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# Laboratory Investigation of Dimensional Changes of Crumb Rubber Reacting with Asphalt Binder

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*ABSTRACT: Studies of binders containing crumb rubber have shown improvements in durability, crack reflection, fatigue resistance, skid resistance, and mechanical characteristics over typical hot mix asphalt (HMA) mixtures. However, an improved understanding of the physical changes to crumb rubber particles as a result of production of asphalt rubber binders is important to stimulate the use of rubberized asphalt mixtures. Although past research has found that the size of crumb rubber will change when it mixes with hot asphalt binder, the result has not yet been identified clearly. The objective of this research was to investigate the permanent dimensional changes of crumb rubber (e.g., size and morphology) after mixing with asphalt binder using the “wet” method. This investigation evaluated the effects of crumb rubber size, binder source, and reaction duration on the dimensional changes of crumb rubber. Binders containing crumb rubber were produced in the laboratory, then the crumb rubber was extracted from the binder and permanent changes to the rubber particles were measured.*

*KEYWORDS: Crumb rubber, asphalt, binder, asphalt-rubber, microscopy, depolymerization.*

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## 1. Introduction

Scrap tire rubber has been used in hot mix asphalt (HMA) for several decades in the United States and other countries. In 1960, Charles McDonald became the first engineer to use scrap tire rubber in asphalt mixtures to improve pavements in Phoenix, Arizona. Since then, many experimental studies and field test sections have been constructed and tested. The mixing of crumb rubber with conventional binders results in an improvement in the binder's resistance to rutting, fatigue cracking and thermal cracking (Dantas Neto *et al.*, 2003; Way, 2003). Over the past several years, researchers have concluded that rubberized asphalt mixes can be helpful in reducing the thickness of asphalt overlays and reflective cracking potential (Amirkhanian, 2003; Holleran and Van, 2000; Cano *et al.*, 1989; Esch, 1982; Choubane *et al.*, 1999; Sousa *et al.*, 2002), in addition to protecting the environment and saving resources (e.g., landfill space).

Rubber, one type of polymer, is known to absorb liquids and swell. The extent of swelling is dependent on the nature, temperature and viscosity of the liquid (or solvent) and the type of polymers (Treloar, 1975). The bulk of the rubber absorbs the solvent, which increases the dimensions of the rubber network until the concentration of liquid is uniform and equilibrium swelling is achieved (Airey *et al.*, 2003). The amount of solvent diffused into the rubber depends on the shape and number of cross-links in the rubber and the compatibility of the solvent. The greater the number of cross-links in the rubber, the shorter the average lengths of rubber chains between cross-links and the lower the rate of diffusion (McCrum *et al.*, 1999).

Furthermore, asphalt is a complex mixture of organic molecules, which include mainly hydrocarbon with minor amounts of oxygen, nitrogen, sulfur and other trace elements. Asphalt can be separated into four main fractional groups, namely saturates, aromatics, resins, and asphaltenes (Whiteoak, 1990; Isacson and Lu, 1995). Some researchers have discovered that the molecular size distribution of asphalt has a definite effect on its physical properties, and define the asphalt into three

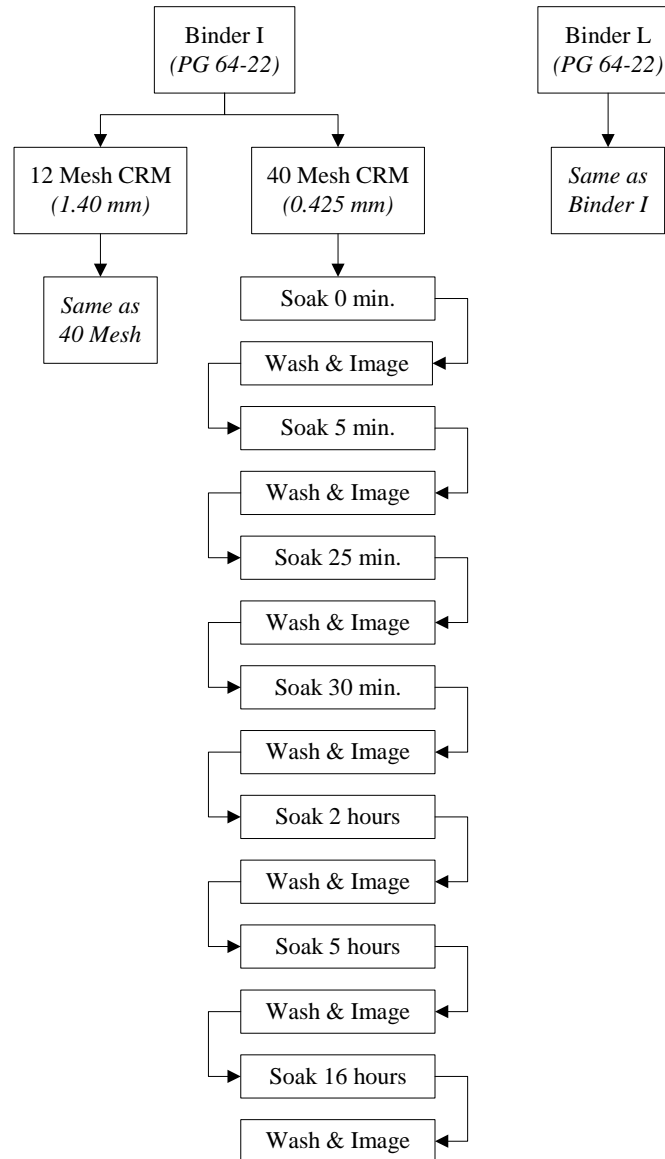
main fractional groups (large molecular size, medium molecular size, and small molecular size) according to the distribution of asphalt binders based on high-pressure gel permeation chromatography (Bynum and Traxler, 1970; Jennings *et al.*, 1985; Brule *et al.*, 1986; Glover *et al.*, 1987; Kim and Burati., 1993; Shen *et al.*, 2005).

Most of the rubberized asphalt projects conducted in the United States use the “wet” process; which entails adding the crumb rubber to the binder before mixing it with aggregate. The research conducted and reported in this paper used the wet process to blend the crumb rubber with the virgin binder. Previous research has indicated that the crumb rubber particles reacting with asphalt binder swell and form a viscous gel due to absorption of some of the lighter fractions in the asphalt binder (Green and Tolonen, 1997; Heitzman, 1992; Bahia and Davies, 1994; Zanzotto and Kennepohl, 1996; Kim *et al.*, 2001; Airey *et al.*, 2003). Furthermore, Mathias Leite *et al.* discovered that the proportion of the crumb rubber in the mixture changes significantly since a rubber particle can swell to 3 to 5 times its original size when blended with an asphalt binder (Mathias Leite *et al.*, 2003). To measure the swelling of crumb rubber particles, researchers have developed several useful methods to analyze the swelling of crumb rubber particles in asphalt binders (Airey *et al.*, 2003; Gailliard and Leblanc, 2004).

The main objective of this research was to investigate the permanent dimensional changes of crumb rubber (e.g., size and morphology) after mixing with asphalt binder using the “wet” method. This was accomplished by extracting the crumb rubber from the asphalt binder and analyzing the particles. Additionally, the change in elemental composition of crumb rubber was also evaluated. This investigation evaluated the effects of crumb rubber size, binder source, and mixing duration on the dimensional changes of crumb rubber.

## **2. Experimental Program and Procedures**

In this study, the experimental design was divided into two parts: 1) individual rubber particle soaking in asphalt binder (Figure 1), and 2) 10

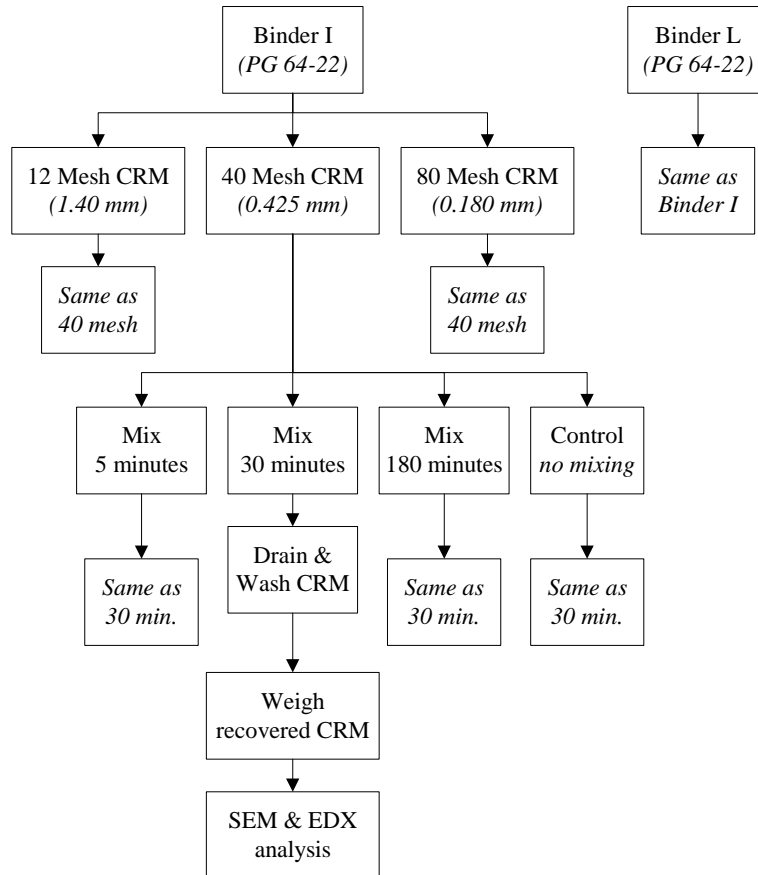


**Figure 1** Experimental design for first phase of study.

grams of crumb rubber mixed with 100 grams of asphalt binder (Figure 2). Crumb rubber produced by an ambient grinding process was used for this study with two asphalt binder sources (I and L). The binders were both PG 64-22 grade binders per AASHTO M320 (AASHTO, 2004). For the first phase of the research, two crumb rubber sizes were evaluated: 12 mesh (1.40 mm) and 40 mesh (0.425 mm). The second phase evaluated 12 mesh, 40 mesh, and 80 mesh (0.180 mm). It should be noted that the crumb rubber was separated into individual size fractions with the use of sieves, so the 12 mesh crumb rubber was that passing the No. 10 (2.00 mm) sieve and retained on the No. 12 (1.40 mm) sieve. The 40 mesh crumb rubber consisted of the rubber passing the No. 30 (0.600 mm) sieve and retained on the No. 40 (0.425 mm) sieve. The material passing the No. 50 (0.300 mm) sieve and retained on the No. 80 (0.180 mm) sieve was called the 80 mesh crumb rubber.

The first phase of this study evaluated the dimensional changes of individual crumb rubber particles after soaking in asphalt binder. To accomplish this, three rubber particles of each rubber size were individually soaked in binder. One rubber particle was placed in a 100 mL glass beaker, which was then filled with 10 grams asphalt binder. The beaker was then placed in an oven at 177°C (350°F). After the proper soaking duration, the beaker was removed from the oven and the rubber particle was washed with trichloroethylene (TCE) to remove all of the binder.

Washing was accomplished by emptying the beaker over a No. 200 (0.075 mm) sieve. The rubber particle was then removed and placed in another beaker, covered with 40 mL of trichloroethylene, and allowed to soak for 30 minutes. The particle was removed and washed a second time in the same manner to remove all of the binder from the rubber particle. Each rubber particle was soaked for a total of 0, 30, 60, 180, 480, and 1440 minutes. After each duration, the particle was washed and several magnified digital images of the particle were captured using a Nikon SMZ1000 optical microscope with a 10x optical magnification and 8x objective magnification (up to 80x magnification). The microscope was



**Figure 2** Experimental design for second phase of research.

equipped with a digital camera. To avoid the influence of the trichloroethylene, three rubber particles were also conditioned at the same conditions as the soaking particles, but no binder was used (i.e., the particles were placed in the oven in an empty beaker instead and washed in the same manner as the soaking particles).

Eight digital images were captured of each rubber particle after each soaking duration (1008 images total). Each of the eight images was taken

with the rubber particle in a different orientation, so the dimensional change of multiple sides could be identified. To measure the size of the crumb rubber particles after soaking and being washed, the digital images were imported into AutoCAD where the images were digitized and the cross-sectional area of each particle was measured. Similar processes have been used by other researchers to measure crumb rubber particles (Miknis and Michon, 1998; Putman, 2005). This was completed for four of the eight images at each soak time (504 measurements). Since this process was repeated on the same particles over the soaking duration, it was possible to measure the area of each particle in the same orientation throughout.

For the second phase of this study, small batches of crumb rubber modified (CRM) binder were produced in the laboratory. Each batch consisted of 10 grams of crumb rubber blended with 100 grams of binder. Mixing was conducted at 177°C (350°F) using a mechanical mixer equipped with an impeller rotating at 700 rpm for three mixing durations (5, 30, and 180 minutes). After mixing, the contents of the mixing container (glass beaker) was poured over a No. 200 (0.075 mm) sieve and the material retained on the sieve was placed back into the beaker, along with the mixing impeller, which was then filled with trichloroethylene to remove the binder from the crumb rubber. After soaking, the mixture was poured over a No. 200 sieve. This process was repeated until the solvent was clear. The final washed crumb rubber was then dried in a 60°C (140°F) oven for 12 hours to ensure all of the solvent was evaporated. This process was also performed on rubber that was not mixed with binder to remove the effects of the trichloroethylene from the analysis.

The crumb rubber recovered from this second phase was first used to determine the change in mass of the rubber resulting from the process of mixing with the asphalt binder. This was accomplished by measuring the change in mass of the rubber after recovery relative to the mass of the material added to the binder. Additionally, morphological and elemental analyses of particles from each sample of rubber were accomplished using a Hitachi S-3400N scanning electron microscope equipped with an Oxford INCAEnergy Energy Dispersive System (EDS).

### **3. Experimental Results**

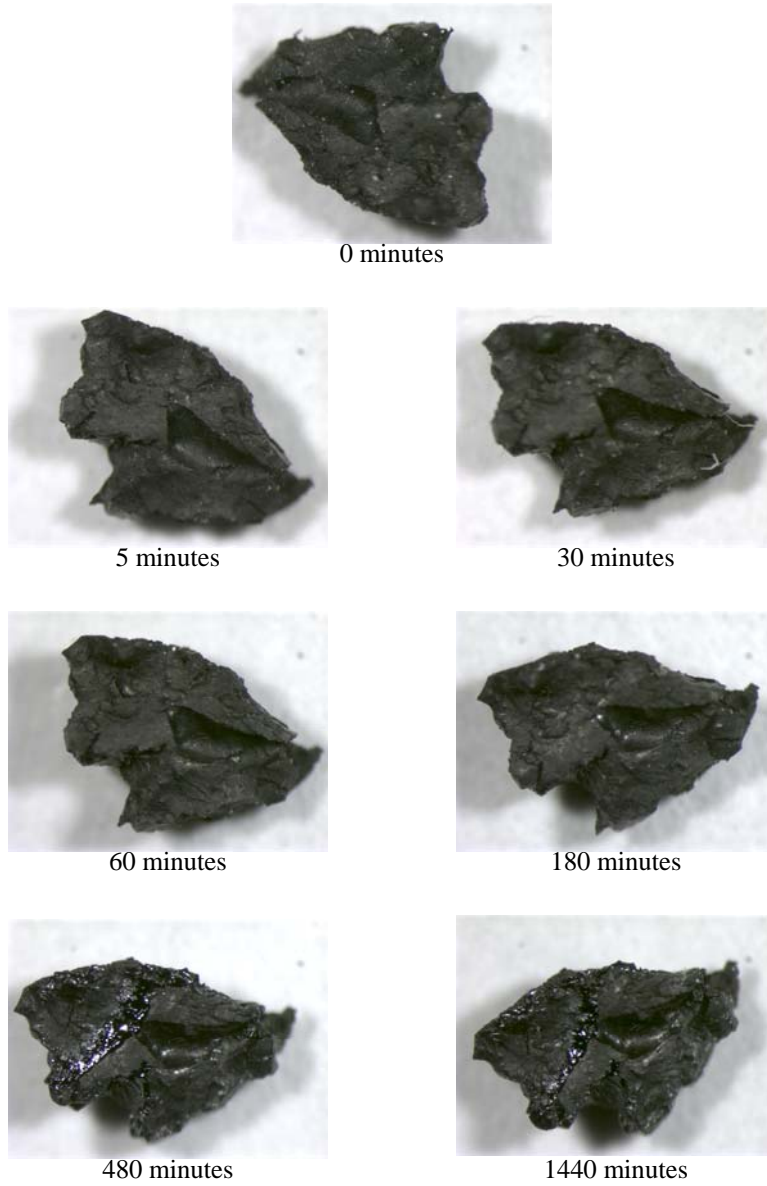
This study, which was divided into two phases, evaluated the permanent changes to crumb rubber particles resulting from interaction with asphalt binders. The four main means of particle evaluation included dimensional changes (cross-sectional area), mass changes, morphological changes, and changes in chemical composition.

#### ***3.1. Dimensional Changes***

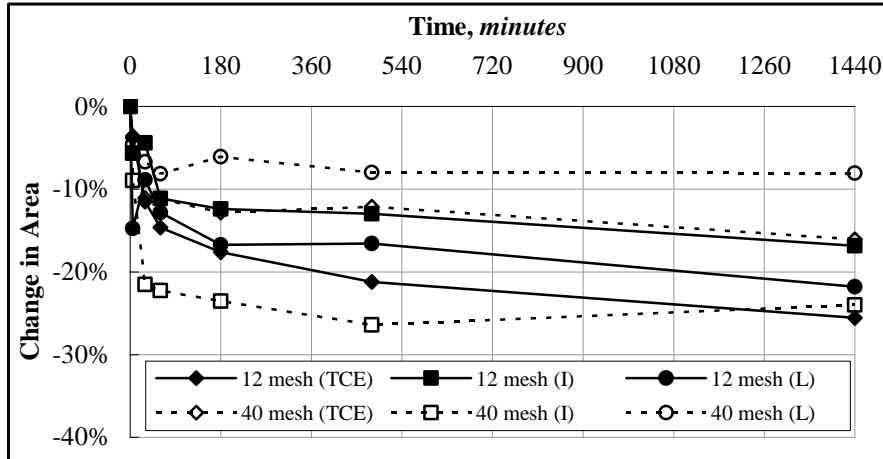
Figure 3 shows digital images of an individual crumb rubber particle after being soaked in asphalt binder for varying durations up to 24 hours. The particle was washed with trichloroethylene to remove the binder prior to imaging. The size of the rubber particles decreased between the soaking durations of 60 to 480 minutes. This reduction in size of the rubber particles is also seen in Figure 4, which shows the relationship between the change in cross-sectional area of the particles with respect to the soaking duration. In this figure, the majority of the size reduction occurs in the first three hours of interaction with the binder.

Additionally, visual inspection of the rubber particles lead to the finding that the swelling of the rubber particles in the binder caused micro-cracks in the particles to open wider as the soaking duration increased. This is seen in Figure 3 where the binder was not able to be completely washed away after 480 minutes (8 hours) of soaking. In one case, the crack grew so much that the particle split into two pieces (not pictured).

Such changes in the size of crumb rubber particles resulting from digestion in asphalt binders indicate that there was some degree of depolymerization of the crumb rubber particles over time. While this has been concluded by other researchers (Abdelrahman and Carpenter, 1999; Billiter *et al.*, 1997), the degree of depolymerization has not been quantified in this manner previously.



**Figure 3** *Optical images of an individual crumb rubber particle at various soaking durations in asphalt binder.*



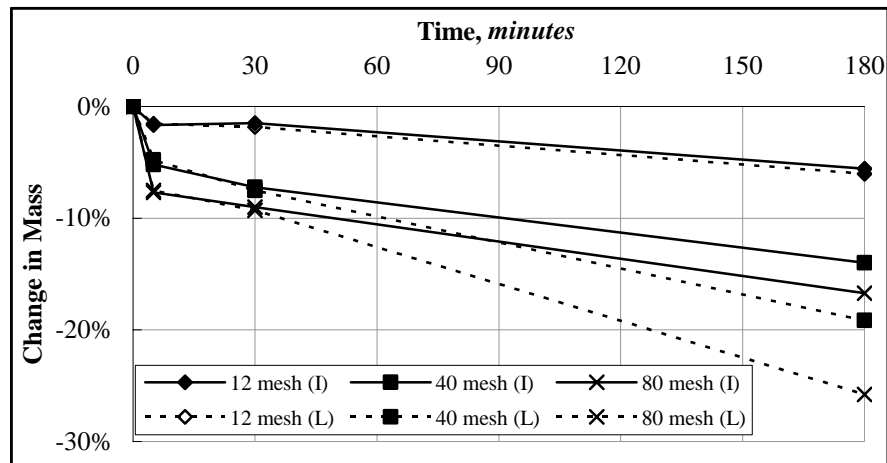
**Figure 4** Change in area of crumb rubber particles relative to soaking duration in asphalt binder. Note: (TCE) – trichloroethylene, (I) – binder source I, and (L) – binder source L.

### 3.2. Mass Changes

Figure 5 summarizes the results of the change in mass of the crumb rubber after being mixed with the asphalt binders for varying durations. The results reported in this figure also account for the mass loss attributed to the effects of the trichloroethylene during the washing process. These results indicate that the mass of the crumb rubber decreases with increasing mixing duration. This, again, provides an indication that there is some level of depolymerization occurring at the mixing conditions used in this study.

The level of particle breakdown appears to be dependent on the size of the crumb rubber and the binder source. The mass of the crumb rubber sample significantly decreases as the crumb rubber size decreases. This is expected since the concentration of solvent (binder) in a particle is dependent on the size of the particle (Blow, 1971; Crank, 1975). Smaller particles will have a higher concentration than larger particles after the

same duration. As a rubber particle nears saturation, it will swell more and the potential for fracture increases.

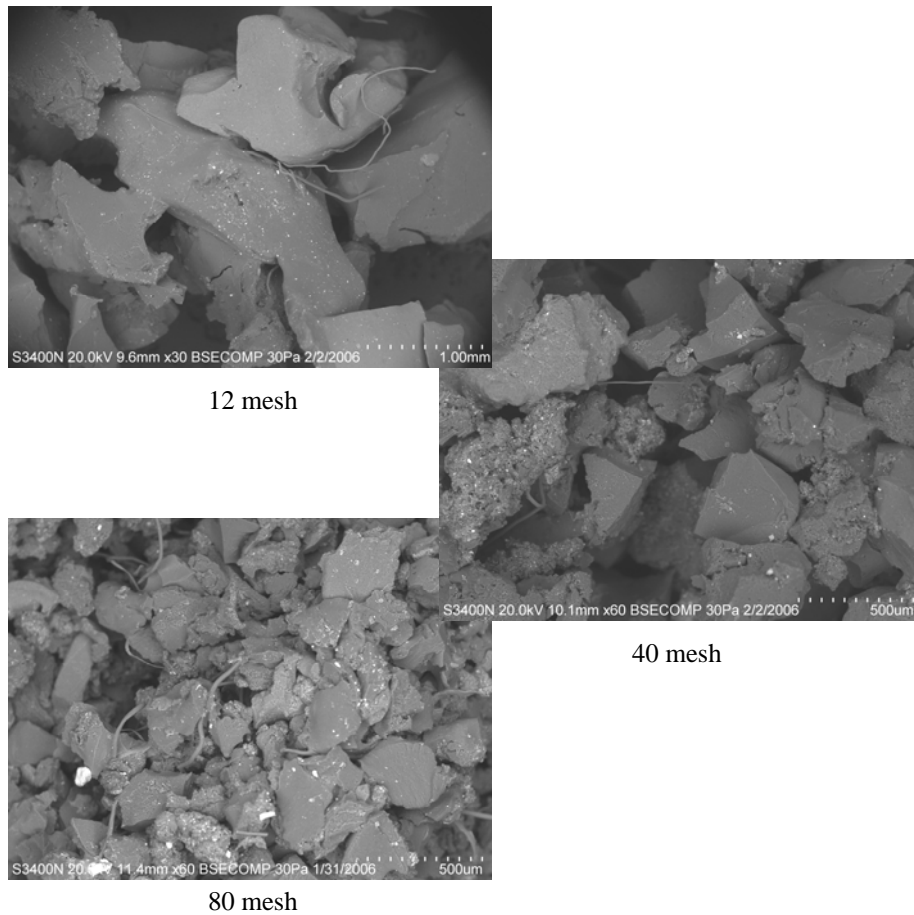


**Figure 5** Change in mass of crumb rubber relative to mixing duration with asphalt binder. Note: (I) – binder source I and (L) – binder source L.

### 3.3. Changes in Morphology

Based on visual examination of the recovered crumb rubber from the second phase of this study, it was determined that the longer the mixing duration, the more rubber particles stuck together after washing. Additionally, the finer 80 mesh crumb rubber stuck together more than the coarser particles. Following this finding, closer examination of the recovered crumb rubber was conducted using a scanning electron microscope (SEM). SEM micrographs of 12, 40, and 80 mesh crumb rubber recovered from the CRM binders are included in Figure 6. The images in Figure 6 indicate that the morphology of the individual particles does not change a significant amount meaning that clumping of

the crumb rubber is not the result of fusing of the particles, but rather possibly from the presence of small quantities of binder remaining in the particles.



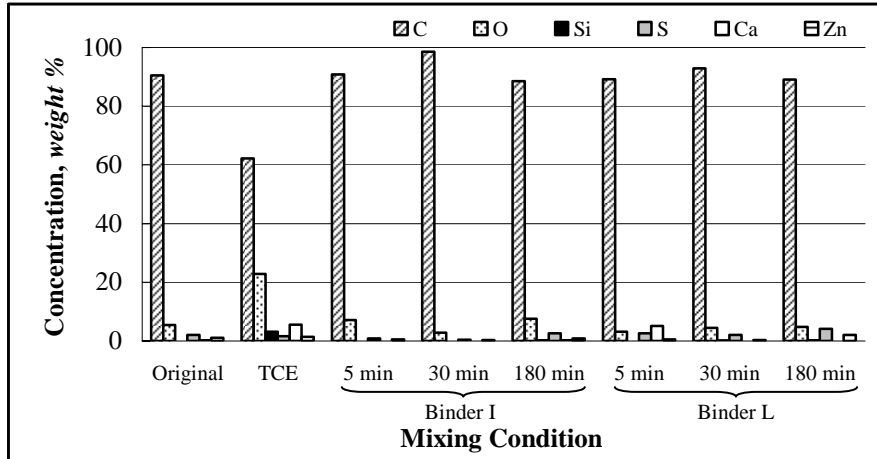
**Figure 6** SEM micrographs of crumb rubber.

In addition to the conglomeration of the crumb rubber particles, the presence of fibers and other non-rubber material was also more prevalent in the finer crumb rubber samples as the mixing duration increased. Examples of the fibers and non-rubber material can be seen in Figure 6. Again, these materials were seen more in the 80 mesh crumb rubber images than the coarser material. The particles having light color in Figure 6 were the subjects of the elemental analysis to be discussed in the next section.

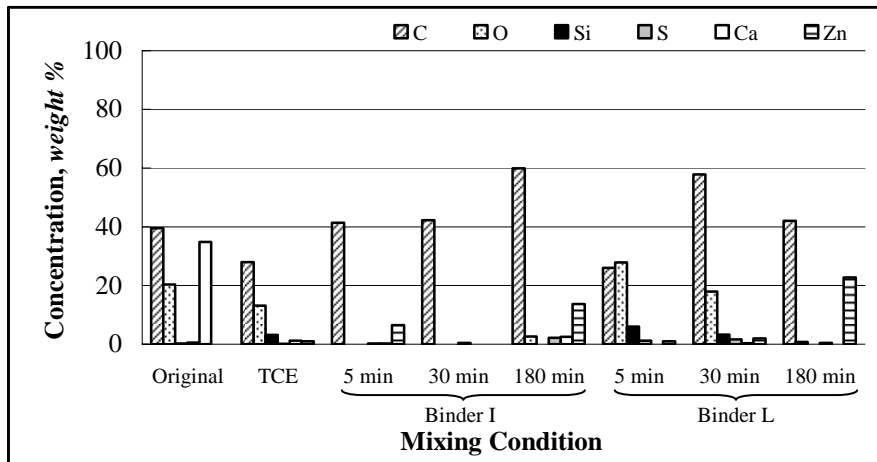
The presence of such quantities of fiber and other non-rubber material is most likely a result of the breakdown of the rubber particles, thus liberating the material encapsulated by the rubber. The effect of the short fiber material present in CRM binders could provide some benefit to the rheological properties of the binders and should be further evaluated.

### ***3.4. Changes in Elemental Composition***

Identification of the composition of the dark and light areas shown in the SEM micrographs was accomplished using an Energy Dispersive System (EDS) that introduces an energy dispersive x-ray (EDX) spectrum to identify the elemental composition of individual points on an SEM image. For each sample of crumb rubber, several points in the black and white colored areas of multiple rubber particles were analyzed. Figures 7 through 12 summarize the concentration of different elements present in the different areas. Direct comparisons of the elements common to the black and white areas in the 12, 40, and 80 mesh crumb rubber particles are shown in Figures 7 through 9, respectively. These comparisons indicate that the black (rubber) areas have significantly higher carbon contents than the white areas, which is expected since carbon is represented by black color in an SEM image. The black areas also included greater concentrations of zinc as compared to the white areas. The presence of zinc in the black areas is expected as zinc oxide (ZnO) is a vulcanization component (Mark *et al.*, 2005). The white areas contain greater amounts of oxygen, calcium, and silicon.

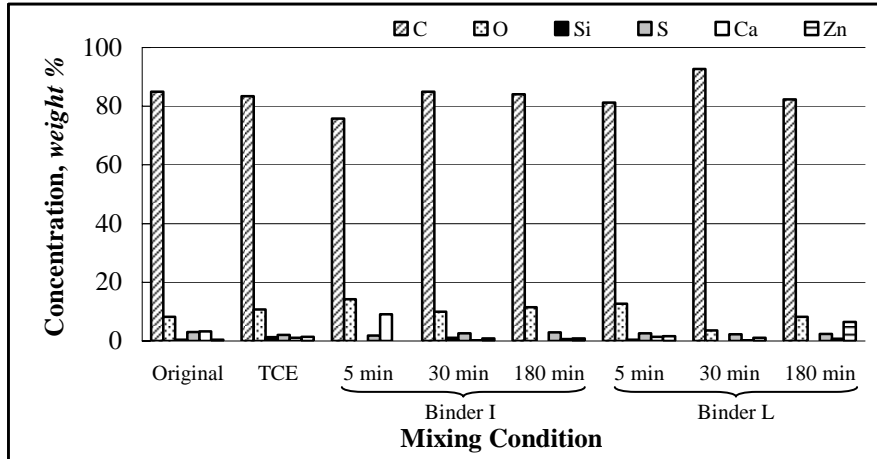


(a)

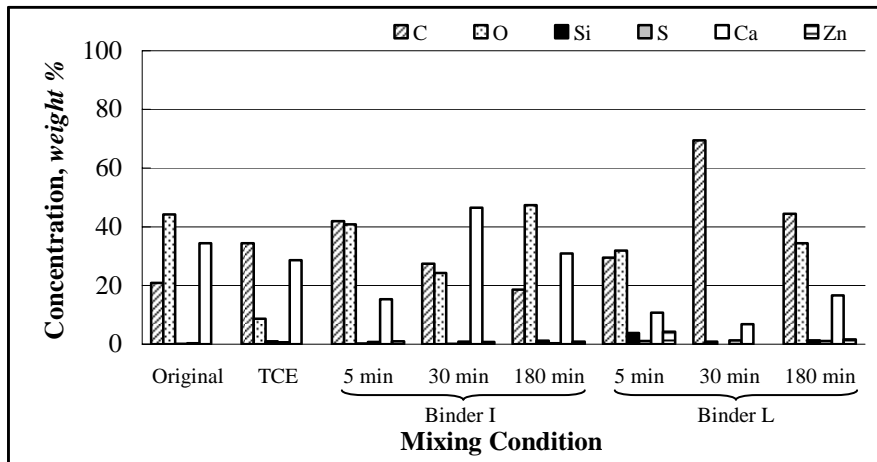


(b)

**Figure 7** Elemental composition of (a) black areas and (b) white areas of 12 mesh crumb rubber (C-carbon, O-oxygen, Si-silicon, S-sulfur, Ca-calcium, and Zn-zinc).

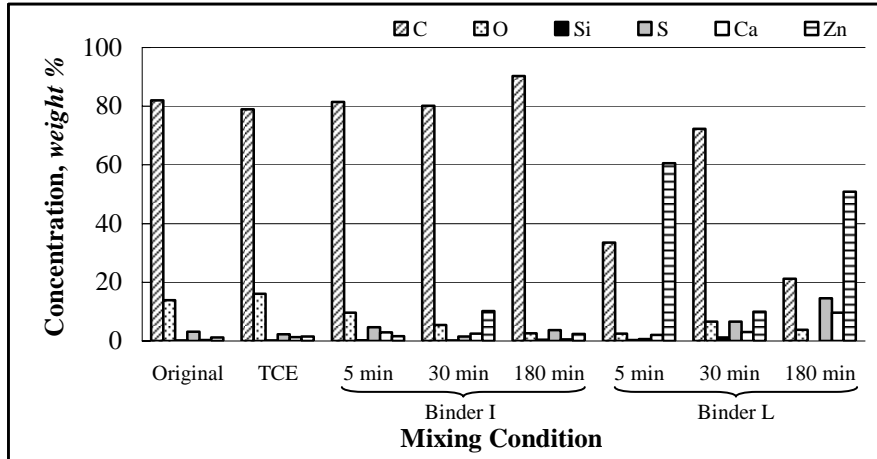


(a)

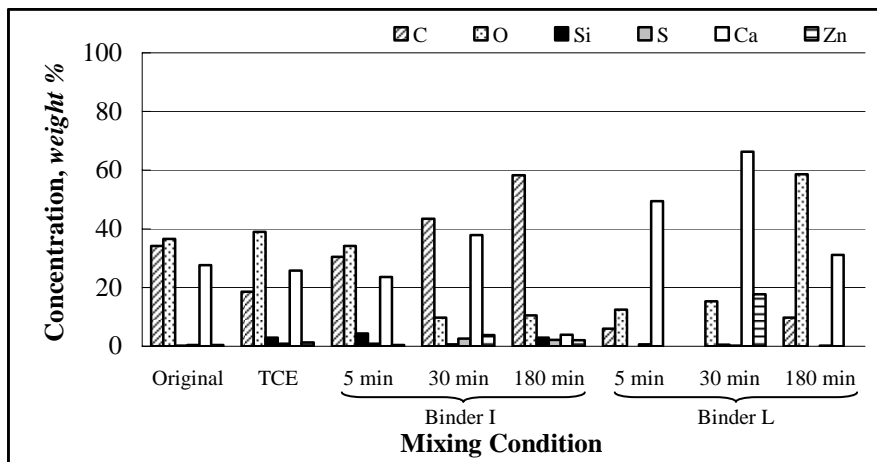


(b)

**Figure 8** Elemental composition of (a) black areas and (b) white areas of 40 mesh crumb rubber (C-carbon, O-oxygen, Si-silicon, S-sulfur, Ca-calcium, and Zn-zinc).



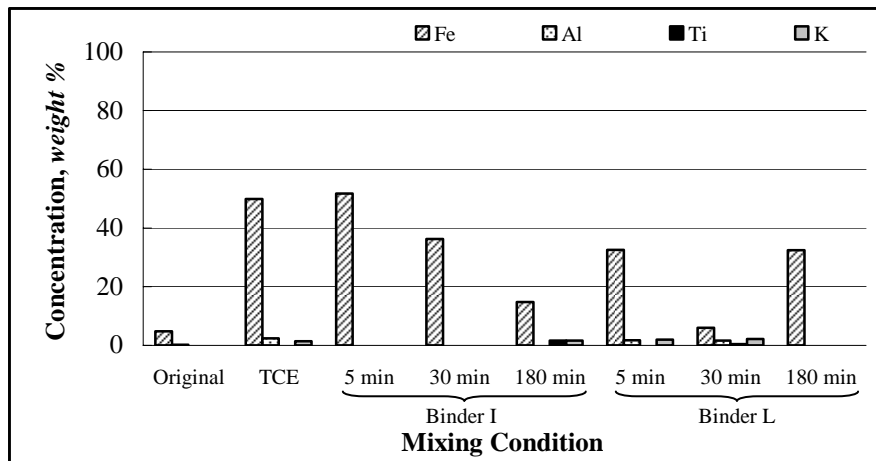
(a)



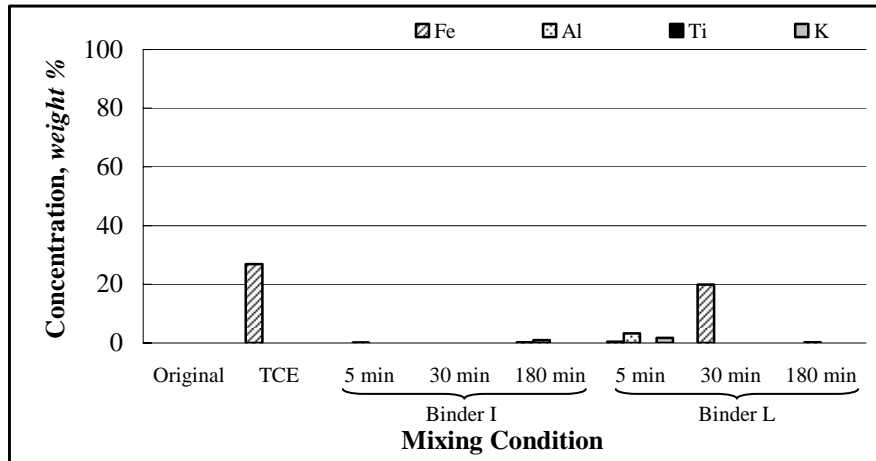
(b)

**Figure 9** Elemental composition of (a) black areas and (b) white areas of 80 mesh crumb rubber (C-carbon, O-oxygen, Si-silicon, S-sulfur, Ca-calcium, and Zn-zinc).

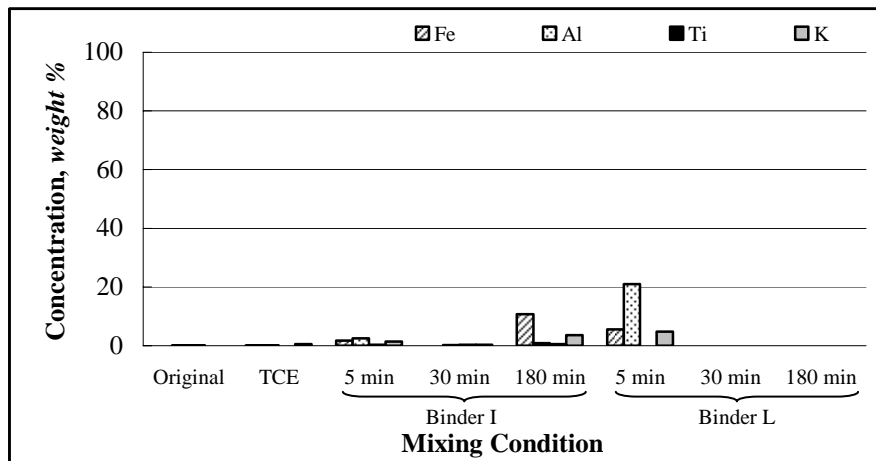
Additional elements were also identified in the white areas as summarized in Figures 10 through 12. These elements included iron, aluminum, titanium, and potassium. Based on this analysis, the white areas and particles are most likely the filler materials included in the rubber compounds. Aside from carbon black, typical filler systems used in rubber compounding include silica, kaolin clay (hydrous aluminum silicate), mica (potassium aluminum silicate), talc (magnesium silicate), limestone (calcium carbonate), and titanium dioxide (Mark *et al.*, 2005). As mentioned in the previous section, this filler material may be liberated from the rubber due to the particle breakdown resulting from the interaction with asphalt binder.



**Figure 10** Concentration of additional elements present in the white areas of 12 mesh crumb rubber (Fe-iron, Al-aluminum, Ti-titanium, and K-potassium).



**Figure 11** Concentration of additional elements present in the white areas of 40 mesh crumb rubber (Fe-iron, Al-aluminum, Ti-titanium, and K-potassium).



**Figure 12** Concentration of additional elements present in the white areas of 80 mesh crumb rubber (Fe-iron, Al-aluminum, Ti-titanium, and K-potassium).

#### 4. Conclusions

This laboratory study investigated the permanent changes to crumb rubber that occur as a result of the interaction with asphalt binders. These findings could provide valuable information when considering the use of rubber modified asphalt as a reclaimed asphalt pavement (RAP) source in the future. Based on the results of this investigation, the following conclusions were made:

- After removal of asphalt binder from crumb rubber particles, the dimensions of the crumb rubber are reduced as a result of interaction with asphalt binder. This can be attributed to the breakdown, or depolymerization, of the rubber particles digesting in hot asphalt binder.
- The size reduction of rubber material increases with mixing, or digestion, duration and with decreasing crumb rubber size.
- The binder source has an effect on the breakdown of crumb rubber material in CRM binders.
- The breakdown of crumb rubber particles results in the liberation of short fibers and filler material included in the rubber compounds as determined through scanning electron microscopy.
- Due to the variability of the EDX data, it was difficult to detect statistically significant differences between the elemental compositions of different treatments. However, the experimental method does have merit and should continue to be used, but with larger sample sizes.

#### 5. Bibliography

Abdelrahman, M.A. and Carpenter, S.H., "Mechanism of Interaction of Asphalt Cement with Crumb Rubber Modifier," *Transportation Research Record 1661*, Transportation Research Board, National Research Council, Washington, D.C., 1999.

Airey G.D, Rahman M. M., and Collop A. C., "Absorption of Bitumen into Crumb Rubber Using the Basket Drainage Method," *International Journal of Pavement Engineering*, Vol. 4(2), 2003.

American Association of State Highway and Transportation Officials (AASHTO), *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, 22<sup>nd</sup> Edition, AASHTO, Washington D.C., 2002.

- Amirkhanian, S. N., "Establishment of an Asphalt-Rubber Technology Service (ARTS)," *Proceedings of the Asphalt Rubber 2003 Conference*, Brasilia, Brazil, 2003.
- Bahia H.U. and Davies R., "Effect of Crumb Rubber Modifier (CRM) on Performance Related Properties of Asphalt Binders," *Journal of the Association of Asphalt Paving Technologists* Vol. 63, 1994.
- Billeter, T.C., Davison, R.R., Glover, C.J., and Bullin, J.A., "Production of Asphalt-Rubber Binders by High-Cure Conditions," *Transportation Research Record No. 1586*, Transportation Research Board, National Research Council, Washington, D.C., 1997.
- Blow, C.M., *Rubber Technology and Manufacturing*, Institution of the Rubber Industry, Butterworths, London, 1971.
- Bynum, D.Jr. and Traler, R.N., "Gel Permeation Chromatography Data on Asphalts Before and After Service in Pavement," *Proceedings of the Association of Asphalt Paving Technologists*, Vol.39, 1970.
- Choubane, B., Sholar, G.A., Musselman, J.A., and Page, G. C., "A Ten-year Performance Evaluation of Asphalt-Rubber Surface Mixes," *Transportation Research Record No. 1681*, Washington, DC, 1999.
- Crank, J., *The Mathematics of Diffusion*, Oxford University Press, Oxford, U.K., 1975.
- Dantas Neto, S. A., Farias, M. M., Pais, J. C., Pereira ,P. A., and Picado Santos, L., "Behavior of Asphalt-Rubber Hot Mixes Obtained with High Crumb Rubber Contents," *Proceedings of the Asphalt Rubber 2003 Conference*, Brasilia, Brazil, 2003.
- Esch, D.C., "Construction and Benefits of Rubber Modified Asphalt Pavements," *Transportation Research Record No. 860*, TRB, National Research Council, Washington, DC, 1982.
- Gaulliard, V., and Leblanc, J.L., "A Rheometrical Technique to Study the Swelling Kinetics of Vulcanized Rubber Particles by Paraffinic Solvents Using a Torque Rheometer," *Journal of Applied Polymer Science*, Vol. 94, 2004.
- Green E.L. and Tolonen W.J., *The Chemical and Physical Properties of Asphalt-Rubber Mixtures*, Arizona Department of Transport, Report ADOT-RS-14 (162), 1977.
- Heitzman M., "Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier," *Transportation Research Record 1339*, TRB, National Research Council, Washington, DC, 1992.
- Holleran, G. and Van, K. J., "Asphalt Rubber Concrete Leads to Cost Effective Pavement Rehabilitation Reduced Thickness," *Synopses for 1st International Conference World of Pavement*, Sydney, Australia, 2000.
- Isacson, U. and Lu, X., "Testing and Appraisal of Polymer Modified Road Bitumens-State of the Art," *Material and Structures* 28, 1995.
- Jennings, P.W., Pribanic, J.A., Dawson, K.R., Smith, J.A., and Koontz, S., "Uses of High Performance Gel Permeation Chromatography for Asphalt Analysis," *Proceedings of the 64th Annual Meeting of the Transportation Research Board*, Washington, D.C., 1985.

- Kim, Kwang W., Burati, J. L., "Use of GPC Chromatograms to Characterize Aged Asphalt Cements," *Journal of Materials in Civil Engineering*, Vol.5, No.1, 1993.
- Kim S., Loh S.W. Zhai, H. and Bahia H., "Advanced Characterization of Crumb Rubber-Modifier Asphalts, Using Protocols Developed for Complex Binder," *Transportation Research Record 1767*, TRB, National Research Council, Washington, DC, 2001.
- Kneen, M.A., and Annegarn, H.J., "Algorithm for Fitting XRF, SEM and PIXE X-Ray Spectra Backgrounds," *Nuclear Instruments & Methods in Physics Research*, Vol. 109-110, 1996.
- Kotula, P.G., Keenan, M.R., and Anderson, A.M., "SEM/EDX Spectrum Imaging and Statistical Analysis of a Metal/Ceramic Braze," *Materials Research Society Symposium - Proceedings*, v 589, 2001.
- Mark, J.E., Erman, B., and Eirich, F.R., *The Science and Technology of Rubber, 3<sup>rd</sup> Edition*, Elsevier Academic Press, 2005.
- Mathias Leite, L. F., Almeida da Silva, P., Edel, G., Goretta da Motta, L., and Herrmann do Nascimento, L. A., "Asphalt Rubber in Brazil: Pavement Performance and Laboratory Study," *Proceedings of the Asphalt Rubber 2003 Conference*, Brasilia, Brazil, 2003.
- McCrum, N.G., Buckley, C.P. and Bucknall, C.B., *Principles of Polymer Engineering, 2nd Ed.*, Oxford Science Publications, Oxford, 1999.
- Miknis, F.P. and Michon, L.C., "Some Application of Nuclear Magnetic Resonance Imaging to Crumb Rubber Modified Asphalts," *Fuel*, Vol. 77, No. 5, 1998.
- Putman, B.J., Quantification of the Effects of Crumb Rubber in CRM Binders, Dissertation, Clemson University, Clemson, SC, 2005.
- Shen, J.N., Amirkhania S.N, Xiao F.P., "High-Pressure Gel Permeation Chromatography Characterization of Aging of Recycled Crumb-Rubber-Modified Binders Containing Rejuvenating Agents," *Proceedings of the 85<sup>th</sup> Annual Meeting of the Transportation Research Board*, Transportation Research Board, Washington, D.C. 2005.
- Sousa, J.B, Pais J.C., Saim R., Way G.B., and Stubstad R.N., "Mechanistic-Empirical Overlay Design Method for Reflective Cracking," *Transportation Research Record 1809*, Transportation Research Board, National Research Council, Washington, D.C., 2002.
- Treloar, L.R.G., *The Physics of Rubber Elasticity, 3rd Ed.*, Oxford University Press, Oxford, UK, 1975.
- Way, G. B., "The Rubber Pavements Association, Technical Advisory Board Leading the Way in Asphalt Rubber Research," *Proceedings of the Asphalt Rubber 2003 Conference*, Brasilia, Brazil, 2003.
- Whiteoak, C.D., *The Shell Bitumen Handbook*, Shell Bitumen, Surrey, UK, 1990.
- Zanzotto L. and Kennepohl G., "Development of Rubber and Asphalt Binders by Depolymerization and Devulcanization of Scrap Tires in Asphalt," *Transportation Research Record 1530*, TRB, National Research Council, Washington, DC, 1996.