MT/2005/023143

Rutting Resistance of Rubberized Asphalt Concrete Pavements Containing Reclaimed Asphalt Pavement Mixtures

ASCE Journal of Materials in Civil Engineering

Feipeng Xiao[1], Serji Amirkhanian[2], M., ASCE, and C. Hsein Juang[3], M., ASCE

Abstract: Improved understanding of rutting resistance of a rubberized asphalt concrete (RAC) pavement that contains reclaimed asphalt pavement (RAP) is important to stimulating the use of rubberized asphalt mixtures. Use of RAP in the past has proved to be economical, environmentally sound and effective in increasing the rutting resistance of asphalt mixtures. Rubberized asphalt has been used successfully in improving the mechanical characteristics, such as rutting resistance, of typical hot mix asphalt (HMA) mixture around the country and the world. The objective of this research was to investigate the rutting resistance characteristics of the rubberized asphalt mixtures through a laboratory testing program. The experimental design included use of two rubber types (ambient and cryogenically produced), four rubber contents, and three crumb rubber sizes. The results of the experiments indicated that the use of RAP and crumb rubber in the HMA can improve effectively the rut resistance of these mixes.

CE Database subject headings: Asphalt Concrete, Rubberized Asphalt, Asphalt Pavements, Binders, Crumb Rubber, Rutting, Tensile Strength.

---

[1] Reasearch Assistant, Department of Civil Engineering, Clemson University, Clemson, SC 29634-0911. E-mail: feipenx@clemson.edu

[2] Professor, Department of Civil Engineering, Clemson University, Clemson, SC 29634-0911. E-mail: kcdoc@clemson.edu

[3] Professor, Department of Civil Engineering, Clemson University, Clemson, SC 29634-0911. E-mail: hsein@clemson.edu

INTRODUCTION

Rutting, loosely defined as longitudinal depressions in wheel paths as a result of continued densification by the traffic load, is a type of structural distress in asphalt concrete pavements. It is a primary measure of the performance of pavements in several pavement design methods. Past studies (Chen et al. 2004) on the rutting of asphalt concrete pavements have resulted in various predictive models. However, the incorporation of reclaimed asphalt pavement (RAP) materials containing crumb rubber has not been investigated in great detail. For the past several years, several researchers have concluded that the rubberized asphalt mixes can be helpful in reducing the overlay thickness (Holleran and Van 2000) and its reflective cracking (Cano et al. 1989; Esch 1982; Choubane et al. 1999). Another research also indicated that these mixtures have a high resistance to rutting and fatigue cracking (Way 2003), in addition to protecting the environment and saving resources (e.g., landfill spaces).

In 1960, Charles McDonald became the first engineer to use tire rubber in asphalt mixtures to improve pavements in the United States; 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 resistance to rutting, fatigue cracking and thermal cracking (Way 2003; Sebaaly et al. 2003). Antunes et al. (2003) pointed out; however, that the stiffness of the asphalt rubber being somewhat lower than the values generally obtained from the conventional asphalt mixture at test temperature (about 150 to 177°C).

Most of the rubberized asphalt projects conducted in the United States use the wet process; which is 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 to the virgin binder. There are many issues involved with the wet process that must be considered before the completion of the mix design including rubber size and percentage, rubber particle shape, etc. For example, the proportion of the crumb rubber change significantly in the mixture since a rubber particle swells to 3 to 5 times its size (Mathias Leite et al. 2003).

The recycling of existing damaged asphalt pavement materials produces new pavements with considerable savings in material, money, and energy. Aggregate and binder from old asphalt pavements are still valuable even though these pavements have reached the end of their service lives. They have been used with virgin resources to produce new asphalt pavements, proving to be both economical and effective in protecting the environment. Furthermore, mixtures containing reclaimed asphalt pavement (RAP) have been found, for the most part, to perform as well as virgin mixtures with respect to rutting resistance. The NCHRP (2001) report provides basic concepts and recommendations concerning the components of mixtures, including new aggregate and RAP materials. The Superpave Mixtures Expert Task Group of the Federal Highway Administration (FHWA) developed interim guidelines for using RAP based on past experience (FHWA 1997a). In NCHRP Project 9-12 (NCHRP 2001), use of the tiered approach for RAP was considered appropriate. The relatively low levels of RAP can be used without extensive testing of the binder, but when higher RAP contents are desirable, conventional Superpave binder tests must be used to determine how much RAP should be added or which virgin binder is recommended to be added to the mixture.

Since the mid-1970’s, tens of millions of tons of RAP have been used to produce recycled Hot Mix Asphalt (HMA) around the country. The use of RAP has evolved into routine practice in many areas around the world. In the United States, the Federal Highway Administration reported that 73 of the 91 million metric tons of asphalt pavement removed each year during resurfacing and widening projects are reused as part of new roads, roadbeds, shoulders and embankments (FHWA 2002). Meanwhile, there were approximately 290 million scrap tires generated in the United States at the end of 2003, 233.3 million of which were recycled and reused (RMA 2003; Amirkhanian 2003). In recent years, more and more states have begun to ban whole tires from landfills, and most states have laws specially dealing with scrap tires. As a result, it is necessary to find safer and economical ways for disposing these tires. The civil engineering market involves a wide range of uses for scrap tires, exemplified by the fact that currently 39 states have approved the use of tire shreds in civil engineering application (RMA 2003). The market for crumb rubber has been growing over the past several years both in the United States and in other countries. Rubberized asphalt, the largest single Civil engineering market for crumb rubber, is being used in increasingly large amounts by several Departments of Transportations (e. g., Arizona, California, Florida, Texas, and South Carolina). Most laboratory and field experiments indicate that the rubberized asphalt mixtures, in general, show an improvement in durability, crack reflection, fatigue resistance, skidding resistance, and resistance to rutting not only in an overlay, but also in stress absorbing membrane layers (Hicks et al. 1995).

The goal of this study was to gain an improved understanding of the rutting resistance characteristics of the rubberized asphalt mixtures. Experiments were carried out to evaluate the indirect tensile strength (ITS) and rutting susceptibility of each rubberized asphalt concrete (RAC) and RAP mixtures using Asphalt Pavement Analyzer. Tests were also performed to determine the rutting properties of various mixtures with respect to rubber production type, content, and size in the mixture.

EXPERIMENTAL PROGRAM AND PROCEDURES

Materials

The experimental design was divided into two parts. For the first phase of the research work, two rubber types (Ambient and Cryogenic), four rubber contents (0%, 5%, 10%, and 15% by weight of virgin binder), and three crumb rubber sizes (-14 mesh (-1.4 mm), -30 mesh (-0.60 mm), and -40 mesh (-0.425 mm)) were used to make various mixtures. To avoid the influence of blending, one aggregate source (designated as L) and one binder source and grade (PG 64-22) were used for preparing the samples. A total of 13 mix designs were conducted in this phase. The second part of the work included the validation of the findings from the first phase by using another aggregate source (designated as C) and another binder grade (PG52-28). A total of 3 mix designs were conducted for this phase of the research.

The RAPs were taken from the same geographical area as the new aggregates to ensure that the aggregate in the RAP had similar properties as the new one. Both RAP sources (L and C) were approved by the South Carolina DOT and mixed with an original binder equivalent to a PG 64-22. Four RAP percentages (0%, 15%, 25%, and 30%) were used in the mixtures made with aggregate L and three RAP percentages (0%, 15% and 38%) with aggregate C.

Binder Mixing

A mechanical mixer was used to blend the rubber and the virgin binder. The crumb rubber was added to asphalt binder using a reaction time of 30 minutes, a reaction temperature of 350 °F (177 °C) and a reaction speed of 700 rpm. The reaction time of 30 minutes was considered suitable based on a preliminary study indicating that the mixing time did not significantly influence the binder properties (Thompson and Xiao 2004).

Mixture Sample Fabrication

The original Superpave mix design system did not address the use of RAP and no guidelines on such use were available. However, several studies have been conducted on this subject in the past several years. For example, research has led to the Black Rock Study, the use of the 3-Tier Approach, the use of linear blending, and the development of technician manuals for the use of RAP, as summarized in Superpave Mixes (FHWA 1997b; McDaniel et al. 2000; NCHRP 2001). In the present study, the Superpave system was used to obtain the optimum binder contents (OBCs) for all sixteen mixtures (13 mix designs for aggregate L and 3 for aggregate C) containing various materials (i.e., 2 rubber types; 3 rubber sizes; 4 rubber contents; and 4 RAP contents). The Asphalt Pavement Analyzer (APA) test specimens were compacted by the Superpave Gyratory Compactor to diameters of 150 mm and thicknesses of 75 mm, in which the air void content was controlled to be 4.0 ± 0.5 percent.

Mix Design

A nominal maximum size 9.5mm Superpave mixture was used for the mix design in this experiment. This particular mix design is used as a primary route surface course mix in many states including South Carolina. The SCDOT 9.5 mm Superpave volumetric and compaction specifications, shown in Table 1, were used. The procedures described in AASHTO PP 19 (Volumetric Analysis of Compacted Hot Mix Asphalt) and AASHTO T312 (Preparing and Determining the Density of Hot Mix Asphalt Specimens by Means of the Superpave Gyratory Compactor) regarding the preparation of HMA specimens were followed. In addition, the procedures described in SCDOT-T-70 for moisture susceptibility were used.

In this study, a conventional HMA mixture composed of new virgin binder and aggregate is used as a control. For each mixture, six specimens were fabricated and tested. Comparisons were made among the following groups:

- Mixtures with the modified binder and different percentages of RAP,
- Mixtures with the same RAP percentages and different binder types (e.g., rubber content, rubber type, rubber size).

The details of the mix design of two RAP sources are shown in Table 2 and Table 3(b). The RAP materials are first oven-dried and sieved to obtain particles with target sizes shown in Table 2. Then, these materials are blended with the virgin aggregate at the specified (target) mixing temperatures. The mixture is heated for about one hour in order to maintain the target mixing temperature. Finally, the modified binder (rubber and virgin binder) is added to the mixtures and the final mixture is heated for about two hours before compaction.

The flowchart of the experimental design is depicted in Figure 1. Two granite aggregate sources are used in this study. Hydrated lime, which is used as an anti-strip additive, was added at a rate of 1% by dry mass of virgin aggregate. Gradations of the 9.5mm mixtures are illustrated in Figure 2. All mixes satisfied the requirements as specified in Table 1 and Figure 2 for the optimum binder content before performing the ITS and rutting tests. When the rubber content and size were varied for other mix designs, the same gradation of the aggregate as shown in Figure 2 was used.

ANALYSIS OF TEST RESULTS

Statistical Considerations

The effects on the physical properties of various mixtures (i.e., ITS and rut depth), caused by the incorporation of crumb rubber and RAP, were statistically analyzed at the 5%

level of significance. For these comparisons, it should be noted that all specimens were produced at OBC.

Optimum Binder Content Analysis

The optimum asphalt binder content, for this work, is defined as the amount that is required to achieve 4.0% air voids at a given number of design gyrations (N_{design}). Table 3 gives the optimum binder content (OBC), maximum specific gravity (MSG) and bulk specific gravity (BSG) data of the mix designs with various percentages of RAP and rubber types. As shown in Table 3, the OBCs of the mixtures decrease slightly as the percentage of RAP increases for both types of rubber (cryogenic and ambient), the only exception being the mixture that is composed of the cryogenic rubber with 30% RAP. The OBCs of the cryogenic modified binder are found to be slightly higher than those of the ambient. Table 3 also shows that as the percentage of RAP increases, OBCs in the mixtures slightly decreases, while both gravities (MSG and BSG) of the two types of rubber binder mixtures increase.

Table 4 gives the OBC, MSG, and BSG for the mixtures containing the four different percentages of rubber content and the three rubber sizes. The OBCs of these mixtures are compared with respect to the differences in the percentage and size of rubbers. In general, the OBCs increase from 4.7% to 5.65% as the percentage of rubber content in the modified binder increases from 0 to 15%. Here, the virgin binder in the modified asphalt binders is approximately equal to 4.7%, regardless of whether the rubber content is 5%, 10%, or 15%. In this situation, rubber can be considered as filler. On the other hand, the rubber content affects the density of the mixtures, and thus, the workability, because the MSG and BSG of the mixtures decrease with the increase in the rubber content. In the case of the -30 mesh (-

0.60 mm) and -40 mesh (-0.425 mm) size, the OBC is the same for both sizes; however, the -14 mesh (-1.4 mm) rubber exhibits slightly higher OBC in the mixtures used in this study.

Indirect Tensile Strength (ITS) Analysis

Rutting in HMA can occur from two types of mechanical response: viscous flow and plastic deformation. Plastic deformation occurs as aggregate particles move slightly relative to one another, which are accompanied by viscous flow in the asphalt binder binding these particles together (Zaniewski and Srinivasan 2004). The behavior of asphalt concrete can be analyzed by the Mohr-Coulomb failure theory. This theory predicts that the strength of a material such as asphalt concrete depends upon both cohesion and internal friction. Furthermore, previous research (Christensen et al, 2000) introduced a simplified method for determining mixture cohesion and internal friction by testing asphalt concrete specimens in indirect tension and unconfined compression. A study conducted jointly by The Pennsylvania Transportation Institute of The Pennsylvania State University, and Advanced Asphalt Technologies, evaluated cohesion and angle of internal friction values determined using tri-axial , unconfined compression and indirect tensile strength (ITS) tests (Christensen and Bonaquist 2002, Anderson et al. 2003). In analyzing the data for this paper, a very good correlation between ITS and rut resistance was found. In this study, cohesion and angle of internal friction values among the virgin binder, the aged binder, and crumb rubber will be expressed in the ITS test

After the OBC for each mixture was determined, the ITS and the rutting resistance were obtained according to the specifications and procedures described in ASTM D4123 and the APA rutting test specifications. For the ITS tests, three wet and three dry samples were tested at room temperature (25^{o}C). The specimens were fabricated to meet the target air void content of 7% ± 1%. All mixes passed the SCDOT specified tensile strength ratio (TSR) value of 85% except samples made with 15% rubber. The ITS and TSR values of the RAP content, rubber type, rubber content and rubber size for all six samples are compared in Figures 3 through 6; respectively.

Figure 3 shows that the ITS values of both the dry and wet samples increase as the percentage of RAP in the mixtures increases. The average values of the wet samples including 0% and 15% RAP are slightly lower than those of the dry samples; however, wet samples with the 25% and 30% RAP show a slightly increase over those of the dry samples. Furthermore, the ITS values indicate an apparent improvement from the 15% to 25% RAP under the same conditions. These findings suggest that the use of relatively higher RAP percentage with the cryogenic modified binder can increase the moisture resistance of these mixtures.

When using the same virgin binder and virgin aggregate as the control sample, the ITS values of the dry and the wet samples are 421 kPa (61 psi) and 496 kPa (72 psi), respectively; results are similar to those shown in Figures 3 and 4 for the 10% RAP, -40 mesh rubber modified binders. Using the same virgin asphalt binder mixed with aggregate source C, the values of ITS show an improvement. For example, the dry ITS value improves from 524 kPa (76 psi) to 627 kPa (91 psi) and the wet from 476 kPa (69 psi) to 565 kPa (82 psi) for the samples prepared with the 0% RAP and 10% -40 mesh (-0.425 mm) ambient rubber. However, the comparison of the ITS values of the 15% RAP shows no apparent difference between the two aggregates; the dry and wet samples of aggregate source L have a 689 kPa (100 psi) and 703 kPa (102 psi), respectively; while aggregate source C has a 614 kPa (89 psi) and 717 kPa (104 psi). The properties of the aggregate sources are shown in Table 5.

The results presented previously suggest that the aged binders play a key role in improving the ITS values in the HMA, which confirms the results obtained by McDaniel et al. (2002). A possible reason for this improvement might be the role that the aged binder plays in increasing the internal friction between the aggregate and the binder.

Figure 4 shows that the ITS values of the samples containing 0% and 30% RAP and made with modified binder (10% -40 mesh ambient rubber) increase from 524 kPa (76 psi) to 1000 kPa (145 psi) in the dry samples, and from 476 kPa (69 psi) to 910 kPa (132 psi) in the wet samples; respectively. A comparison of Figure 4 with Figure 3 shows that the influence of the rubber type on the ITS values for both dry and wet samples is similar.

Figure 5 shows the effect of the percentage of -40 mesh (-0.425 mm) ambient rubber on the ITS and TSR values in samples with 25% RAP. Although the effect is primarily binder dependent, the trend is very clear—as rubber content increases, the ITS value decreases Khedaywi et al. (1993) pointed out that rubberized asphalt concrete mixes have lower Marshall stability and higher flow values than the conventional mixtures. On the other hand, the RAP in the mixes can increase stability and decrease flow.

The effect of rubber sizes in the modified binder is shown in Figure 6. The results indicate that the OBC and ITS values for all three rubbers do not exhibit a marked change due to the difference in the surface area. Based on this limited data, the effect of the rubber size on ITS value of mixtures made with 10% ambient rubber and 25% RAP is negligible. Further research, however, is needed to verify this finding.

Rutting Analysis

Several loaded wheel testers have been developed and used in Europe and in the United States. These include 1) the Hamburg wheel tracking device, 2) the French rutting tester, 3) the Nottingham rutting tester, 4) the Georgia loaded wheel tester, and 5) the Asphalt Pavement Analyzer (Kandhal and Cooley 2002). In this study, only the Asphalt Pavement Analyzer (APA) was used for the rutting test of all mixtures.

Six dry cylindrical specimens, for each mix type, were compacted by a Superpave gyratory compactor under dry conditions. All testing with APA was carried out to 8,000 cycles to measure the rut depth of the HMA at specified temperature (Kandhal and Cooley 2002). The testing temperature was based on the virgin binder's "performance grade" used in this study. If the influence of modified asphalt binder had been taken into account, the specimens would have been tested under different temperatures. To be able to compare the potential rut depth under the same test conditions, it was necessary to conduct all tests at the same temperature based on the original asphalt binder PG grade. As a result, a test temperature of 64^{o}C (147^{o}F) was employed in this study.

The results of the rut depth tests are shown in Figures 7 through 10 for various HMA mixtures examined. These results show the effects of the percentage of RAP, the percentage of rubber, the rubber size, and the rubber type. Figure 7 shows the effect of rubber percentage on the rut depth of the HMA with 25% RAP and -40 mesh ambient rubber, indicating that the rut depth decreases as the percent of rubber increases. Thus, the permanent rutting resistance increases as the percent of rubber increases in the HMA. Comparing to indirect tensile strength of asphalt pavement, the rutting resistance is subjected to repetitive loading. It is hypothesized that the modified binder with the crumb rubber exhibits much more capability in absorbing the traffic loading than indirect tension test.

Figure 8 shows that as the percentage of RAP in the mixes increases, the rut depth of mixtures using source L substantially decreases with 10% ambient and cryogenic rubber. However, rut depth of mixtures made with ambient rubber is less than cryogenic in this study. Furthermore, for specimens made with aggregate source C, the rut depth of mixtures does not decrease much as percentage of RAP in the mixes increases. This could be because the rut depth of mixture with no RAP is very small for aggregate source C, which has better engineering properties (e.g., the smaller LA abrasion and absorption) than aggregate L as shown in Table 5. Although the stiffness of the mixture is increasing as the percentages of RAP increase, it is difficult to decrease the rut depth during 8000 cycles loading.

Figure 9 shows the effect of three rubber sizes on the rut depth, which suggests that there is an optimal size when the rut depth is at minimum. It should be noted that this result was based on limited test data and should be further examined. However, in a recent study by Nourelhuda et al. (2003) and Sebaaly et al. (2003), the effect of the size of the crumb rubber on the rutting resistance was found to be dependent on the asphalt binder type. Figure 10 shows that as the air voids decrease, the rut depth decreases for the samples made with 0% RAP and containing 10% -40 mesh cryogenic rubber.

CONCLUSIONS

The following conclusions are based on the experimental results presented regarding the HMA which included both RAP and RAC:

- Increasing the percentages of RAP in the mixtures containing crumb rubber leads to higher stiffness and ITS values, indicating higher stability; this increase is also very effective in improving rutting resistance over the conventional mixtures. It was observed, during the mixing process, that the aged binder in RAP containing crumb rubber had a good workability.
- The effect of the rubber content on the ITS is clearly distinguishable. Increasing the rubber content leads to a decrease in the ITS value and creep stiffness. However, adding crumb rubber into the HMA effectively increases the rutting resistance. Increasing the percentage of rubber considerably improves the ability of the mixtures to resist deformation as measured by the APA test. In general, the mixtures containing rubberized binder produced samples that yield lower rut depths than the mixes using the virgin binder.
- The results of the ITS tests suggest that the ambient rubber has produced results similar to those of the cryogenic rubber when the same percentage of the rubber content is used. However, the rut depth of the two types of rubber mixtures suggests that the ambient rubber has higher rutting resistance when mixed with 25% RAP.
- The results of the ITS and rutting tests of mixtures made with 10% ambient rubber and 25% RAP show that the effect of rubber size is rather small; The ITS values and the rut depths of these mixtures using various rubber sizes are similar.
- The results of the study show that as air voids in the modified mixtures decrease, the rut depth from the APA test decreases, exhibiting a similar trend as in the conventional asphalt mixtures.

ACKNOWLEDGEMENTS

The authors would like to thank Ms. Jennifer Aune for providing some of the data presented in this paper. The assistance of Dr. Junan Shen and Dr. Brad Putman are very much appreciated. The financial support from the South Carolina Department of Health and Environmental Control through the Asphalt Rubber Technology Services (ARTS) of Clemson University is also greatly appreciated.

References

Amirkhanian, S. N. (2003). “Establishment of an Asphalt-Rubber Technology Service (ARTS).” Proceedings of the Asphalt Rubber 2003 Conference, Brasilia, Brazil, 577-588

Anderson, R. M., Christensen, W. D., and Bonaquist, R. (2003), “Estimating the Rutting Potential of Asphalt Mixtures Using Superpave Gyratory Compaction Properties and Indirect Tensile Strength”, Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions, Vol. 72, 1-26

Antunes, M. L., Domingos, P., Eusébio, M., and Sá da Costa, M. (2003). “Studies Concerning the Use of Asphalt Rubber in Portugal.” Proceedings of the Asphalt Rubber 2003 Conference, Brasilia, Brazil, 195-210

Cano, J.O. and Charania E. (1989). “The Phoenix Experiences Using Asphalt-Rubber Proceedings.” National Seminar on Asphalt-Rubber, Kansas City Missouri

Chen, J. S., Lin, C. H., Stein, E., and Hothan, J. (2004). “Development of a Mechanistic-Empirical Model to Characterize Rutting in Flexible Pavements.” Journal of Material in Civil Engineering, V130, 519-525

Choubane, B., Sholar, G.A., Musselman, J.A., and Page, G. C. (1999). “A Ten-year Performance Evaluation of Asphalt-Rubber Surface Mixes.” Transportation Research Record CD, Washington, DC.

Christensen, W. D., Bonaquist, R., and Jack, D.P. (2000), “Evaluation of Triaxial Strength as a Simple Test for Asphalt Concrete Rut Resistance”, Final Report, Pennsylvania Department of Transportation.

Christensen, W. D., and Bonaquist, R. (2002), “Use of Strength Tests for Evaluating the Rut Resistance of Asphalt Concrete”, Asphalt Paving Technology, Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions, Vol. 71, 692-711.

Esch, D.C. (1982). “Construction and Benefits of Rubber Modified Asphalt Pavements.” Transportation Research Record No. 860, TRB, National Research Council, Washington, DC.

Federal Highway Administration (1997a). Superpave Mixture Expert Task Group, “Guidelines for the Design of Superpave Mixtures Containing Reclaimed Asphalt Pavement.” Washington, D.C.

Federal Highway Administration (1997b). “Pavement Recycling Guidelines for State and Local Governments.” Report No. FHWA-SA-98-042, Washington, D.C.

Federal Highway Administration (2002). “User Guidelines for Waste and Byproduct Materials in Pavement Construction.” Washington, D.C.

Hicks, R.G., Lundy, J.R., Leahy, R.B., Hanson, D., and Epps, J., (1995). “Crumb Rubber Modifier in Asphalt Pavement – Summary of Practice in Arizona, California and Florida.” Report Nr. FHWA-SA-95-056-Federal Highway Administration.

Holleran, G. and Van, K. J. (2000). “Asphalt Rubber Concrete Leads to Cost Effective Pavement Rehabilitation Reduced Thickness.” Synopses for 1st International Conference World of Pavement Sydney, Australia.

Kandhal, P. S. and Cooley, L. A. (2002). “Evaluation of Permanent Deformation of Asphalt Mixtures Using Loaded Wheel Tester.” Journal of the Association of Asphalt Paving Technologists, V71, 739-753

Khedaywi, T.S., Tamimi, A.R., Al-Masaeid, H.R., and Khamaiseh, K. (1993). “Laboratory Investigation of Properties of Asphalt Rubber Concrete Mixtures.” Transportation Research Record, TRR 1417, 93-98

Mathias Leite, L. F., Almeida da Silva, P., Edel, G., Goretti da Motta, L., and Herrmann do Nascimento, L. A. (2003). “Asphalt Rubber in Brazil: Pavement Performance and Laboratory Study.” Proceedings of the Asphalt Rubber 2003 Conference, Brasilia, Brazil, 229-245

McDaniel, R. S., Soleymani, H., and Shah, A., (2002). “Use of Reclaimed Asphalt Pavement (RAP) Under Superpave Specifications.” FHWA/IN/JTRP-2002/6

National Cooperative Highway Research Program (2001). “Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician’s Manual.” Transportation Research Board, NCHRP Report 452. Washington, D.C.

Nourelhuda, M., Mikhail, M. Y., and Mamlouk, M. S. (2003). “Rutting Prediction of Asphalt Concrete and Asphalt Rubber Mixture.” Proceedings of the Asphalt Rubber 2003 Conference, Brasilia, Brazil, 181-194.

Rubber Manufacturers Association (2003). “U. S. Scrap Tire Markets 2003 Edition”, Rubber Manufactures Association 1400K Street, NW, Washington, D.C.

Sebaaly, P. E., Bazi, G., Weitzel D., Coulson, M. A., and Bush D. (2003). “Long Term Performance of Crumb Rubber Mixtures in Nevada.” Proceedings of the Asphalt Rubber 2003 Conference, Brasilia, Brazil, 111-126

Thompson J. and Xiao F. P., The High Temperature Performance of CRM Binders. ARTS Quarterly, Volume 4, Issue 2, March 2004.

Way, G. B. (2003). “The Rubber Pavements Association, Technical Advisory Board Leading the Way in Asphalt Rubber Research.” Proceedings of the Asphalt Rubber 2003 Conference, Brasilia, Brazil, 17-33

Zaniewski J. P. and Srinivasan G. (2004). “Evaluation of Indirect Tensile Strength to Identify Asphalt Concrete Rutting Potential.” Asphalt Technology Program, Department of Civil and Environmental Engineering, West Virginia University, West Virginia, May, 2004

LIST OF TABLES

LIST OF FIGURES

TABLE 1. SCDOT 9.5 mm Superpave Volumetric Specifications

Superpave 9.5 mm Mix Specifications	
% Max. Density at N_{des}	96
% VMA	15.5 – 17.5
%Voids Filled	70 - 80
% Max. Density at N_i	< 89
% Max. Density at N_m	< 98
Dust to Asphalt Ratio	0.6-1.2

TABLE 2. The Component Properties of Two RAPs

Aggregate Source	RAP Size	9.5 mm 3/8"	4.75 mm #4	2.36 mm #8	0.60 mm #30	0.150 mm #100	0.075 mm #200	Asphalt Binder Percentage	Aged Binder Viscosity (c.P)	Aged Binder G*Sin(delta) (MPa)
L	*+4*	97	59	45	30	14	8	4.66	5980	9.5
	-4	100	100	88	57	24	14	6.96		
C	*+4*	84	43	33	21	9	5.4	4.46	2550	11
	-4	100	100	90	56	16	8	5.66		

TABLE 3. OBC, MSG and BSG Values of 10% -40 mesh Mixtures for (a) aggregate L and (b) aggregate C

		Types of Superpave Mixture							
		LM0		LM15		LM25		LM30	
Specification		AMB	CRY	AMB	CRY	AMB	CRY	AMB	CRY
% by weight of aggregate	**Stone 789**	59	59	52	53	56	56	53	53
	R. S.	22	22	12	12	8	8	8	8
	M. S.	18	18	19	19	10	10	8	8
	Lime	1	1	1	1	1	1	1	1
	-4RAP	0	0	9	9	15	15	18	18
	+4RAP	0	0	6	6	10	10	12	12
O.B.C		5.90%	6.08%	5.80%	5.90%	5.08%	5.18%	5.10%	5.30%
Dust to Asphalt Ratio		0.75	0.68	0.83	0.76	1.01	1.11	1.06	1.07
M.S.G		2.420	2.397	2.441	2.412	2.429	2.433	2.466	2.444
B.S.G		2.323	2.301	2.343	2.316	2.332	2.336	2.367	2.346

(a)

Specification		Types of Superpave Mixture		
		CM0	CM15	CM38
		AMB	AMB	AMB
% by weight of aggregate	**Stone 789**	50	49	32
	R. S.	18	15	5
	M. S.	31	20	25
	Lime	1	1	1
	-4RAP	0	9	13
	+4RAP	0	6	25
O.B.C		5.75%	5.53%	5.20%
Dust to Asphalt Ratio		0.88	0.95	0.87
M.S.G		2.400	2.414	2.341
B.S.G		2.303	2.317	2.438

(b)

Note:

- O. B. C.: Optimum Binder Content
- M. S. G.: Maximum Specific Gravity; B. S. G.: Bulk Specific Gravity
- LM, CM: Aggregate source L, C with 10% -40mesh modified binder
- 0, 15, 25, 30 represent percentage of RAP in the mixture
- AMB and CRY: ambient and cryogenic rubber
- R. S. and M. S.: Regular Screenings and Manufactured Screenings

TABLE 4. OBC, MSG and BSG Values of Mixtures Containing 25% RAP

	Rubber (-40 mesh, AMB) Content				**Rubber Size (mesh)**		
	% by weight of binder				*% by weight of binder (AMB)*		
Specification	0	5	10	15	-14	-30	-40
Optimum Binder Con.	4.70%	5.02%	5.08%	5.65%	5.23%	5.08%	5.08%
Dust to Asphalt Ratio	1.09	1.02	1.00	0.90	0.98	1.00	1.00
M.S.G	2.460	2.449	2.429	2.421	2.438	2.440	2.429
B.S.G	2.362	2.351	2.332	2.324	2.340	2.342	2.332

Note:

- O. B. C.: Optimum Binder Content
- M. S. G.: Maximum Specific Gravity
- B. S. G.: Bulk Specific Gravity
- AMB: ambient rubber

TABLE 5. Aggregate Properties

Aggregate Source	LA Abrasion Loss (%)	Absorption (%)	Bulk Specific Gravity		Sand Equivalent
			Dry	**SSD**	
L	51	0.5	2.65	2.67	65
C	31	0.3	2.61	2.62	96

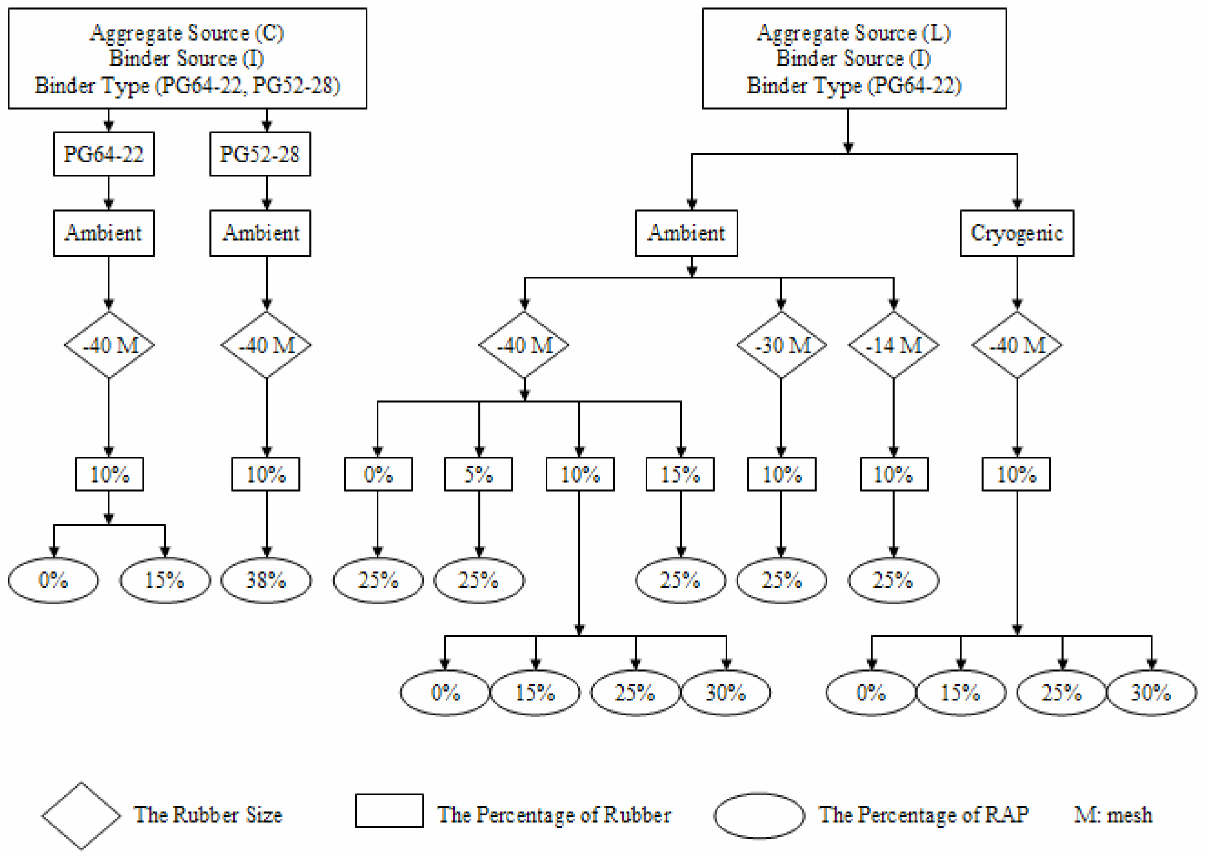

FIG. 1. Experimental Design Flowchart

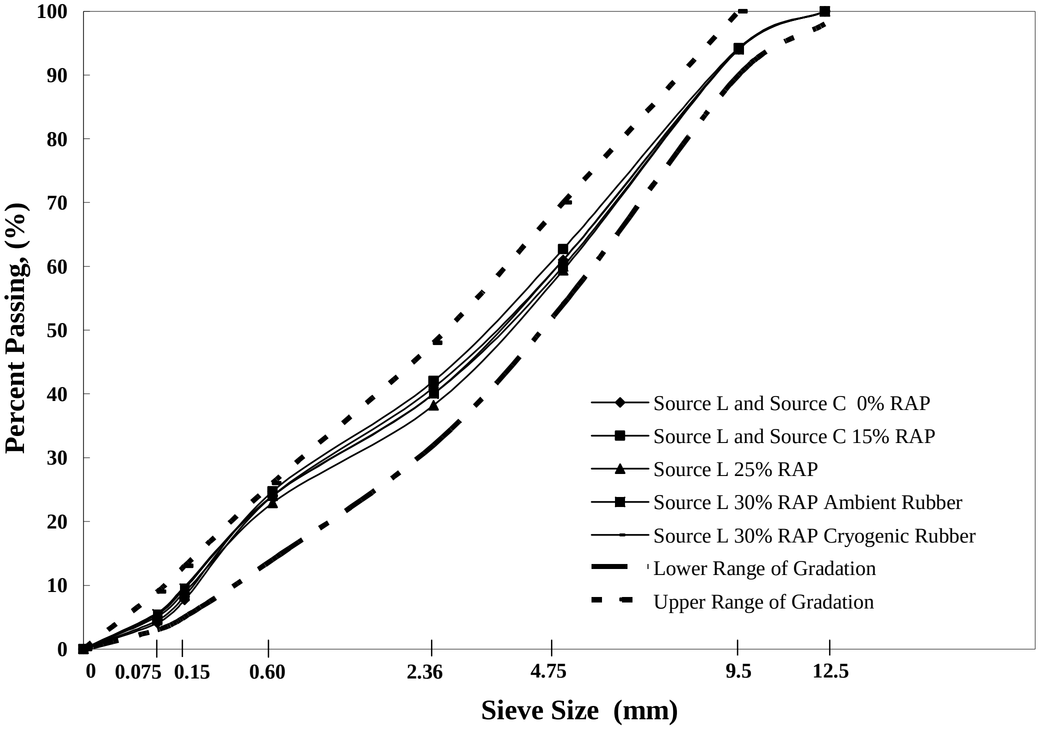

FIG. 2. 9.5-mm Mixture Gradations

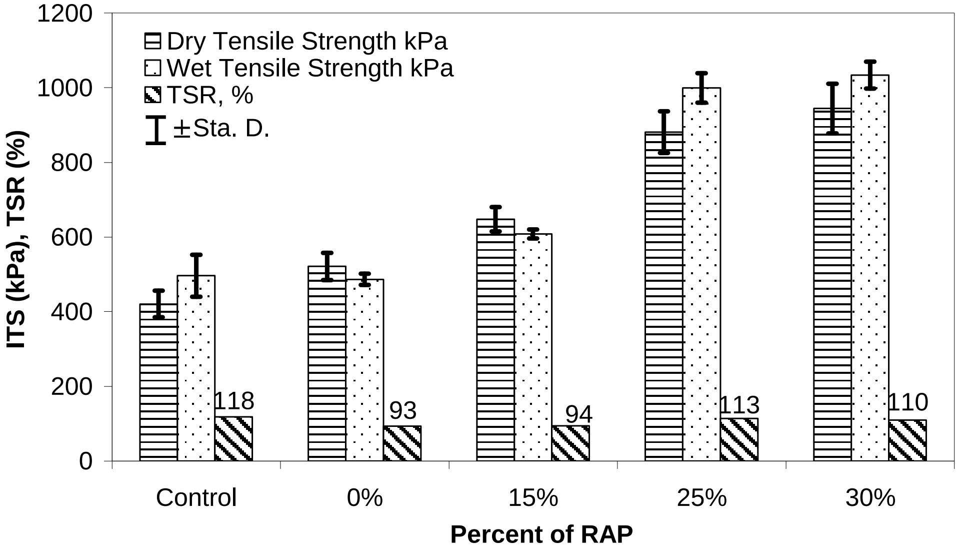

FIG. 3. ITS and TSR Values for Specimens made with 10% -40 Mesh Cryogenic Rubber Using Aggregate Source L

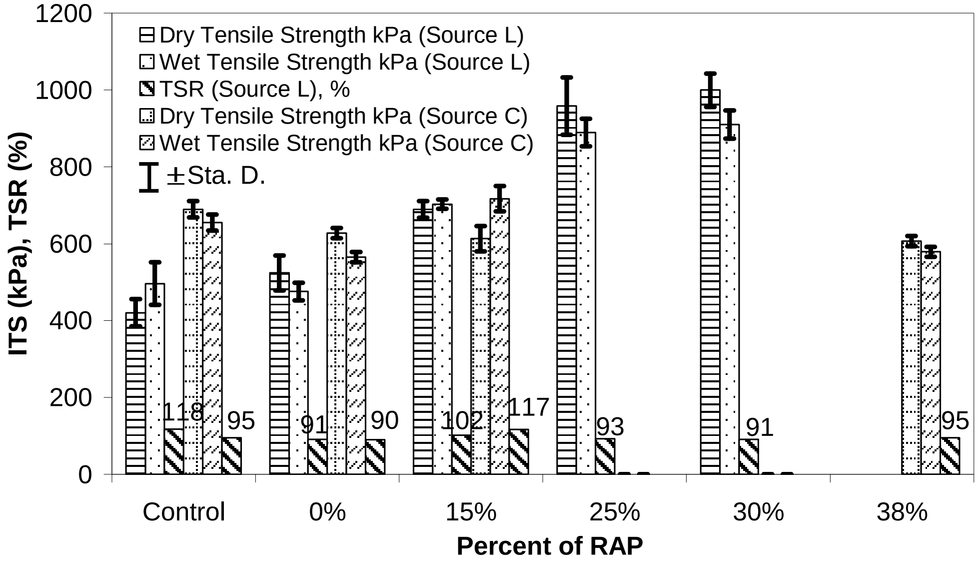

FIG. 4. ITS and TSR Values for Specimens Made with 10% -40 Mesh Ambient Rubber

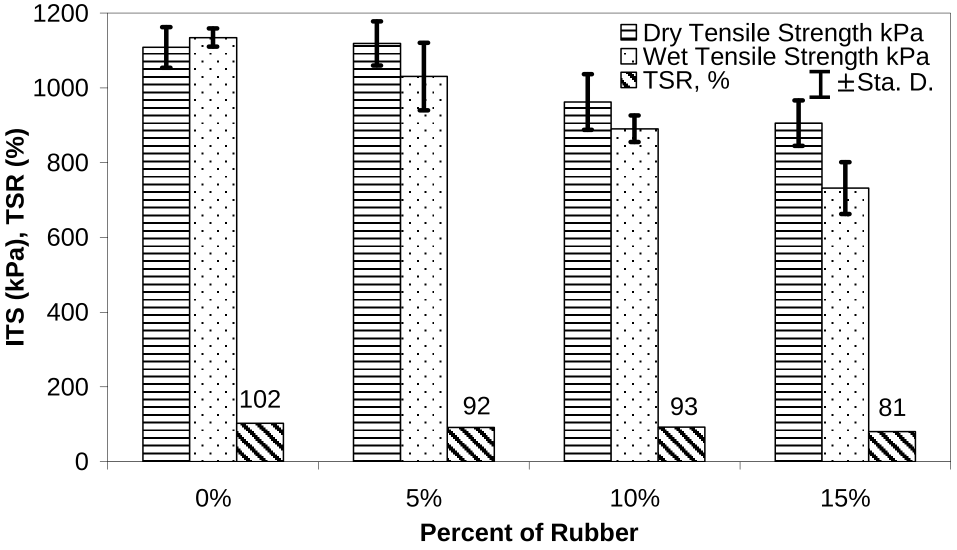

FIG. 5. ITS and TSR Values for Specimens Made with 25% RAP and -40 Mesh Ambient Rubber Using Aggregate Source L

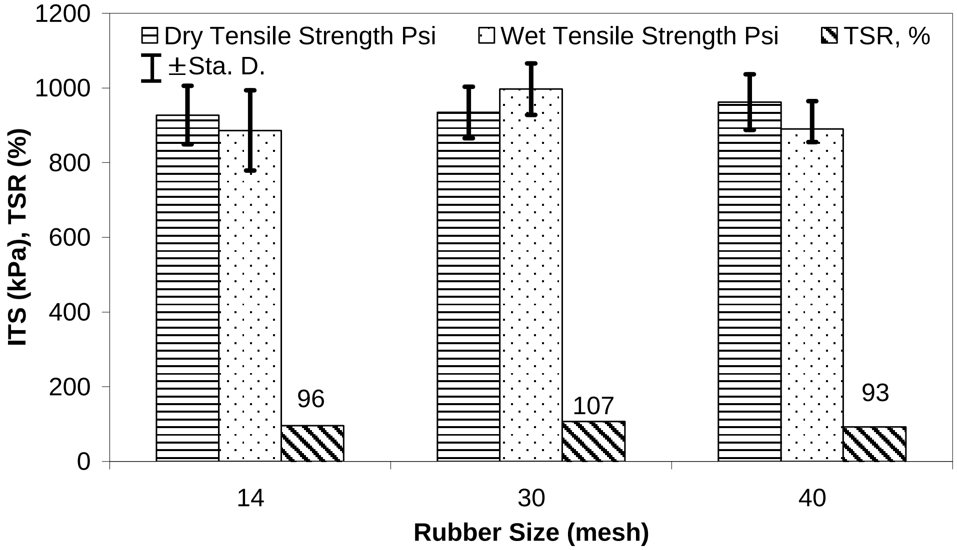

FIG. 6. ITS and TSR Values for Specimens Made with 25% RAP and 10% Ambient Rubber Using Aggregate Source L

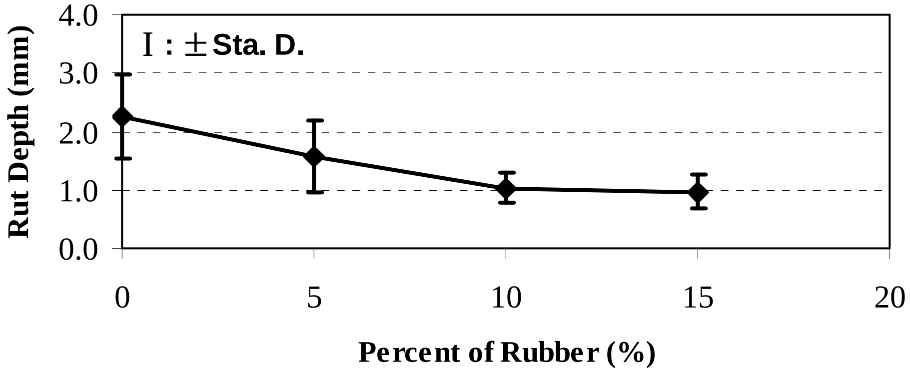

FIG. 7. Rut Depth of Mixtures Made with 25% RAP and -40 Mesh Ambient Rubber Using Aggregate Source L

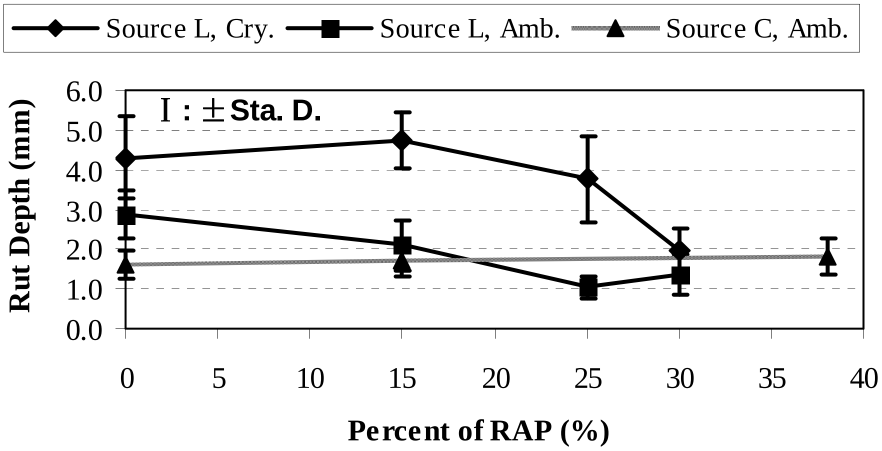

FIG. 8. Rut Depth of Mixtures Made with 10% -40 Mesh Rubber

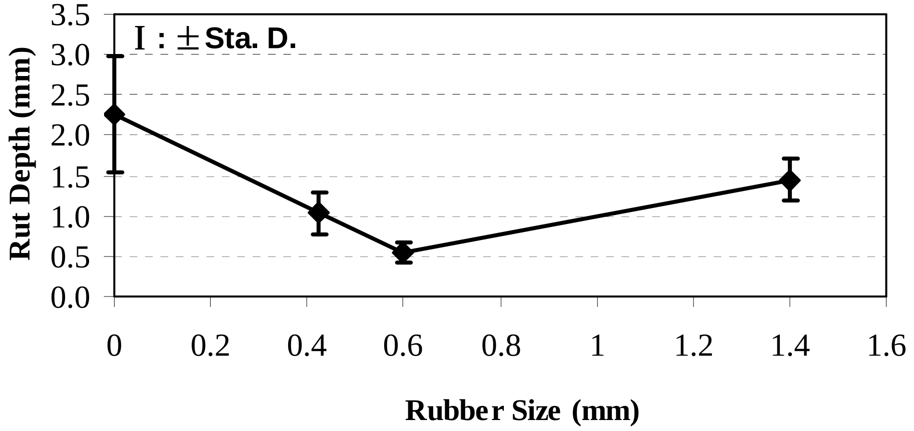

FIG. 9. **Rut Depth of Mixtures Made with 25% RAP and 10% Ambient Rubber Using Aggregate Source L**

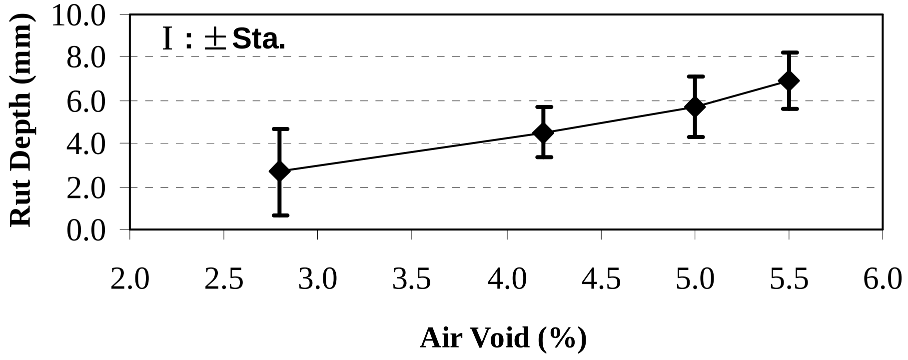

FIG. 10. **Rut Depth of Mixtures Made with 0% RAP and 10% -40 Mesh Cryogenic Rubber Using Aggregate Source L**