EVALUATION OF ENGINEERING BENEFITS OF RJSEAL

Report prepared for

Kalvani International Pte Ltd

by

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September 2006

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EXECUTIVE SUMMARY

RJSeal is a proprietary product marketed as a seal coat material for asphalt pavements. In accordance with the technical specifications of RJSeal, the product meets the specification requirements issued by FAA in its Engineering Brief No. 44 for coal-tar sealer/rejuvenator. The two main functions of a coal-tar sealer/rejuvenator are to (a) seal and protect the surface course of an asphalt pavement, and (b) rejuvenate the asphalt binder of the surface course of an asphalt pavement. The present study was commissioned by Kalvani International Pte Ltd to evaluate the engineering benefits of RJSeal by means of laboratory tests on laboratory fabricated asphalt specimens. The main aim of the laboratory experimental study was to identify the benefits of applying RJSeal to the specimens of standard LTA W3B mix by comparing the engineering performance of W3B specimens with and without RJSeal treatment under various simulated service conditions.

This report describes an experimental study to identify the benefits of the application of RJSeal coating on the surface of asphalt mixtures. The objectives of the experimental program were to evaluate the engineering benefits of RJSeal against the following four forms of damage: moisture damage, diesel fuel damage, gasoline fuel damage, and simulated weathering damage. The engineering benefits of RJSeal were evaluated by considering four treatment processes: immersion in water, immersion in gasoline, immersion in diesel, and laboratory weathering chamber treatment. The three immersion tests were each performed for 3 immersion periods: 1 hour, 4 hours, and 8 hours. The laboratory simulated weathering comprised 120 cycles of 2-hour wetting and 2-hour drying each. Control specimens (i.e. W3B specimens not coated with RJSeal) and W3B specimens coated with RJSeal were each subjected to the same type of treatment and their behaviors and performance after the treatment were evaluated and compared.

The test results of the experimental program have provided conclusive supporting evidence of the following two beneficial effects of RJSeal coating on the engineering performance of asphalt mixtures: (a) rejuvenating effect on the asphalt binder, and (b) protective effect on the asphalt mixture from damaging effect of moisture, gasoline, diesel and laboratory weathering.

The rejuvenating effect of applying the RJSeal coating on asphalt mixtures was quantified by examining the changes brought about by the coating in terms of the three engineering properties: Marshall stability, indirect tensile strength, and resilient modulus. The test results showed that all the three engineering properties reduced by varying degrees when RJSeal was applied onto W3B test specimens. Although the reductions in Marshall stability were not found to be statistically significant at 95% confidence level, the reductions in both the indirect tensile strength and resilient modulus were statistically significant at the same confidence level. The rejuvenating effect of RJSeal as manifested in the lower values of indirect tensile strength and resilient modulus is beneficial to old asphalt pavements with aged asphalt binders. The beneficial effect is expected to be improved ductility of old asphalt pavements, and hence longer fatigue life, brought about by having rejuvenated asphalt binders that are less brittle.

The protective effect of of applying the RJSeal coating on asphalt mixtures was examined by comparing the degrees of weakening of RJSeal-coated and uncoated W3B test specimens under the respective actions of water, gasoline, diesel, and laboratory simulated weathering. Again, the degrees of weakening of the test specimens were quantified in terms of the same three engineering properties: Marshall stability, indirect tensile strength, and resilient modulus. The test results clearly showed that, under the respective actions water immersion, gasoline, diesel immersion and laboratory weathering, RJSeal coated specimens resulted in lower losses of Marshall stability, indirect tensile strength or resilient modulus than the corresponding uncoated specimens. These findings offer conclusive evidence of the effectiveness of RJSeal as a protective coating against the damaging actions of following matters or environmental forces: water, gasoline, diesel and simulated weathering of combined actions of wetting-drying and heating cycles.

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1.0 INTRODUCTION

RJSeal is a proprietary product marketed commercially in the Asia Pacific region as a seal coat material for asphalt pavements. It was introduced in the 1990s in North America under the trade name of RejuvaSeal and has been adopted by airports and highway agencies in North America as a seal coat treatment to airport and road pavements. Since the early 2000s, it has also been used for the same purpose by a number of highway departments in several provinces in China.

In accordance with the technical specifications of RJSeal, the product meets the specification requirements issued by FAA in its Engineering Brief No. 44 for coal-tar sealer/rejuvenator to be used on a prior prepared bituminous pavement surface. The Engineering Brief was revised and re-issued as Engineering Brief 44A (EB44A) on 9 May 2006 [FAA 2006]. It defines a coal-tar sealer/rejuvenator as a bituminous material composed of coal-tar oils and coal-tar conforming to Grade RT-12 of ASTM Standard Specification D490 for Road Tar [ASTM 2005a]. The material properties that EB44A requires a coal-tar sealer/rejuvenator to meet are given in Appendix A.

The two main functions of a coal-tar sealer/rejuvenator are to (a) seal and protect the surface course of an asphalt pavement, and (b) rejuvenate the asphalt binder of the surface course of an asphalt pavement. A coal-tar sealer/rejuvenator satisfies the first function through acting as a seal coat which is fuel and water resistant. The second function is relevant for old asphalt pavement surfaces where the coal-tar sealer/rejuvenator, upon penetrating through the void spaces into the asphalt mixture, reconstitutes aged asphalt and restores its consistency and ductility. Both functions help to reduce the aging rate of asphalt binder, and lengthen the life of the asphalt pavement.

This present study was commissioned by Kalvani International Pte Ltd to evaluate the engineering benefits of RJSeal by means of laboratory tests on laboratory fabricated asphalt specimens. The main aim of the laboratory experimental study was to identify the benefits of applying RJSeal to the specimens of standard LTA W3B mix by comparing the engineering performance of W3B specimens with and without RJSeal treatment under various simulated service conditions. The aggregate grading and binder properties of the W3B mix are shown in **Table 1**.

2.0 OBJECTIVES OF STUDY

To achieve the main aim of the study to evaluate the engineering benefits, if any, of applying RJSeal to W3B specimens, the laboratory experimental program was planned to meet the following objectives:

(1) To evaluate the engineering benefit of RJSeal against moisture damage;

(2) To evaluate the engineering benefit of RJSeal against diesel fuel damage;

(3) To evaluate the engineering benefit of RJSeal against gasoline fuel damage;

(4) To evaluate the engineering benefit of RJSeal against simulated weathering damage;

Table 1 Aggregate Grading and Asphalt Binder Content of W3B Mix

(a) Aggregate Gradation

Sieve Size	Percent Passing
19 mm	100
13.2 mm	85-95
9.5 mm	--
6.3 mm	58-68
3.15 mm	40-50
2.36 mm	--
1.18 mm	21-31
600 μm	--
300 μm	11-17
212 μm	-
75 μm	4-8

(b) Bitumen Content: (Pen Grade 60/70) (5.0 ± 0.5)% Adopted 5.25 %

3.0 EVALUATION METHODOLOGY

The engineering benefits, if any, of the application of RJSeal to W3B specimens will be quantified by means of the physical engineering performance of the mixture. The standard W3B mix specimens will serve as the control reference for the evaluation of the performance of the W3B mix treated with RJSeal. Essentially, control specimens (i.e. W3B specimens not coated with RJSeal) and W3B specimens coated with RJSeal were subjected to the same type of treatment and their behaviors and performance after the treatment were evaluated and compared.

The following aspects of mixture performance will be evaluated:

(a) Effect on the Marshall stability which is the main strength criterion for conventional mix design control;

(b) Effect on the tensile strength which is related to the ability of mixes to resist repeated traffic loading;

(c) Effect on the resilient modulus which is a measure of elastic stiffness under repeated traffic loading,

The above performance tests were conducted on the uncoated control W3B specimens and the RJSeal coated specimens respectively after each of the following four treatment processes: immersion in gasoline, immersion in diesel, immersion in water, and laboratory weathering chamber treatment. The respective durations of the four treatments were as follows:

(1) Immersion in gasoline for the following durations: 1 hour, 4 hours, and 8 hours

(2) Immersion in diesel for the following durations: 1 hour, 4 hours, and 8 hours

(3) Immersion in water for the following durations: 1 hour, 4 hours, 8 hours.

(4) Weathering chamber treatment of 120 cycles of weathering comprising 2-hour wetting and 2-hour drying per cycle

4.0 EXPEIRMENTAL PROGRAM

4.1 Specimen Preparation

All test specimens were fabricated using W3B mix as specified by the Land Transport Authority (LTA) of Singapore. The aggregate grading limits and the required asphalt binder content of the specified mix are given in Table 1.

Of the four performance tests specified in Section 3.0, the Marshall stability test, the indirect tensile test, and the resilient modulus test were conducted using cylindrical specimens compacted in accordance with the standard procedure specified by the ASTM D1559 [ASTM 2005b].

Cylindrical test specimens were prepared in sets of 24. A set of 24 specimens was batched, mixed and compacted in one day. Of the 24 specimens in a batch, 12 were coated, and 12 were left uncoated. The application of RJSeal coating to 12 of 24 specimens in a given batch was performed 24 hours after the compaction of the specimens. Coating of RJSeal was applied using a normal paint brush at a rate of 4 kg per m^2 of surface area. Coated specimens were left intact for at least another 24 hours before any treatment or test was applied to them.

4.2 Test Program

4.2.1 <u>Test Set A – Water Immersion Treatment</u>

Table 2 shows the number of specimens employed in the water immersion treatment for different performance tests. This series of tests were conducted to evaluate the effects of immersing the uncoated control specimens and the RJSeal coated specimens in a water bath kept at 60°C for three different periods of time.

Table 3 shows the number of specimens tested under each performance test. The specimens with 0 hour exposure to water served as the reference base cases to calculate the effects in the respective performance tests. It is noted that since the resilient modulus test is a non-destructive test, the specimens could be subsequently used for either the Marshall stability or the indirect tensile test. In the present project, for the three specimens in a test group after having tested for resilient modulus, one was used for Marshall stability test, and two were used for indirect tensile test.

Table 2 Test Set A – Number of Specimens for Water Immersion Treatment

Specimen Type	Time Period of Immersion in Water Bath of 60°C			
	0 hr Immersion	1 hr Immersion	4 hr Immersion	8 hr Immersion
Uncoated	3	3	3	3
Coated	3	3	3	3
Total	6	6	6	6

Table 3 Test Set A – Number of Specimens Evaluated under each Performance Test

Test	Time Period of Immersion in Water Bath of 60^{o}C			
	0 hr Immersion	1 hr Immersion	4 hr Immersion	8 hr Immersion
Marshall Test	Uncoated 3 + 1 Coated 3 + 1	Uncoated 3 + 1 Coated 3 + 1	Uncoated 3 + 1 Coated 3 + 1	Uncoated 3 + 1 Coated 3 + 1
Indirect Tensile Test	Uncoated 3 + 2 Coated 3 + 2	Uncoated 3 + 2 Coated 3 + 2	Uncoated 3 + 2 Coated 3 + 2	Uncoated 3 + 2 Coated 3 + 2
Resilient Modulus Test	Uncoated 3 Coated 3	Uncoated 3 Coated 3	Uncoated 3 Coated 3	Uncoated 3 Coated 3

4.2.2 <u>Test Set B – Gasoline Immersion Treatment</u>

Table 4 shows the number of specimens employed in the gasoline immersion treatment for different performance tests. This series of tests were conducted to evaluate the effects of immersing the uncoated control specimens and the RJSeal coated specimens in a gasoline bath kept at room temperature (25^{o}C) for three different periods of time.

Table 5 shows the number of specimens tested under each performance test. The specimens with 0 hour exposure to water served as the reference base cases to calculate the effects in the respective performance tests. It is noted that since the resilient modulus test is a non-destructive test, the specimens could be subsequently used for either the Marshall stability or the indirect tensile test. In the present project, for the three specimens in a test group after having tested for resilient modulus, one was used for Marshall stability test, and two were used for indirect tensile test.

Table 4 Test Set B – Number of Specimens for Gasoline Immersion Treatment

Specimen Type	Time Period of Immersion in Gasoline Bath at 25^{o}C			
	0 hr Immersion	1 hr Immersion	4 hr Immersion	8 hr Immersion
Uncoated	3	3	3	3
Coated	3	3	3	3
Total	6	6	6	6

Table 5 Test Set B – Number of Specimens Evaluated under each Performance Test

Test	Time Period of Gasoline Immersion in Gasoline Bath at 25^{o}C			
	0 hr Immersion	1 hr Immersion	4 hr Immersion	8 hr Immersion
Marshall Test	Uncoated 3 + 1 Coated 3 + 1	Uncoated 3 + 1 Coated 3 + 1	Uncoated 3 + 1 Coated 3 + 1	Uncoated 3 + 1 Coated 3 + 1
Indirect Tensile Test	Uncoated 3 + 2 Coated 3 + 2	Uncoated 3 + 2 Coated 3 + 2	Uncoated 3 + 2 Coated 3 + 2	Uncoated 3 + 2 Coated 3 + 2
Resilient Modulus Test	Uncoated 3 Coated 3	Uncoated 3 Coated 3	Uncoated 3 Coated 3	Uncoated 3 Coated 3

4.2.3 Test Set C – Diesel Immersion Treatment

Table 6 shows the number of specimens employed in the diesel immersion treatment for different performance tests. This series of tests were conducted to evaluate the effects of immersing the uncoated control specimens and the RJSeal coated specimens in a diesel bath kept at room temperature (25^{o}C) for three different periods of time.

Table 7 shows the number of specimens tested under each performance test. The specimens with 0 hour exposure to water served as the reference base cases to calculate the effects in the respective performance tests. It is noted that since the resilient modulus test is a non-destructive test, the specimens could be subsequently used for either the Marshall stability or the indirect tensile test. In the present project, for the three specimens in a test group after having tested for resilient modulus, one was used for Marshall stability test, and two were used for indirect tensile test.

Table 6 Test Set C – Number of Specimens for Diesel Immersion Treatment

Specimen Type	Time Period of Immersion in Diesel Bath at 25^{o}C			
	0 hr Immersion	1 hr Immersion	4 hr Immersion	8 hr Immersion
Uncoated	3	3	3	3
Coated	3	3	3	3
Total	6	6	6	6

Table 7 Test Set C – Number of Specimens Evaluated under each Performance Test

Test	Time Period of Gasoline Immersion in Diesel Bath at 25^{o}C			
	0 hr Immersion	1 hr Immersion	4 hr Immersion	8 hr Immersion
Marshall Test	Uncoated 3 + 1 Coated 3 + 1	Uncoated 3 + 1 Coated 3 + 1	Uncoated 3 + 1 Coated 3 + 1	Uncoated 3 + 1 Coated 3 + 1
Indirect Tensile Test	Uncoated 3 + 2 Coated 3 + 2	Uncoated 3 + 2 Coated 3 + 2	Uncoated 3 + 2 Coated 3 + 2	Uncoated 3 + 2 Coated 3 + 2
Resilient Modulus Test	Uncoated 3 Coated 3	Uncoated 3 Coated 3	Uncoated 3 Coated 3	Uncoated 3 Coated 3

4.2.4 Test Set D – Laboratory Wetting-Drying Weathering

The laboratory weathering chamber has the capacity to apply wetting-and-drying cycles to 36 cylindrical specimens in a batch. In this study, the number of specimens receiving the weathering treatment was set as 36 so that all specimens would be receiving the same treatment in one single operation. This is shown in Table 8.

Table 9 shows the number of weathering-treated specimens tested under each performance test. The specimens without receiving weathering treatment served as the reference base cases to calculate the effects in the respective performance tests. It is noted that since the resilient modulus test is a non-destructive test, the specimens could be subsequently used for either the Marshall stability or the indirect tensile test. In the present project, of the 18 coated specimens that received weathering treatment, 9 were tested for resilient modulus, 4 were tested for Marshall stability, and the remaining 5 were tested for indirect tensile strength. After tested for resilient modulus, 5 of the 9 specimens were next tested for Marshall stability, and the next 4 tested for resilient modulus. Overall, there would be 9 specimens tested for each of the three performance tests. The same test arrangement was also made for the testing of the other three groups of specimens, namely (i) 18 non-weathered coated specimens, (ii) 18 weathered uncoated specimens, and (iii) 18 non-weathered uncoated specimens. This is summarized in Table 9.

Table 8 Test Set D – Number of Specimens for Weathering Treatment

Specimen Type	Treatment in Weathering Chamber at 25°C	
	No	Yes
Uncoated	18	18
Coated	18	18
Total	36	36

Table 9 Test Set D – Number of Specimens Evaluated under each Performance Test

Test	With Weathering		Without Weathering	
Marshall Test	Uncoated	4 + 5	Uncoated	4 + 5
	Coated	4 + 5	Coated	4 + 5
Indirect Tensile Test	Uncoated	5 + 4	Uncoated	5 + 4
	Coated	5 + 4	Coated	5 + 4
Resilient Modulus Test	Uncoated	9	Uncoated	9
	Coated	9	Coated	9

4.3 Test Procedures

The weathering treatment was conducted in a special-purpose weathering chamber built to provide a moisture treatment that combined wetting and drying of test specimens with thermal heating cycles [Fwa and Ang 1993]. The weathering chamber was a concrete tank with an enclosed space that measured 915 mm in height and 940 mm by 1,420 mm in plane cross section. Wetting of test specimens was achieved by spraying tap water at about 28°C through eight equally spaced shower heads that were fitted on the interior of the tank. The number of shower heads was more than sufficient to keep test specimens wet throughout the wetting phase. The thermal cycle was kept in phase with the wetting-drying cycle by means of a single timing device that activated the heater control the moment spraying of water was cut off. Heating was provided by four 500-W ceramic heaters at the underside of the ceiling of the tank. The heaters were positioned such that a near uniform temperature distribution was achieved at the specimen platform level near the floor of the chamber. A 4-hour treatment cycle (i.e. 2 hours of wetting followed by 2 hours of drying) was adopted in this study. During each cycle, the specimen surface temperature varied from 35°C to 62°C.

The Marshall stability test was performed in accordance with ASTM standard D1559 [ASTM 2005b], while the indirect tensile test and the resilient modulus test were performed based on the procedure specified in ASTM standard D4123 [ASTM 2005c].

5.0 RESULTS OF TESTS

5.1 Results of Test Set A – Effect of Water Immersion

The test results of Test Set A are summarized in Tables B1, B2 and B3 of Appendix B, and plotted in Figures 1 to 6.

Effect on Marshall Stability

From the results in Table B1 and Figures 1 and 2, the following observations can be made:

- Prior to water immersion (i.e. the case of 0 hour of water immersion), the RJSeal coated specimens suffered some loss in Marshall stability as compared with the uncoated specimens. This is believed to be caused by softening of the asphalt binder by the application of RJSeal.
- Water immersion caused some losses in the Marshall stability values of both the uncoated control specimens and the RJSeal coated specimens.
- For both the coated and uncoated specimens, the longer the period of water immersion, the higher were the losses in their Marshall stability values.
- In terms of percent losses in Marshall stability after water immersion, although the effects after 1 hour of immersion were not obvious, the uncoated specimens suffered a higher loss after longer hours of immersion (16.9 % loss after 4 hours and 25.3% loss after 8 hours) as compared with the RJSeal coated specimens (7.3% loss after 4 hours and 16.5% loss after 8 hours). This suggests that RJSeal coating had the effect of **reducing infiltration of water** and its weakening damage to the asphalt mixture.

Effect on Indirect Tensile Strength

From the results in Table B2 and Figures 3 and 4, the following observations can be made:

- Prior to water immersion (i.e. the case of 0 hour of water immersion), the RJSeal coated specimens suffered some loss in the indirect tensile strength as compared with the uncoated specimens. This is believed to be caused by softening of the asphalt binder by the application of RJSeal.
- Water immersion caused some losses in the indirect tensile strength of both the uncoated control specimens and the RJSeal coated specimens.
- In general, for both the coated and uncoated specimens, the results suggest that the longer the period of water immersion, the higher were the losses in their indirect tensile strengths.
- In terms of percent losses in indirect tensile strength after 8 hours of immersion, the uncoated specimens suffered a higher loss (24.0% after 1 hour, 21.1 % loss after 4 hours and 41.1% loss after 8 hours) as compared with the RJSeal coated specimens (0% after 1 hour, 0 % loss after 4 hours and 26.3% loss after 8 hours). This suggests that the RJSeal coating had the effect of **reducing infiltration of water** and its weakening damage to the asphalt mixture.

Effect on Resilient Modulus

From the results in Table B3 and Figures 5 and 6, the following observations can be made:

- Prior to water immersion (i.e. the case of 0 hour of water immersion), the RJSeal coated specimens suffered some loss in the resilient modulus as compared with the uncoated specimens. This is believed to be caused by softening the asphalt binder by the application of RJSeal.

- Water immersion caused some losses in the resilient modulus of both the uncoated control specimens and the RJSeal coated specimens.
- In general, for both the coated and uncoated specimens, the results suggest that the longer the period of water immersion, the higher were the losses in their resilient modulus values.
- In terms of percent losses in resilient modulus after 8 hours of immersion, the uncoated specimens suffered a higher loss (35.5% after 1 hour, 35.8% loss after 4 hours and 37.5% loss after 8 hours) as compared with the RJSeal coated specimens (25.5% loss after 1 hour, 28.9% loss after 4 hours and 31.3% loss after 8 hours). This suggests that the RJSeal coating had the effect of **reducing infiltration of water** and its weakening damage to the asphalt mixture.

5.2 Results of Test Set B – Effect of Gasoline Immersion

The test results of Test Set B are summarized in Tables C1, C2 and C3 of Appendix C, and plotted in Figures 7 to 12.

Effect on Marshall Stability

From the results in Table C1 and Figures 7 and 8, the following observations can be made:

- Prior to gasoline immersion (i.e. the case of 0 hour of gasoline immersion), the RJSeal coated specimens suffered some loss in Marshall stability as compared with the uncoated specimens. This is believed to be caused by softening of the asphalt binder by the application of RJSeal.
- Gasoline immersion caused losses in the Marshall stability values of both the uncoated control specimens and the RJSeal coated specimens.
- For both the coated and uncoated specimens, the longer the period of gasoline immersion, the higher were the losses in their Marshall stability values.
- In terms of percent losses in Marshall stability after the gasoline immersion, the uncoated specimens suffered a higher loss (25.3% after 1 hour, 40.3% loss after 4 hours and 51.3% loss after 8 hours) as compared with the RJSeal coated specimens (15.6% loss after 1 hour, 20.1% loss after 4 hours and 24.2% loss after 8 hours). This suggests that the RJSeal coating could **significantly reduce the damaging effect of gasoline** on the asphalt mixture.

Effect on Indirect Tensile Strength

From the results in Table C2 and Figures 9 and 10, the following observations can be made:

- Prior to gasoline immersion (i.e. the case of 0 hour of gasoline immersion), the RJSeal coated specimens suffered some loss in the indirect tensile strength as compared with the uncoated specimens. This is believed to be caused by softening of the asphalt binder by the application of RJSeal.
- Gasoline immersion caused some losses in the indirect tensile strength of both the uncoated control specimens and the RJSeal coated specimens.
- In general, for both the coated and uncoated specimens, the results suggest that the longer the period of gasoline immersion, the higher were the losses in their indirect tensile strengths.
- In terms of percent losses in indirect tensile strength after the gasoline immersion, the uncoated specimens suffered a higher loss (11.6% after 1 hour, 14.7% loss after 4 hours and 26.3% loss after 8 hours) as compared with the RJSeal coated specimens (0% loss

after 1 hour, and 1.1% loss after 4 hours and 13.0% after 8 hours). This suggests that the RJSeal coating could **significantly reduce the damaging effect of gasoline** on the asphalt mixture.

Effect on Resilient Modulus

From the results in Table C3 and Figures 11 and 12, the following observations can be made:

- Prior to gasoline immersion (i.e. the case of 0 hour of gasoline immersion), the RJSeal coated specimens suffered some loss in resilient modulus as compared with the uncoated specimens. This is believed to be caused by softening of the asphalt binder by the application of RJSeal.
- Gasoline immersion caused some losses in the resilient modulus of both the uncoated control specimens and the RJSeal coated specimens.
- In general, for both the coated and uncoated specimens, the results suggest that the longer the period of gasoline immersion, the higher were the losses in their resilient modulus values.
- In terms of percent losses in resilient modulus after the gasoline immersion, the uncoated specimens suffered a higher loss (7.8% after 1 hour, 45.3% loss after 4 hours and 48.3% loss after 8 hours) as compared with the RJSeal coated specimens (0.9% loss after 1 hour, 15.8% loss after 4 hours and 21.2% loss after 8 hours). This suggests that the RJSeal coating could **significantly reduce the damaging effect of gasoline** on the asphalt mixture.

5.3 Results of Test Set C – Effect of Diesel Immersion

The test results of Test Set C are summarized in Tables D1, D2 and D3 of Appendix D, and plotted in Figures 13 to 18.

Effect on Marshall Stability

From the results in Table D1 and Figures 13 and 14, the following observations can be made:

- Prior to diesel immersion (i.e. the case of 0 hour of diesel immersion), the RJSeal coated specimens suffered some loss in Marshall stability as compared with the uncoated specimens. This is believed to be caused by softening of the asphalt binder by the application of RJSeal.
- Diesel immersion caused losses in the Marshall stability values of both the uncoated control specimens and the RJSeal coated specimens.
- For both the coated and uncoated specimens, the longer the period of diesel immersion, the higher were the losses in their Marshall stability values.
- In terms of percent losses in Marshall stability after the diesel immersion, the uncoated specimens suffered a higher loss (5.7% after 1 hour, 5.1% loss after 4 hours and 11.1% loss after 8 hours) as compared with the RJSeal coated specimens (0.3% loss after 1 hour, 0.8% loss after 4 hours and 3.2% loss after 8 hours). This suggests that the RJSeal coating could **significantly reduce the damaging effect of diesel** on the asphalt mixture.

Effect on Indirect Tensile Strength

From the results in Table D2 and Figures 15 and 16, the following observations can be made:

- Prior to diesel immersion (i.e. the case of 0 hour of diesel immersion), the RJSeal coated specimens suffered some loss in the indirect tensile strength as compared with the uncoated specimens. This is believed to be caused by softening of the asphalt binder by the application of RJSeal.
- Diesel immersion caused some losses in the indirect tensile strength of both the uncoated control specimens and the RJSeal coated specimens.
- In general, for both the coated and uncoated specimens, the results suggest that the longer the period of diesel immersion, the higher were the losses in their indirect tensile strengths.
- In terms of percent losses in indirect tensile strength after the diesel immersion, the uncoated specimens suffered a higher loss (14.0% after 1 hour, 19.6% loss after 4 hours and 24.3% loss after 8 hours) as compared with the RJSeal coated specimens (12.7% loss after 1 hour, 19.6% loss after 4 hours and 21.6% loss after 8 hours). This suggests that the RJSeal coating could **reduce the damaging effect of diesel** on the asphalt mixture.

Effect on Resilient Modulus

From the results in Table D3 and Figures 17 and 18, the following observations can be made:

- Prior to diesel immersion (i.e. the case of 0 hour of diesel immersion), the RJSeal coated specimens suffered a loss in resilient modulus as compared with the uncoated specimens. This is believed to be caused by softening of the asphalt binder by the application of RJSeal.
- Diesel immersion caused some losses in the resilient modulus of both the uncoated control specimens and the RJSeal coated specimens.
- In general, for both the coated and uncoated specimens, the results suggest that the longer the period of diesel immersion, the higher were the losses in their resilient modulus values.
- In terms of percent losses in resilient modulus after the diesel immersion, the uncoated specimens suffered a higher loss (10.2% after 1 hour, 17.0% loss after 4 hours and 17.9% loss after 8 hours) as compared with the RJSeal coated specimens (5.7% loss after 1 hour, 4.9% loss after 4 hours and 5.2% loss after 8 hours). This suggests that the RJSeal coating could **significantly reduce the damaging effect of diesel** on the asphalt mixture.

5.4 Results of Test Set D – Effect of Laboratory Wetting-Drying Weathering

The test results of Test Set D are summarized in Tables E1, E2 and E3 of Appendix E, and plotted in Figures 19 to 24.

Effect on Marshall Stability

From the results in Table E1 and Figures 19 and 20, the following observations can be made:

- Prior to the weathering treatment, coating of the specimens with RJSeal resulted in some loss of Marshall stability as compared with the uncoated specimens. This is believed to be caused by softening of the asphalt binder by the application of RJSeal.
- Wetting-and-drying weathering caused losses in the Marshall stability values of both the uncoated control specimens and the RJSeal coated specimens.
- In terms of percent losses in Marshall stability after the wetting-and-drying weathering, the RJSeal coated specimens suffered marginally higher loss (23.3% loss) than the uncoated specimens (18.2%). These results did not show any beneficial effect of RJSeal coating against wetting-and-drying weathering on the asphalt mixture based on Marshall stability.

Effect on Indirect Tensile Strength

From the results in Table E2 and Figures 21 and 22, the following observations can be made:

- Prior to the weathering treatment, coating of the specimens with RJSeal resulted in some loss of indirect tensile strength as compared with the uncoated specimens. This is believed to be caused by softening of the asphalt binder by the application of RJSeal.
- Wetting-and-drying weathering caused losses in the indirect tensile strength values of both the uncoated control specimens and the RJSeal coated specimens.
- In terms of percent losses in indirect tensile strength after the wetting-and-drying weathering, the uncoated specimens suffered a significantly higher loss (71.0% loss) than the RJSeal coated specimens (65.0% loss). This suggests that the RJSeal coating could **reduce the damaging effect of wetting-and-drying weathering** on the asphalt mixture.

Effect on Resilient Modulus

From the results in Table E3 and Figures 23 and 24, the following observations can be made:

- Prior to the weathering treatment, coating of the specimens with RJSeal resulted in some loss of resilient modulus as compared with the uncoated specimens. This is believed to be caused by softening of the asphalt binder by the application of RJSeal.
- Wetting-and-drying weathering caused losses in the indirect tensile strength values of both the uncoated control specimens and the RJSeal coated specimens.
- In terms of percent losses in resilient modulus after the wetting-and-drying weathering, the coated specimens suffered a significantly higher loss (75.0% loss) as compared with the RJSeal coated specimens (64.5% loss). This suggests that the RJSeal coating could **reduce the damaging effect of wetting-and-drying weathering** on the asphalt mixture.

5.5 Rejuvenating Effect of RJSeal Coating

The rejuvenating effect of applying the RJSeal coating on asphalt mixtures can be evaluated by examining the changes brought about by the coating in terms of the three engineering properties: Marshall stability, indirect tensile strength, and resilient modulus. Table 10 summarizes the corresponding laboratory test data obtained from Test Sets A, B, C and E.

The rejuvenating effect of RJSeal coating can be assessed statistically using the Analysis of Variance (ANOVA). The results of ANOVA are found in Appendix F. Table 12 summarizes the conclusions of the hypothesis testing. It is found in the preceding section that all three test methods (i.e. Marshall stability test, indirect tensile test, and resilient modulus test) had shown some loss in the respective engineer properties after the RJSeal coating was applied, suggesting a **rejuvenating effect** brought about by the application of RJSeal. However, the results in Table 11 indicate that the effect as measured by Marshall stability was not statistically significant at 95% confidence level. On the other hand, the rejuvenating effect of RJSeal was found to be statistically significant at 95% confidence level when measured in either indirect tensile strength or resilient modulus.

The findings of the ANOVA tests indicate that the indirect tensile test and the resilient modulus test were more sensitive than the Marshall test in detecting changes in the binder properties caused by the application of RJSeal. The likely reason is the differences in the mode of testing. The Marshall stability test, though not a test that measures a particular engineering property of the test specimen, is compressive in nature in its mode of loading. On the hand, the indirect tensile test is an accepted form of test to measure the tensile strength of the test specimen, and the resilient modulus test is an accepted form of test for the elastic property of the test specimen under a repeated loading. Marshall stability cannot be used to study the expected performance of an asphalt mixture under traffic loading [Low et al. 1993, Fwa et al. 1998], while the indirect tensile strength and resilient modulus are appropriate engineering properties that can be used to analyze the fatigue behavior of asphalt pavements under the action of repeated traffic loading.

The rejuvenating effect of RJSeal as manifested in the lower values of indirect tensile strength and resilient modulus is beneficial to old asphalt pavements with aged asphalt binders. **The beneficial effect is expected to be improved ductility of old asphalt pavements, and hence longer fatigue life, brought about by having rejuvenated asphalt binders that are less brittle.**

Table 10 Revejunating Effect of RJSeal Coating

Test Set	Marshall Stability (kN)		Indirect Tensile Strength (MPa)		Resilient Modulus (MPa)	
	Uncoated	Coated	Uncoated	Coated	Uncoated	Coated
(Test Set A) Water Immersion	11.98 (σ = 0.63) (n = 4)	11.37 (σ = 0.99) (n = 4)	0.95 (σ = 0.08) (n = 5)	0.80 (σ = 0.06) (n = 5)	3908.0 (σ = 434.0) (n = 3)	3152.8 (σ = 488.9) (n = 3)
(Test Set B) Gasoline Immersion	12.69 (σ = 0.69) (n = 4)	12.23 (σ = 1.61) (n = 4)	1.07 (σ = 0.07) (n = 5)	1.02 (σ = 0.06) (n = 5)	3424.9 (σ = 158.5) (n = 3)	3067.0 (σ = 193.9) (n = 3)
(Test Set C) Diesel Immersion	13.79 (σ = 1.15) (n = 4)	13.25 (σ = 1.38) (n = 4)	0.95 (σ = 0.06) (n = 5)	0.92 (σ = 0.05) (n = 5)	3177.5 (σ = 616.3) (n = 3)	3031.8 (σ = 94.3) (n = 3)
(Test Set D) Laboratory Weathering	11.57 (σ = 0.95) (n = 9)	10.56 (σ = 0.46) (n = 9)	1.17 (σ = 0.07) (n = 9)	1.07 (σ = 0.10) (n = 9)	2919.1 (σ = 475.8) (n = 9)	2909.1 (σ = 474.4) (n = 9)

Table 11 Rejuvenating Effects of RJSeal Coating

Test Parameter	Marshall Stability	Indirect Tensile Strength	Resilient modulus
Conclusion at 95% Level of Significance	Not significant	Significant	Significant

5.6 Protective Effect of RJSeal Coating

The experimental test program conducted in this study also provides affirmative evidence of another beneficial effect of RJSeal, that is its role as a **protective surface coating against harmful spillage and damaging environmental forces**. Table 12 summarizes the results of the tests that were designed to evaluate the effectiveness of RJSeal coating in preventing the weakening of test specimens under the respective actions of water, gasoline, diesel, and laboratory simulated weathering.

As can be seen from Table 12, with the exception of the case of 1 hour water immersion which yielded higher Marshall stability loss of RJSeal coated specimens, in all the remaining cases the RJSeal coated specimens produced **lower losses of Marshall stability, indirect tensile**

strength or resilient modulus than the corresponding uncoated specimens. These results offer conclusive evidence of the effectiveness of RJSeal as a protective coating against the damaging actions of following matters or environmental forces: water, gasoline, diesel and simulated weathering of combined actions of wetting-drying and heating cycles.

Table 12 Effectiveness of RJSeal as Protective Coating

Treatment		Weakening Effect measured as % Loss of Marshall Stability	Weakening Effect measured as % Loss of Indirect Tensile Strength	Weakening Effect measured as % Loss of Resilient Modulus	Effectiveness as Protective Layer measured as % Loss in Value of Mixture Property
Water Immersion	1 hr	5.9% (0.9%)*	0% (24.0%)	25.5% (35.5%)	From 5.9% more loss to 24.0% less loss**
	4 hr	16.9% (7.3%)	0% (21.1%)	28.9% (35.8%)	6.9 to 21.1% less loss
	8 hr	25.3% (16.5%)	26.3% (41.1%)	31.3% (37.5%)	6.2 to 24.8% less loss
Gasoline Immersion	1 hr	15.6% (25.3%)	0% (11.6%)	0.9% (7.8%)	6.9 to 11.6% less loss
	4 hr	20.1% (40.3%)	1.1% (14.7%)	15.8% (45.3%)	13.6 to 29.5% less loss
	8 hr	24.2% (51.3%)	13.0% (26.3%)	21.2% (48.3%)	13.3 to 27.1% less loss
Diesel Immersion	1 hr	0.3% (5.7%)	12.7% (14.0%)	5.7% (10.2%)	1.3 to 5.4% less loss
	4 hr	0.8% (5.1%)	19.6% (19.6%)	4.9% (17.0%)	0 to 12.1% less loss
	8 hr	3.2% (11.1%)	21.6% (24.3%)	5.2% (17.9%)	2.7 to 12.7% less loss
Laboratory Weathering		18.2% (23.3%)	65.0% (71.0%)	64.5% (75.0%)	5.1 to 10.5% less loss

Notes: * In each cell, the first value is the percent loss for RJSeal coated specimens, the second value in parentheses is the percent loss for uncoated specimens
** Of all the test results, the higher Marshall stability loss of RJSeal coated specimens after 1 hour water immersion was the only case that RJSeal coated specimens registered a higher loss.

6.0 SUMMARY AND CONCLUSIONS

This report describes an experimental study to identify the benefits of the application of RJSeal coating on the surface of asphalt mixtures. The objectives of the experimental program were to evaluate the engineering benefits of RJSeal against the following four forms of damage: moisture damage, diesel fuel damage, gasoline fuel damage, and simulated weathering damage. The engineering benefits of RJSeal were evaluated by considering four treatment processes: immersion in water, immersion in gasoline, immersion in diesel, and laboratory weathering chamber treatment. The three immersion tests were each performed for 3 immersion periods: 1 hour, 4 hours, and 8 hours. The laboratory simulated weathering comprised 120 cycles of 2-hour wetting and 2-hour drying each. Control specimens (i.e. W3B specimens not coated with RJSeal) and W3B specimens coated with RJSeal were each subjected to the same type of treatment and their behaviors and performance after the treatment were evaluated and compared.

The test results of the experimental program have provided conclusive supporting evidence of the following two beneficial effects of RJSeal coating on the engineering performance of asphalt mixtures: (a) rejuvenating effect on the asphalt binder, and (b) protective effect on the asphalt mixture from damaging effect of moisture, gasoline, diesel and laboratory weathering.

The rejuvenating effect of applying the RJSeal coating on asphalt mixtures was quantified by examining the changes brought about by the coating in terms of the three engineering properties: Marshall stability, indirect tensile strength, and resilient modulus. The test results showed that all the three engineering properties reduced by varying degrees when RJSeal was applied onto W3B test specimens. Although the reductions in Marshall stability were not found to be statistically significant at 95% confidence level, the reductions in both the indirect tensile strength and resilient modulus were statistically significant at the same confidence level. The rejuvenating effect of RJSeal as manifested in the lower values of indirect tensile strength and resilient modulus is beneficial to old asphalt pavements with aged asphalt binders. The beneficial effect is expected to be improved ductility of old asphalt pavements, and hence longer fatigue life, brought about by having rejuvenated asphalt binders that are less brittle.

The protective effect of of applying the RJSeal coating on asphalt mixtures was examined by comparing the degrees of weakening of RJSeal-coated and uncoated W3B test specimens under the respective actions of water, gasoline, diesel, and laboratory simulated weathering. Again, the degrees of weakening of the test specimens were quantified in terms of the same three engineering properties: Marshall stability, indirect tensile strength, and resilient modulus. The test results clearly showed that, under the respective actions water immersion, gasoline, diesel immersion and laboratory weathering, RJSeal coated specimens resulted in lower losses of Marshall stability, indirect tensile strength or resilient modulus than the corresponding uncoated specimens. These findings offer conclusive evidence of the effectiveness of RJSeal as a protective coating against the damaging actions of following matters or environmental forces: water, gasoline, diesel and simulated weathering of combined actions of wetting-drying and heating cycles.

REFERENCES

ASTM [2005a] D490 Standard Specification for Road Tar. Annual Book of ASTM Standards, Vol. 04.03, American Society for Testing and Materials.

ASTM [2005b] D1559 Standard Test Method for Resistance to Plastic Flow of Bituminous Mixtures using Marshall Apparatus. Annual Book of ASTM Standards, Vol. 04.03, American Society for Testing and Materials.

ASTM [2005c] D4123 Indirect Tension Test for Resilient Modulus of Bituminous Mixtures. Annual Book of ASTM Standards, Vol. 04.03, American Society for Testing and Materials.

FAA [2006] Coal-Tar Sealer/Rejuvenator, Engineering Brief No. 44A, Federal Aviation Administration.

Fwa T. F. and T. S. Ang [1993] Effects of moisture on Properties of Asphalt Mixes in a Wet Tropical Climate: Laboratory Study. Transportation Research Record, No. 1417, pp. 29 – 37.

Fwa T. F., S. A. Tan and B. H. Low [1998] Relating Triaxial Test Properties of Asphalt mixtures to Mix Parameters Determined by Marshall Stability Test. Journal of Testing and Evaluation, Vol. 25, No. 5, pp. 471-479.

Low B. H., S. A. Tan and T. F. Fwa [1993] Analysis of Marshall Test Behavior with Triaxial Test Determined Material Properties. Journal of Testing and Evaluation, Vol. 21, No. 3, pp. 192-198.

FIGURES

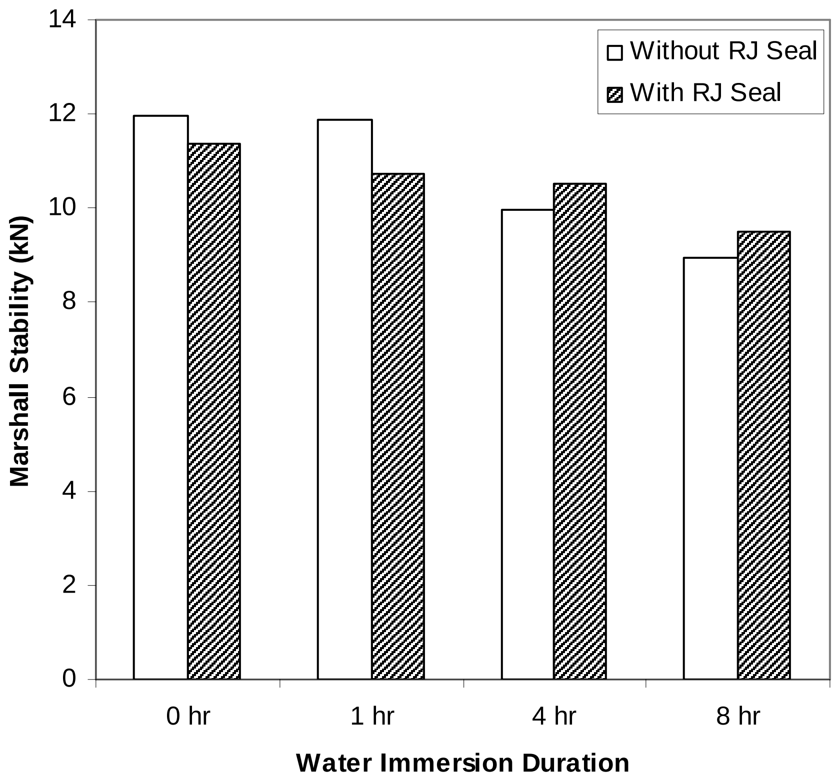

Figure 1: Marshall Stability Values for Different Water Immersion Durations

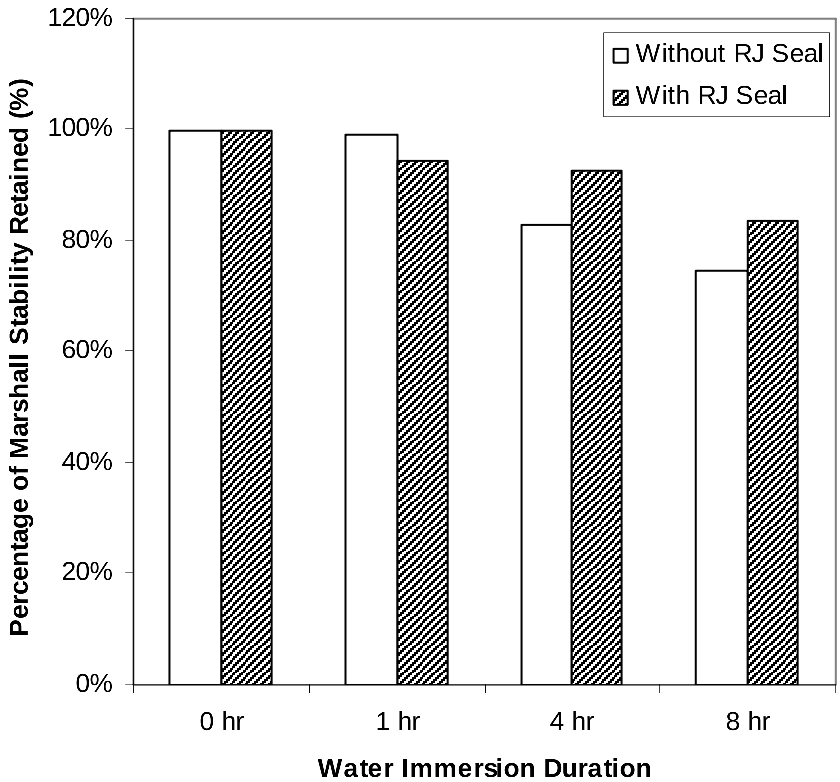

Figure 2: Percent Retained Marshall Stability for Different Water Immersion Durations

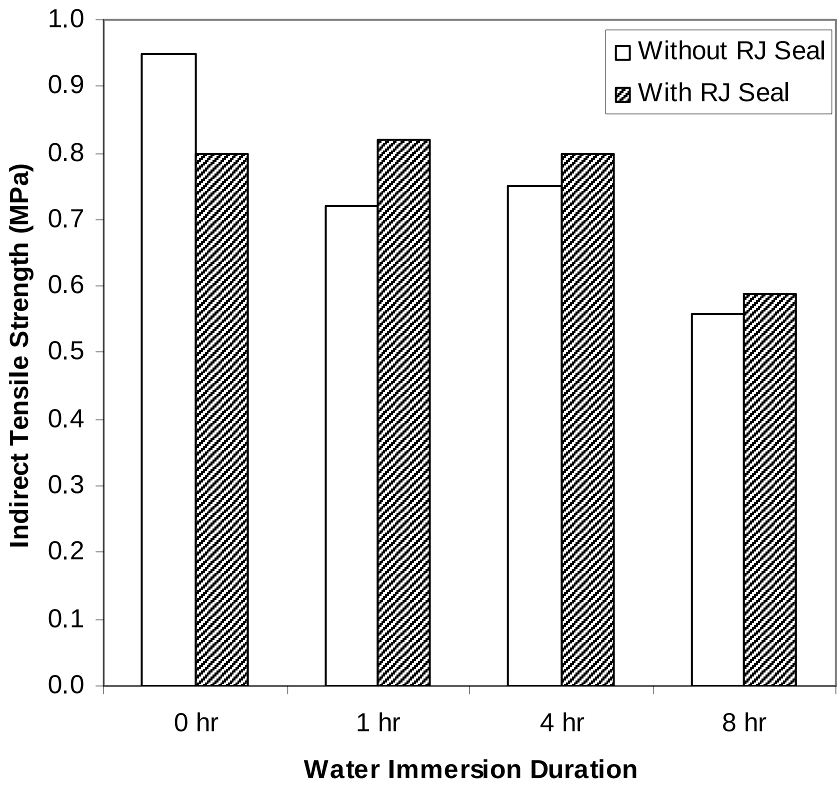

Figure 3: Indirect Tensile Strength Values for Different Water Immersion Durations

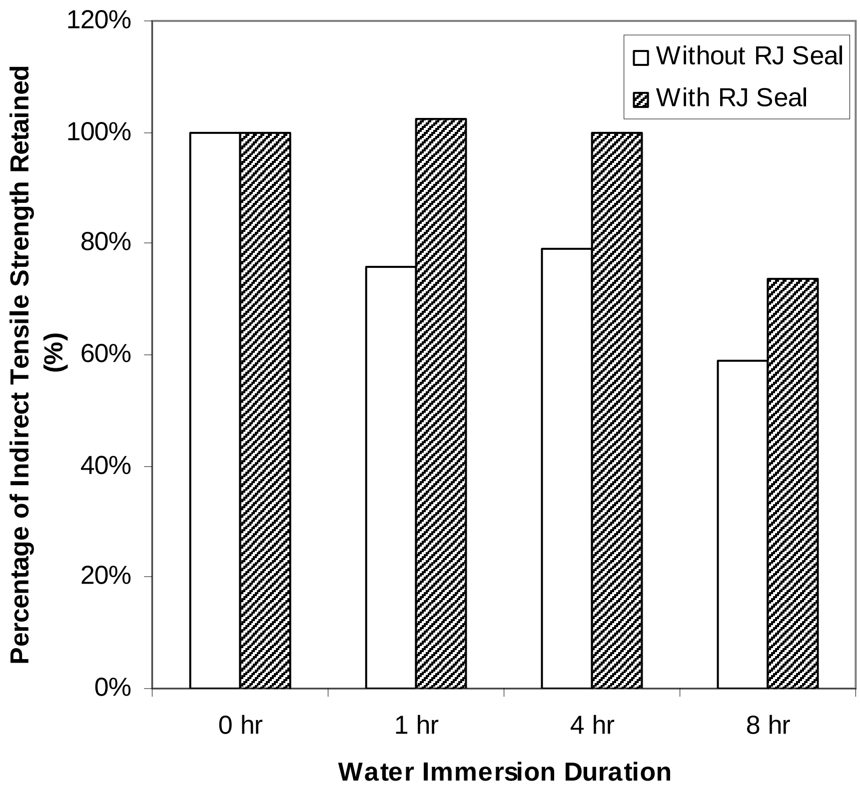

Figure 4: Percent Retained Indirect Tensile Strength for Different Water Immersion Durations

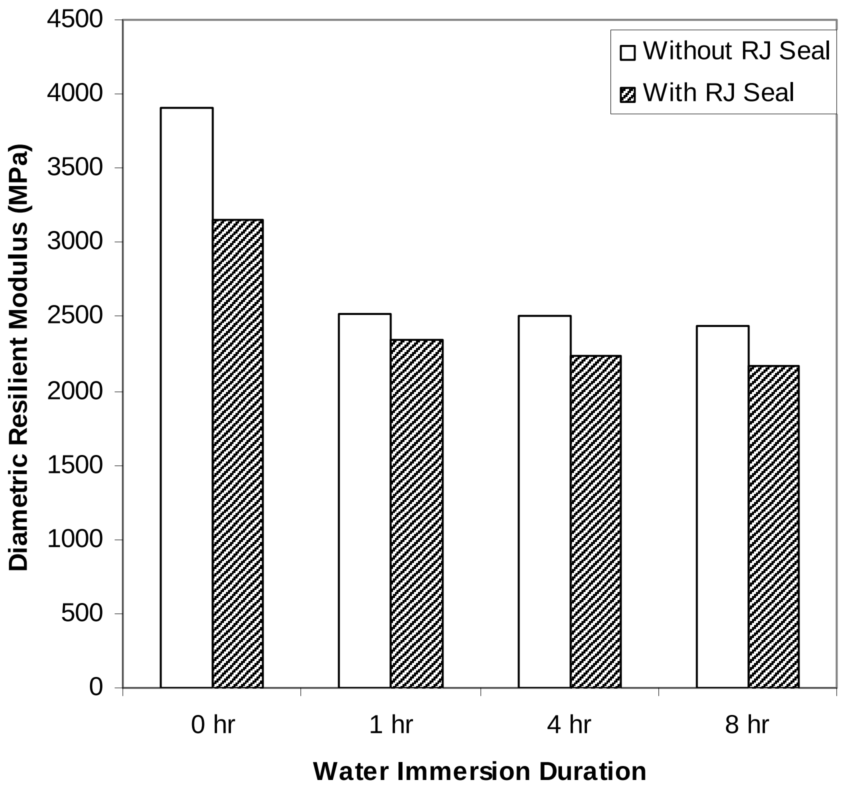

Figure 5: Resilient Modulus Values for Different Water Immersion Durations

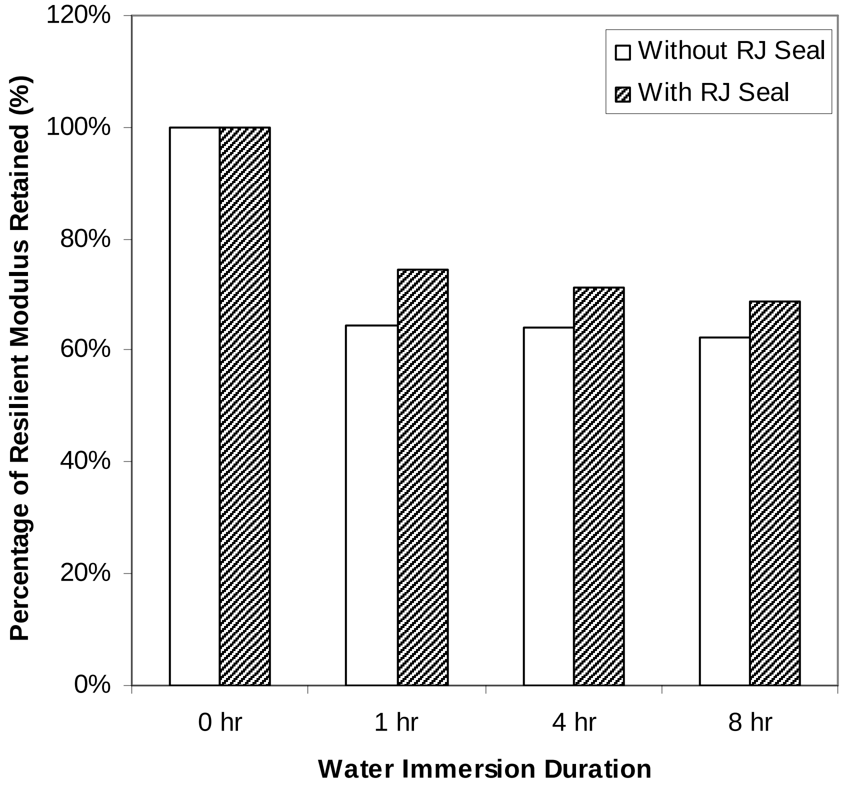

Figure 6: Percent Retained Resilient Modulus for Different Water Immersion Durations

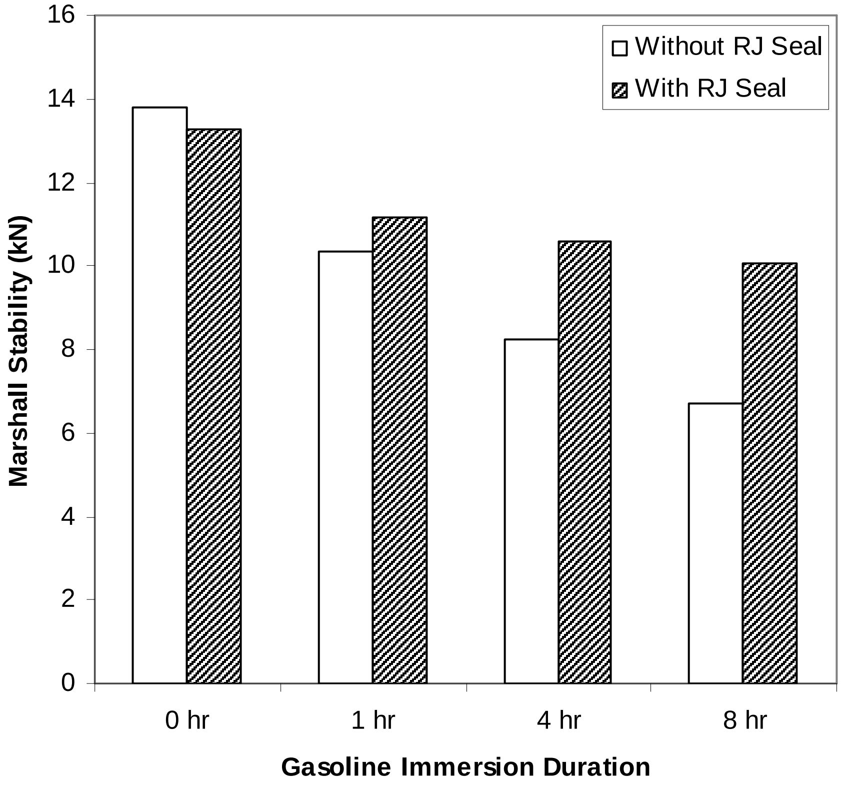

Figure 7: Marshall Stability Values for Different Gasoline Immersion Durations

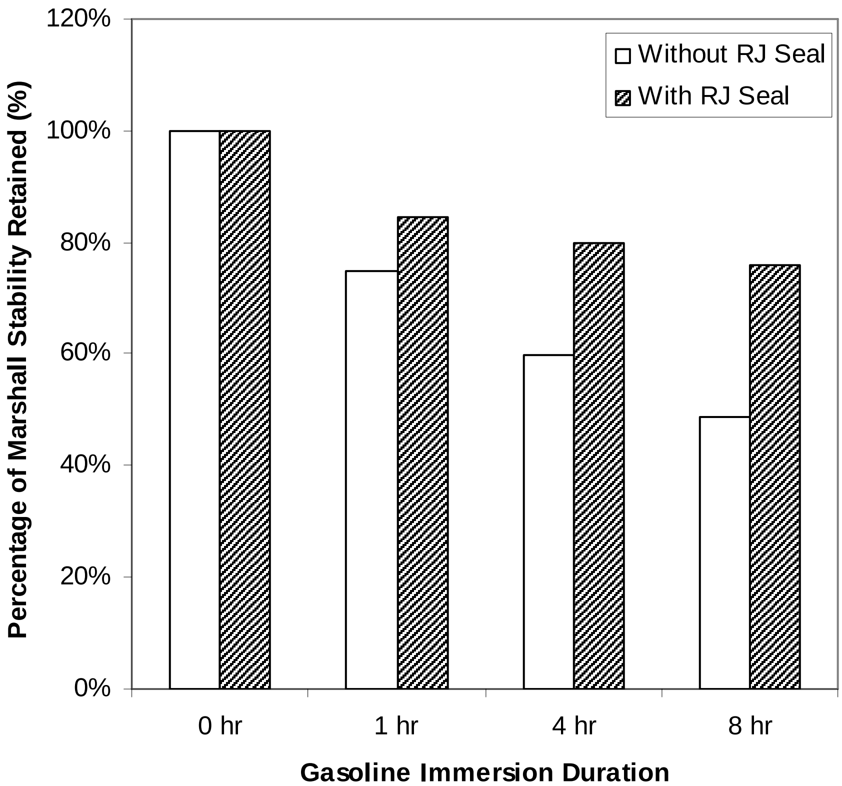

Figure 8: percent Retained Marshall Stability for Different Gasoline Immersion Durations

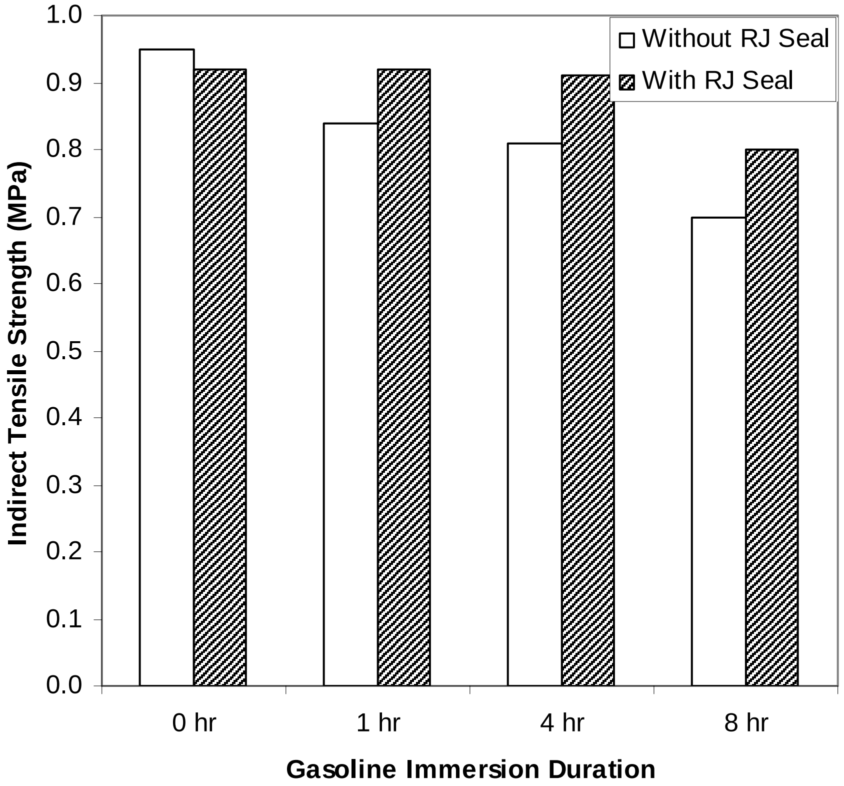

Figure 9: Indirect Tensile Strength Values for Different Gasoline Immersion Durations

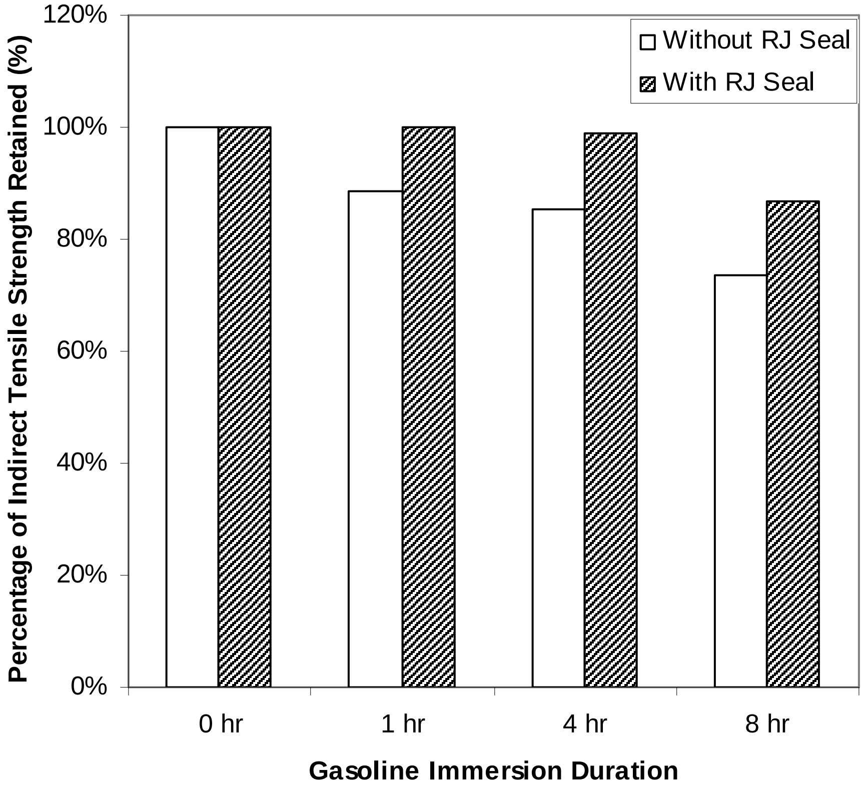

Figure 10: Percent Retained Indirect Tensile Strength for Different Gasoline Immersion Durations

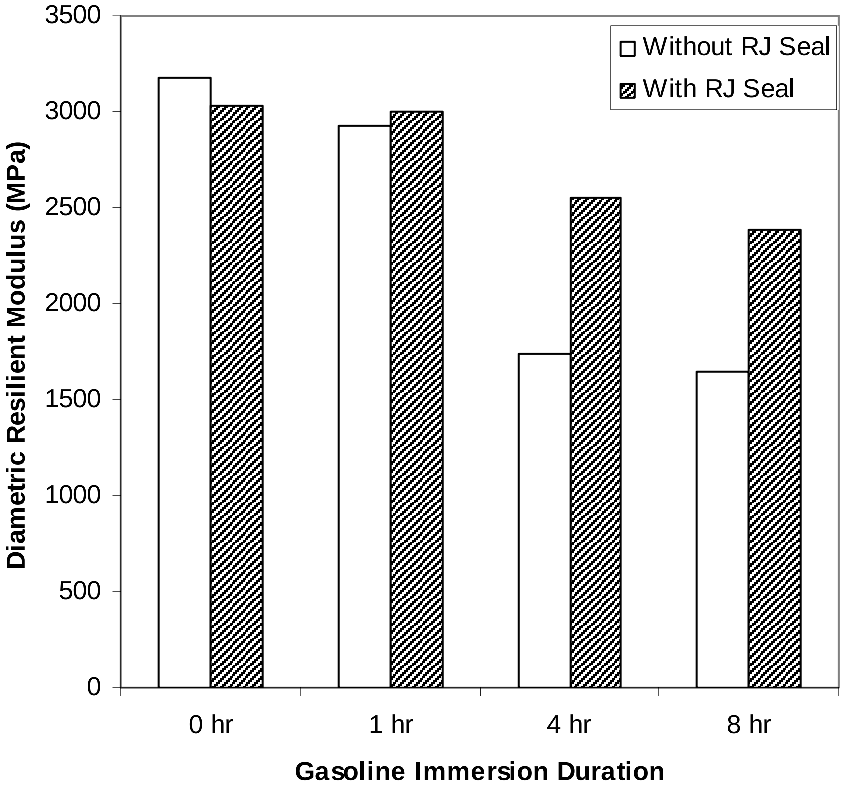

Figure 11: Resilient Modulus Values for Different Gasoline Immersion Durations

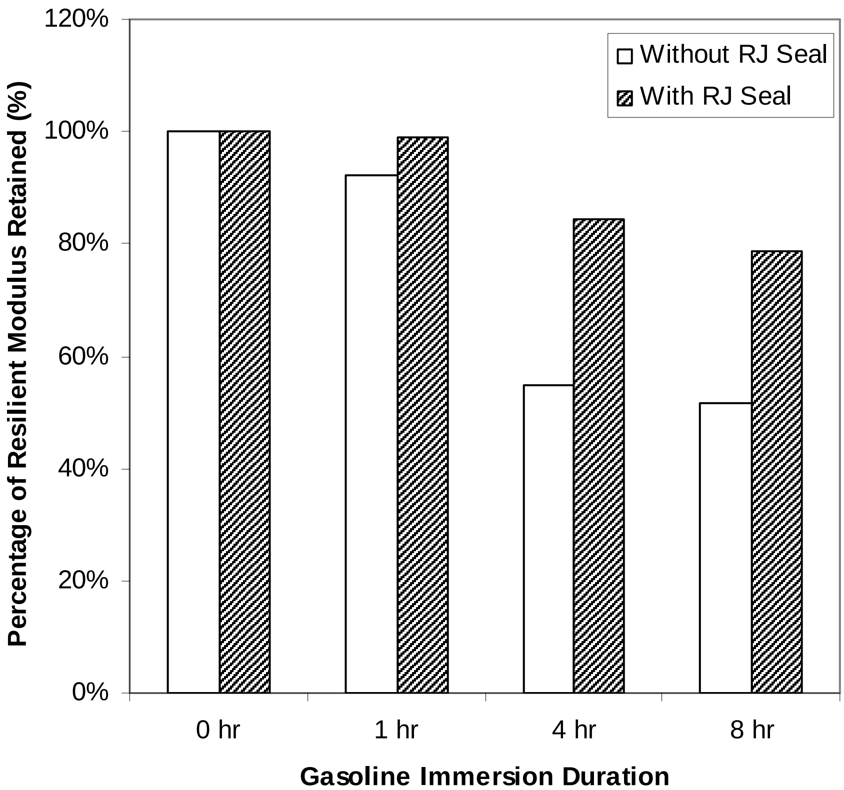

Figure 12: Percent Retained Resilient Modulus for Different Gasoline Immersion Durations

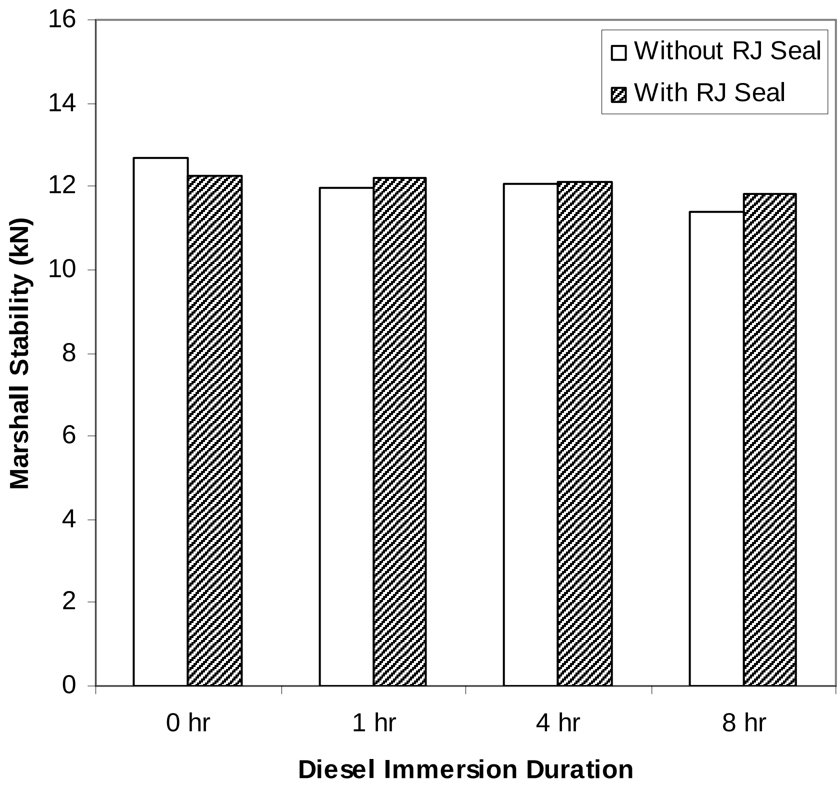

Figure 13: Marshall Stability Values for Different Diesel Immersion Durations (Test #2)

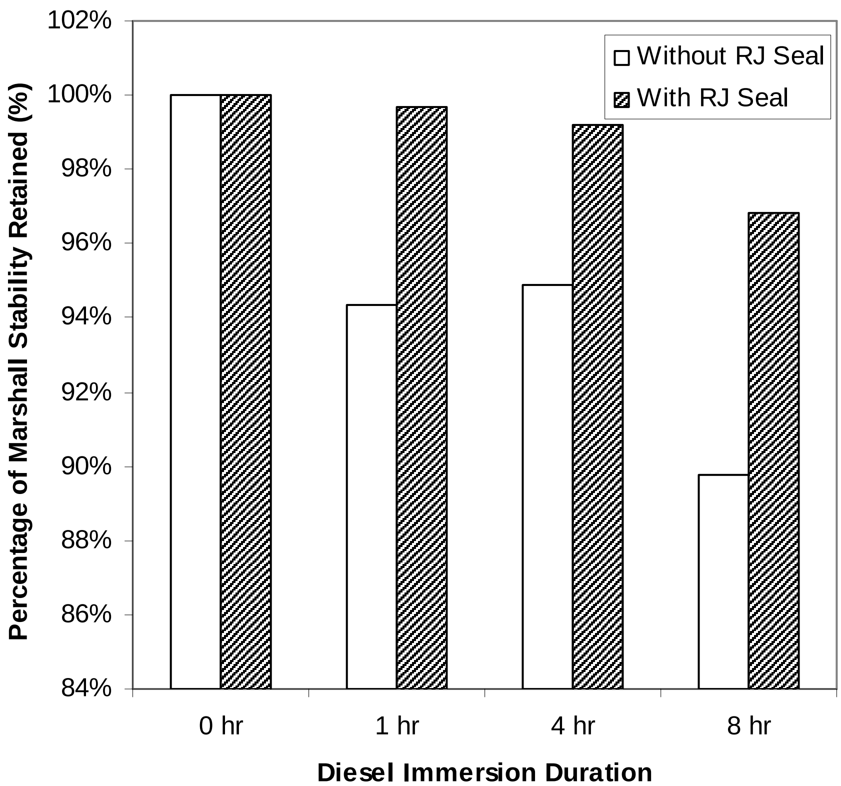

Figure 14: Marshall Stability Retained in Percentage for Different Diesel Immersion Durations (Test #2)

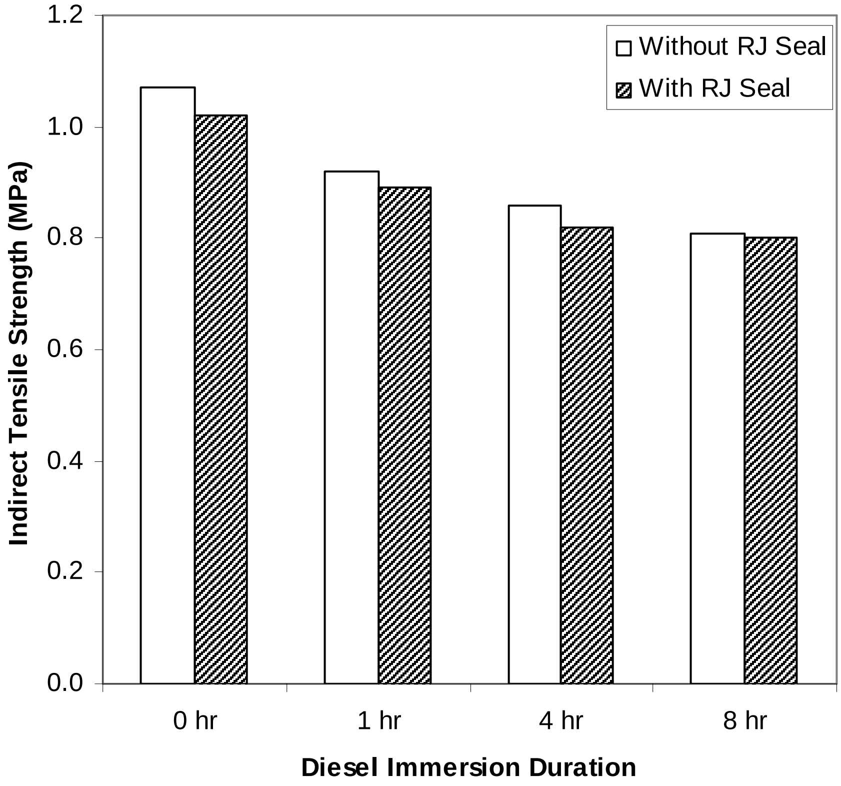

Figure 15: Indirect Tensile Strength Values for Different Diesel Immersion Durations (Test #2)

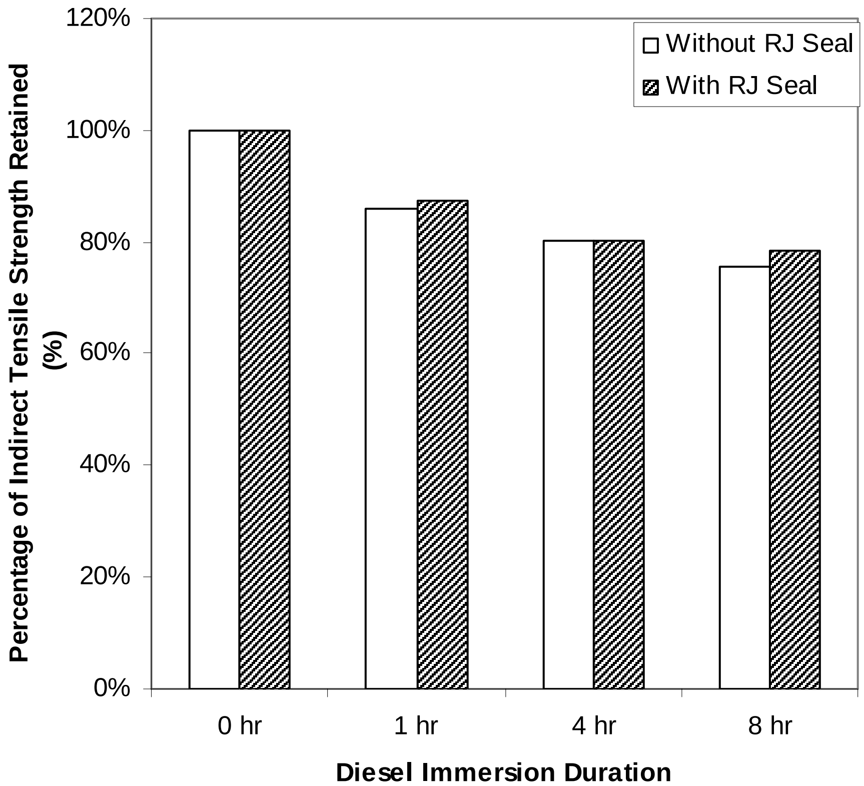

Figure 16: Indirect Tensile Strength Retained in Percentage for Different Diesel Immersion Durations (Test #2)

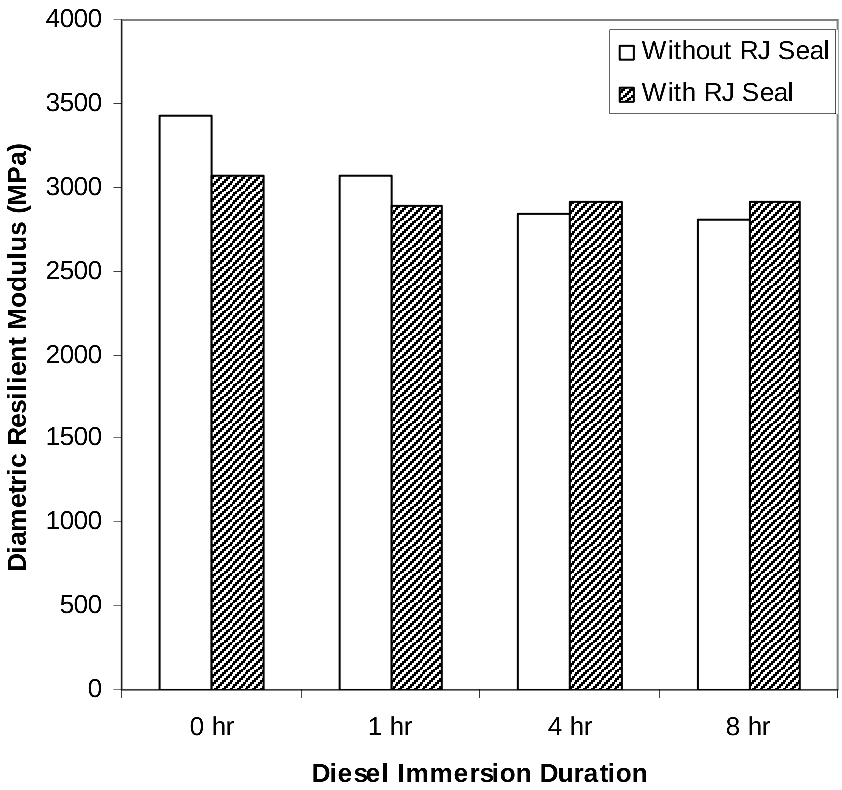

Figure 17: Resilient Modulus Values for Different Diesel Immersion Durations (Test #2)

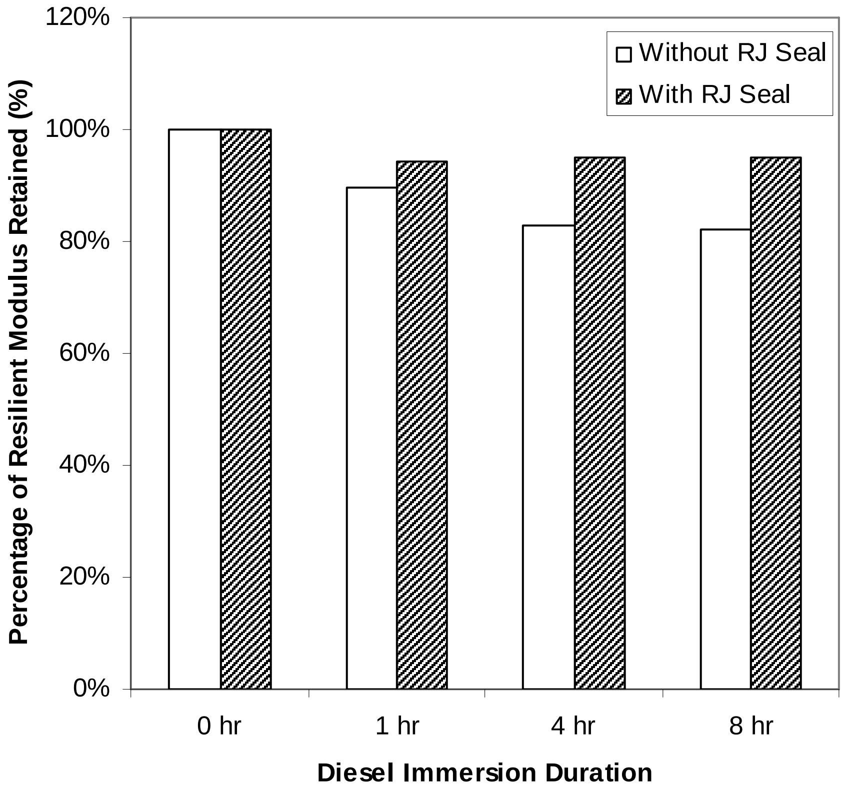

Figure 18: Resilient Modulus Retained in Percentage for Different Diesel Immersion Durations (Test #2)

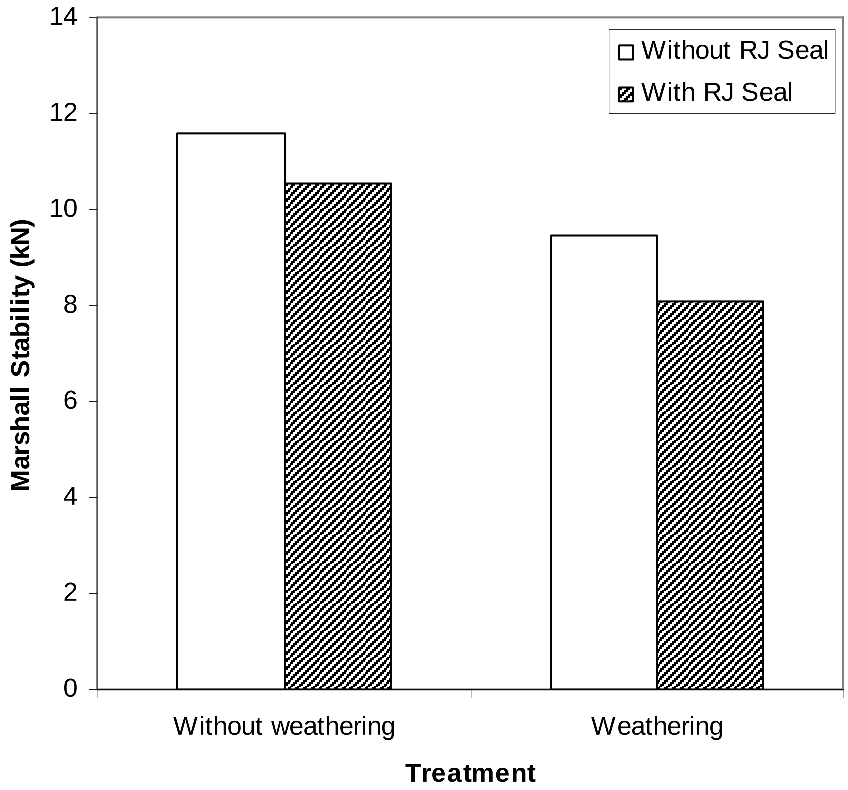

Figure 19: Marshall Stability Values for Different Treatments

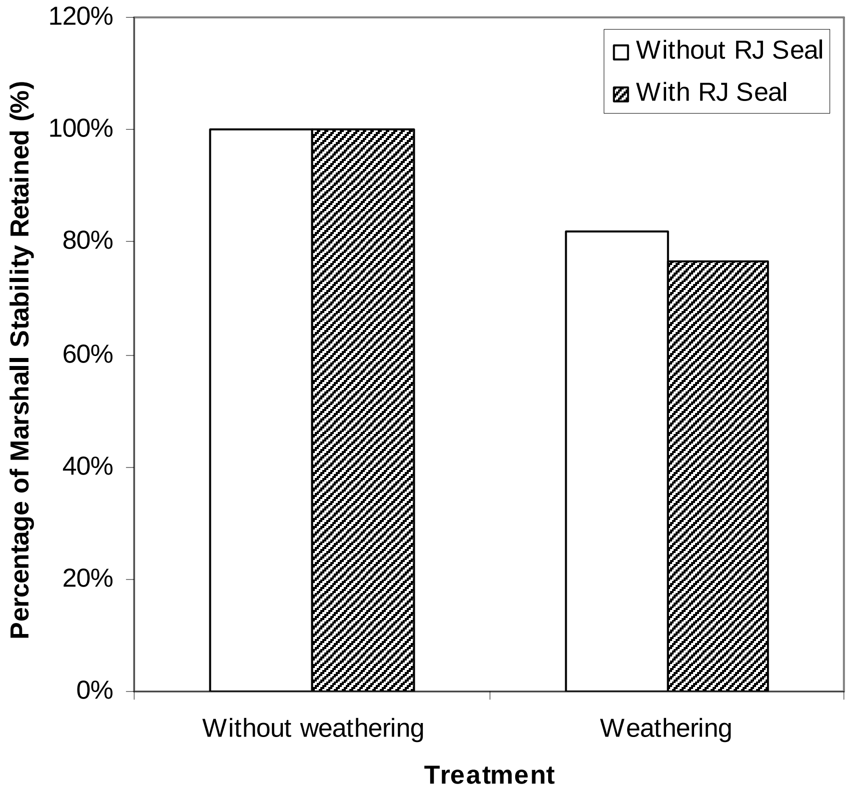

Figure 20: Percent Retained Marshall Stability for Different Treatments

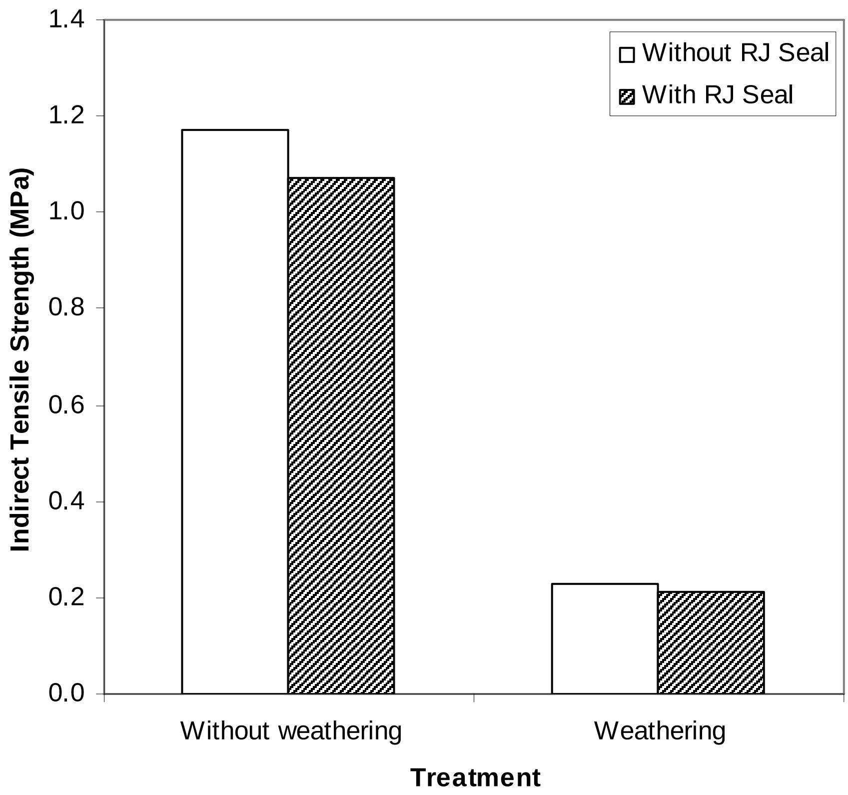

Figure 21: Indirect Tensile Strength Values for Different Treatments

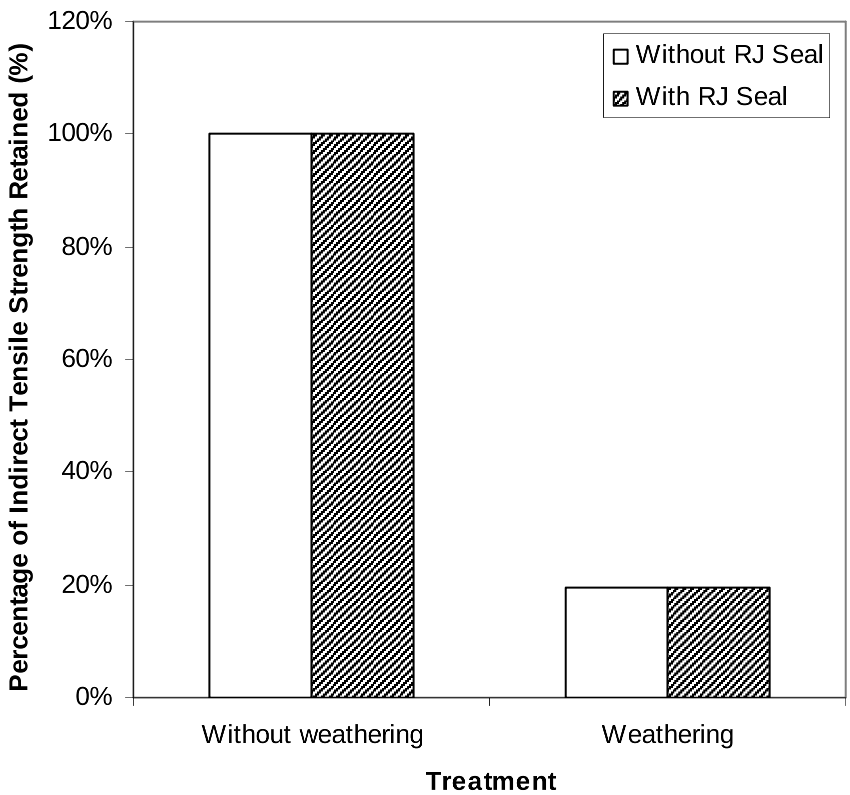

Figure 22: Percent Retained Indirect Tensile Strength for Different Treatments

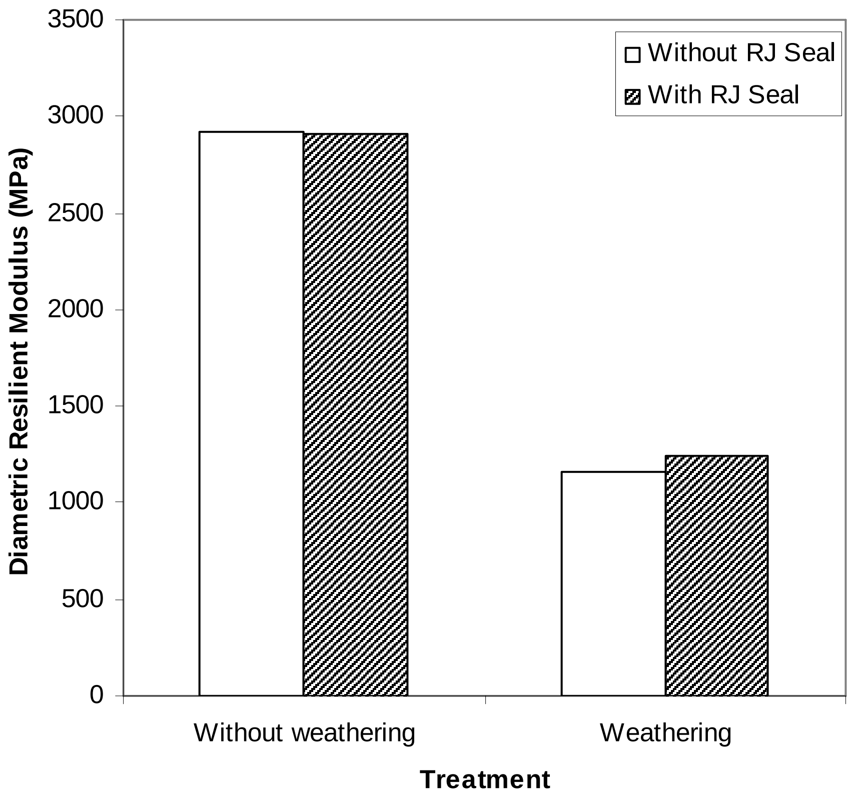

Figure 23: Resilient Modulus Values for Different Treatments

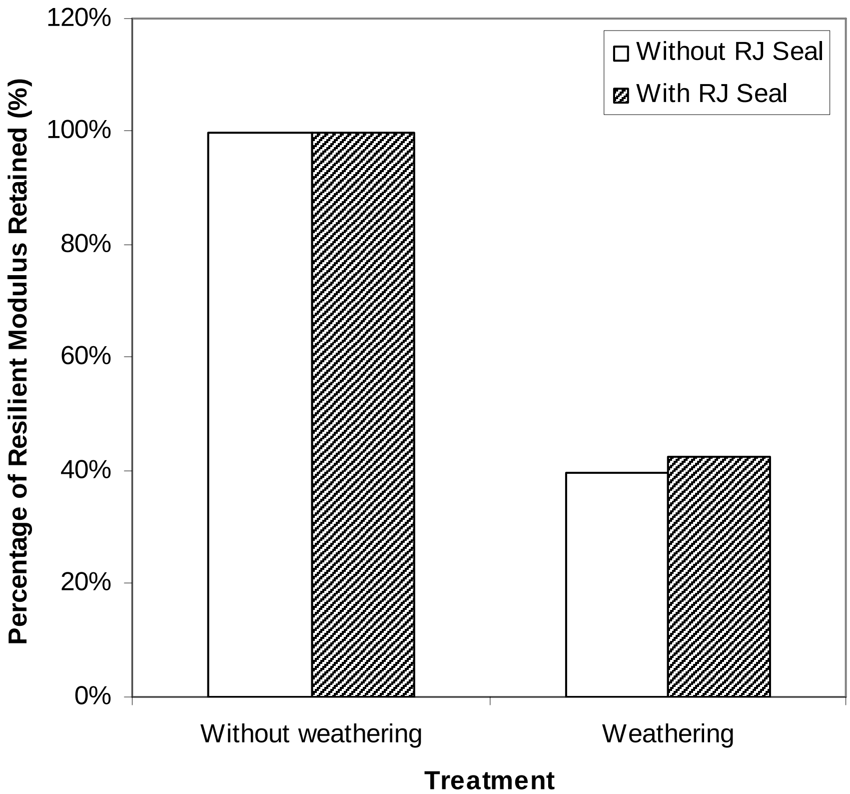

Figure 24: Percent Resilient Modulus Retained for Different Treatments

APPENDIX A

Property Requirements of Coal-Tar Sealer/Rejuvenator by FAA Engineering Brief No. 44A

Test Property	Test Method	Requirements
Specific Gravity @ 25/ 25 °C	ASTM D 70	1.04 minimum
Viscosity Engler 50 cc @ 50° C	ASTM D 1665	8.0 maximum
Water, % by volume	ASTM D 95	2.0 maximum
Distillation % by weight to 170°C % by weight to 270°C % by weight to 300°C	ASTM D 20	20 maximum 20 – 50 60 maximum
Softening Point °C of Residue above 300°C	ASTM D 36	65 maximum

APPENDIX B

TEST DATA OF WATER IMMERSION EFFECTS

Table B1 -- Marshall Test Results for Water Immersion Treated Specimens
(Specimen series U and W)

Water Immersion Duration	Not coated with RJ Seal				Coated with RJ Seal			
	Marshall Stability (kN)		Flow (mm)		Marshall Stability (kN)		Flow (mm)	
	Data	Average	Data	Average	Data	Average	Data	Average
0 hr	11.47	11.98	6.6	5.5	10.96	11.37	5.0	4.8
	12.68		6.1		12.31		4.5	
	12.35		4.5		10.16		5.2	
	11.42		4.7		12.05		4.6	
1 hr	12.31	11.87	5.4	4.9	11.21	10.72	4.6	5.5
	12.14		4.8		11.59		6.4	
	11.47		4.4		9.74		4.6	
	11.55		4.9		10.33		6.5	
4 hr	11.17	9.95	4.2	4.7	10.92	10.54	3.8	5.2
	9.49		3.7		9.24		6.3	
	10.21		6.2		10.37		6.0	
	8.95		4.5		11.63		4.7	
8 hr	9.45	8.95	5.3	5.0	4.45	9.50	4.3	5.0
	7.39		6.0		9.62		5.1	
	6.55		4.3		11.97		5.1	
	12.39		4.5		11.97		5.4	

Table B2 Indirect Tensile Strength Test Results for Water Immersion Treated Specimens
(Specimen series V and W)

Water Immersion Duration	Not coated with RJ Seal Tensile Strength (MPa)		Coated with RJ Seal Tensile Strength (MPa)	
	Data	Average	Data	Average
0 hr	1.08	0.95	0.77	0.80
	0.93		0.86	
	0.98		0.88	
	0.86		0.78	
	0.90		0.74	
1 hr	0.72	0.72	0.81	0.82
	0.66		0.80	
	0.79		0.82	
	0.73		0.78	
	0.67		0.86	
4 hr	0.79	0.75	0.64	0.80
	0.71		0.87	
	0.77		0.79	
	0.71		0.88	
	0.68		0.82	
8 hr	0.62	0.56	0.57	0.59
	0.56		0.41	
	0.40		0.53	
	0.64		0.72	
	0.57		0.75	

Table B3 Diametric Resilient Modulus Test Results for Water Immersion Treated Specimens (Specimen series W)

Water Immersion Duration	Not coated with RJ Seal Resilient Modulus (MPa)				Coated with RJ Seal Resilient Modulus (MPa)			
	Dir 1	Dir 2	Specimen Average	Average	Dir 1	Dir 2	Specimen Average	Average
0 hr	4281.2	3646.2	3963.7	3908.0	2161.6	3808.0	2984.8	3152.8
	4449.7	4173.2	4311.5		2712.1	2828.1	2770.1	
	4373.0	2524.6	3448.8		3585.6	3821.4	3703.5	
1 hr	1143.6	4989.9	3066.8	2521.5 (65% retained)	3394.5	1058.9	2226.7	2349.5 (75% retained)
	580.8	2166.4	1373.6		2191.7	2799.2	2495.5	
	2130.4	4117.7	3124.1		843.7	3809.2	2326.4	
4 hr	4287.8	2999.1	3643.5	2507.7 (64% retained)	4023.8	1846.3	2935.1	2242.4 (71% retained)
	1320.5	1956.6	1638.6		2088.2	4308.4	3198.3	
	2343.9	2138.0	2241.0		427.7	758.7	593.2	
8 hr	3537.0	3141.0	3339.0	2441.0 (63% retained)	2191.1	2773.0	2482.1	2165.1 (69% retained)
	3074.6	1911.6	2493.1		3759.3	2663.0	3211.2	
	1849.6	1132.3	1491.0		936.4	668.1	802.2	

APPENDIX C

TEST DATA OF GASOLINE IMMERSION EFFECTS

Table C1 Marshall Test Results for Gasoline Immersion Treated Specimens
(Series AA and CC)

Gasoline Immersion Duration	Not coated with RJ Seal				Coated with RJ Seal			
	Marshall Stability (kN)		Flow (mm)		Marshall Stability (kN)		Flow (mm)	
	Data	Average	Data	Average	Data	Average	Data	Average
0 hr	13.02	13.79	3.1	3.5	11.80	13.25	2.8	3.5
	13.44		3.9		14.49		2.7	
	14.57		3.0		14.78		4.3	
	14.11		4.0		11.93		4.0	
1 hr	10.54	10.33	3.3	3.3	9.03	11.18	4.9	4.6
	9.70		3.4		12.31		4.2	
	8.82		2.6		11.05		5.0	
	12.26		3.7		12.35		4.3	
4 hr	9.41	8.23	4.7	4.3	9.45	10.59	4.2	3.9
	7.56		4.7		10.46		3.1	
	7.06		3.6		11.55		4.1	
	8.90		4.3		10.92		4.3	
8 hr	7.01	6.72	6.6	5.5	10.79	10.05	5.1	5.6
	5.54		5.6		9.49		5.2	
	7.52		4.6		9.79		6.5	
	6.80		5.2		10.12		5.6	

Table C2 Indirect Tensile Strength Test Results for Gasoline Immersion Treated Specimens (Series BB and CC)

Gasoline Immersion Duration	Not coated with RJ Seal		Coated with RJ Seal	
	Tensile Strength (MPa)		Tensile Strength (MPa)	
	Data	Average	Data	Average
0 hr	0.89	0.95	0.95	0.92
	1.05		0.90	
	0.90		0.91	
	0.99		0.85	
	0.94		1.01	
1 hr	0.87	0.84	0.88	0.92
	0.91		1.01	
	0.91		1.04	
	0.81		0.82	
	0.68		0.84	
4 hr	0.70	0.81	0.91	0.91
	0.87		0.92	
	0.74		1.02	
	0.93		0.79	
	0.81		0.91	
8 hr	0.72	0.70	0.88	0.80
	0.73		0.83	
	0.72		0.79	
	0.63		0.74	
	0.71		0.78	

Table C3 Diametric Resilient Modulus Test Results for Gasoline Immersion Treated Specimens (Series CC)

Gasolinel Immersion Duration	Not coated with RJ Seal				Coated with RJ Seal			
	Resilient Modulus (MPa)				Resilient Modulus (MPa)			
	Dir 1	Dir 2	Specimen Average	Average	Dir 1	Dir 2	Specimen Average	Average
0 hr	3306.6	3248.2	3277.4	3177.5	3174.4	3230.1	3202.3	3031.8
	2924.3	3065.1	2994.7		3716.2	2619.3	3167.8	
	3301.0	3219.8	3260.4		2938.2	3010.1	2974.2	
1 hr	3069.0	2910.3	2989.7	2928.1	3131.7	2922.5	3027.1	3005.1
	2742.6	2523.8	2633.2		3009.9	2956.8	2983.4	
	3304.0	3018.9	3161.5		2997.9	3012.0	3005.0	
4 hr	1981.7	2045.6	2013.7	1737.5	2135.2	2246.9	2191.1	2553.3
	1772.0	1828.7	1800.4		2836.2	2967.4	2901.8	
	1306.4	1490.5	1398.5		2504.8	2629.4	2567.1	
8 hr	1893.0	1766.9	1830.0	1642.9	2315.7	2133.5	2224.6	2389.2
	1547.1	1329.8	1438.5		2479.9	2344.7	2412.3	
	1851.9	1468.6	1660.3		2522.6	2539.0	2530.8	

APPENDIX D

TEST DATA OF DIESEL IMMERSION EFFECTS

Table D1 Marshall Test Results for Diesel Immersion Treated Specimens
(Series X and Z)

Diesel Immersion Duration	Not coated with RJ Seal				Coated with RJ Seal			
	Marshall Stability (kN)		Flow (mm)		Marshall Stability (kN)		Flow (mm)	
	Data	Average	Data	Average	Data	Average	Data	Average
0 hr	11.47	12.69	4.1	3.9	13.36	12.23	3.6	3.7
	14.32		3.8		10.92		3.5	
	13.36		3.2		13.02		3.5	
	11.63		4.4		11.63		4.4	
1 hr	11.00	11.97	4.3	4.1	12.81	12.19	4.7	4.5
	12.10		3.8		12.10		4.3	
	12.10		3.3		11.51		3.4	
	12.68		5.1		12.35		5.5	
4 hr	12.22	12.04	3.7	3.5	13.36	12.13	3.8	4.0
	12.39		3.8		11.76		4.0	
	12.39		3.1		11.00		3.7	
	11.17		3.4		12.39		4.5	
8 hr	10.79	11.39	4.4	4.1	13.15	11.84	4.2	4.2
	10.79		4.1		11.00		4.0	
	12.77		4.4		10.84		4.1	
	11.21		3.7		12.39		4.5	

Table D2 Indirect Tensile Strength Test Results for Diesel Immersion Treated Specimens (Series Y and Z)

Diesel Immersion Duration	Not coated with RJ Seal		Coated with RJ Seal	
	Tensile Strength (MPa)		Tensile Strength (MPa)	
	Data	Average	Data	Average
0 hr	1.13	1.07	1.05	1.02
	1.11		0.95	
	1.05		0.98	
	1.06		1.08	
	0.99		1.05	
1 hr	0.92	0.92	0.86	0.89
	0.90		0.74	
	0.83		0.82	
	0.93		0.89	
	1.00		1.13	
4 hr	0.75	0.86	0.72	0.82
	0.88		0.76	
	0.89		0.77	
	0.88		0.96	
	0.92		0.91	
8 hr	0.73	0.81	0.70	0.80
	0.76		0.80	
	0.77		0.75	
	0.89		0.87	
	0.88		0.88	

Table D3 Diametric Resilient Modulus Test Results for Gasoline Immersion Treated Specimens (Series Z)

Diesel Immersion Duration	Not coated with RJ Seal				Coated with RJ Seal			
	Resilient Modulus (MPa)				Resilient Modulus (MPa)			
	Dir 1	Dir 2	Specimen Average	Average	Dir 1	Dir 2	Specimen Average	Average
0 hr	4279.2	3531.5	3905.4	3424.9	3491.1	2727.7	3109.4	3067.0
	4065.3	3449.1	3757.2		3445.5	2819.9	3132.7	
	3778.6	3225.9	3502.3		2745.6	3172.3	2959.0	
1 hr	2960.0	2716.6	2838.3	3073.9	3319.7	1087.9	2203.8	2892.4
	2701.1	3788.2	3244.7		2952.3	3033.3	2992.8	
	3087.5	3190.0	3138.8		3523.4	3437.9	3480.7	
4 hr	2485.5	2593.6	2539.6	2841.3	2561.2	3371.2	2966.2	2918.1
	2899.6	3257.2	3078.4		2996.8	3376.5	3186.7	
	2933.4	2878.4	2905.9		2710.7	2492.4	2601.6	
8 hr	2998.9	2966.5	2982.7	2810.8	2871.6	2933.7	2902.7	2908.4
	2853.5	2480.1	2666.8		2514.3	2811.7	2663.0	
	2809.5	2756.2	2782.9		3075.7	3243.5	3159.6	

APPENDIX E

TEST DATA OF LABORATORY WEATHERING EFFECTS

Table E1 Marshall Test Results for Laboratory Weathering Treated Specimens (Series L and N)

Treatment	Not coated with RJ Seal				Coated with RJ Seal			
	Marshall Stability (kN)		Flow (mm)		Marshall Stability (kN)		Flow (mm)	
	Data	Average	Data	Average	Data	Average	Data	Average
Non-weathered	12.47	11.57	4.0	4.4	10.37	10.56	3.9	4.4
	11.89		5.0		10.29		4.6	
	10.42		4.9		10.42		5.1	
	10.21		4.5		11.34		4.5	
	11.00		3.6		10.12		4.6	
	11.76		4.0		10.37		4.6	
	12.26		4.5		10.33		4.0	
	13.02		3.6		10.42		4.7	
	11.13		5.3		11.38		3.8	
Weathered	8.69	9.46	8.2	7.8	9.93	8.10	6.6	7.6
	10.08		7.7		8.32		7.9	
	10.29		7.0		8.27		8.0	
	11.00		7.0		9.24		8.4	
	8.86		7.0		6.97		7.1	
	9.16		8.5		8.36		7.5	
	9.24		7.3		6.80		8.0	
	9.32		8.3		7.10		7.9	
	8.53		9.2		7.94		7.4	

Table E2 Indirect Tensile Strength Test Results for Laboratory Weathering Treated Specimens (Series M and N)

Treatment	Not coated with RJ Seal		Coated with RJ Seal	
	Tensile Strength (MPa)		Tensile Strength (MPa)	
	Data	Average	Data	Average
Non-weathered	1.37	1.38	0.82	1.00
	1.31		1.07	
	1.48		1.20	
	1.48		1.33	
	1.37		0.99	
	1.59		1.23	
	1.28		0.72	
	1.28		0.88	
	1.23		0.80	
Weathered	0.36	0.40	0.26	0.35
	0.32		0.27	
	0.36		0.28	
	0.33		0.32	
	0.40		0.35	
	0.28		0.27	
	0.58		0.48	
	0.57		0.49	
	0.43		0.43	

Table E3 Diametric Resilient Modulus Test Results for Laboratory Weathering Treated Specimens (Series L and N)

Treatment	Not coated with RJ Seal				Coated with RJ Seal			
	Resilient Modulus (MPa)				Resilient Modulus (MPa)			
	Dir 1	Dir 2	Specimen Average	Average	Dir 1	Dir 2	Specimen Average	Average
Non-weathered	3202.0	1790.6	2496.3	3441.8	648.14	1188.7	918.4	2755.5
	4597.3	4220.1	4408.7		1171.2	782.7	977.0	
	4190.5	3219.0	3704.8		1811.6	580.58	1196.1	
	7153.9	4821.4	5987.7		3705.4	2635.6	3170.5	
	5353.1	1453.0	3403.1		5361.5	4393.4	4877.5	
	5031.1	2591.3	3811.2		4703.2	3369.9	4036.6	
	4594.4	2200.1	3397.3		3112.8	1727.3	2420.1	
	3202.0	1790.6	2496.3		4456.1	3293.6	3874.9	
	4597.3	4220.1	4408.7		3519.6	3137.2	3328.4	
Weathered	405.55	973.12	689.3	859.0	439.16	553.27	496.2	978.6
	504.37	773.88	639.1		735.55	751.21	743.4	
	787.87	1061.9	924.9		376.61	740.38	558.5	
	590.34	1101.6	846.0		507.71	1244.9	876.3	
	202.63	1713.6	958.1		1168.2	692.41	930.3	
	602.94	599.03	601.0		1845.2	841.20	1343.2	
	704.82	1417.1	1061.0		1565.1	1059.4	1312.3	
	561.54	1603.5	1082.5		1657.8	1388.5	1523.2	
	812.25	1046.2	929.2		1255.2	793.26	1024.2	

APPENDIX F

ANOVA TESTS FOR REJUVENATING EFFECT OF APPLICATION OF RJSEAL COATING

Effect on Marshall Stability Value

Factor	Type	Levels	Values
batch	fixed	4	A, B, C, D
treatment	fixed	2	coat, uncoat

Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Batch	3	52.179	52.179	17.393	14.21	0.000
Treatment	1	1.624	1.624	1.624	1.33	0.257
Error	37	45.298	45.298	1.224		
Total	41	99.101				

Indirect Tensile Testing Hypothesis Testing

Factor	Type	Levels	Values
batch_1	fixed	4	A, B, C, D
treatment_1	fixed	2	coat, uncoat

Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
batch_1	3	0.77235	0.77235	0.25745	12.97	0.000
treatment_1	1	0.41255	0.41255	0.41255	20.79	0.000
Error	43	0.85324	0.85324	0.01984		
Total	47	2.03815				

Resilient Modulus Hypothesis Testing

Factor	Type	Levels	Values
batch	fixed	4	A, B, C, D
treatment	fixed	2	coat, uncoat

Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
batch	3	519027	519027	173009	0.19	0.903
treatment	1	5238148	5238148	5238148	5.73	0.023
Error	31	28356465	28356465	914725		
Total	35	34113639				