of the fact that it demonstrates such higher recovery in MSCR.

## 5 SUMMARY AND RECOMMENDATIONS

A laboratory experiment was conducted to quantify the level of rebounding and volume expansion in crumb rubber modified (CRM) asphalt mixes after compaction. In this study, the effects of aging, compaction energy, and aggregate gradation were considered. The mesh 30 asphalt rubber was added to a PG 58-22 binder through laboratory shear blending at elevated temperatures. Rubber was added at 15 percent by the mass of the modified binder. The rebound of compacted specimens was quantified using two parameters: the volume change and the air void change. Additionally, MSCR binder test results were analyzed to determine the impact of binder aging on the rebound behavior of compacted specimens. The following conclusions can be drawn from the observations and analyses under this study:

- There was no significant volume change for mixes produced with virgin binder without rubber particles. Long-term conditioned (LTOA) CRM mixes exhibited a similar behavior with no volume expansion. Short-term conditioned (STOA) CRM mixes, on the other hand, demonstrated considerable rebound after compaction. For these mixes, three to four percent volume increase was observed for the dense graded CRM mixes.

- Corresponding to volume change, significant air void increase was observed for STOA CRM mixes after compaction, while no dramatic change in air void was found in STOA virgin mixes and LTOA CRM mixes.
- The rate of volume expansion was not affected by the level of compaction energy. For all, higher compaction energy resulted in lower initial volume. Expansion after this initial volume was only observed for short-term aged specimens of CRM mix.
- Specimens at lower air void exhibit higher expansion ratio.
- Using MSCR results, it was demonstrated that the swell of long-term aged mixtures is significantly lower than the swell of short-term aged mixtures due to significant change in the binder stiffness.
- Careful attention must be paid to the design of these mixes in terms of aggregate gradation and compaction as the asphalt mixes produced with dense aggregate gradations are susceptible to severe rebounding after compaction.

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