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Virgin and Aged Binder Interaction Measured on Mixture Bars via Repeated Creep in the Dynamic Shear Rheometer

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Abstract: A repeated creep (RC) test was performed on mixture bars in the dynamic shear rheometer (DSR) to investigate the interaction of aged Reclaimed Asphalt Pavement (RAP) binder and virgin binder in different mixtures. The focus of the paper was testing compacted specimens made from 100% RAP and virgin binder. Three RAP sources were tested with three different virgin asphalt contents and two different 100% RAP mixing temperatures. A total of 144 torsion bars were prepared and tested. The overall result of the investigation was that the RC test does not appear optimal for the purpose of evaluating the interaction of 100% RAP mixed with virgin binder. One of the difficulties encountered was preparing torsion bars over a wide range of RAP material properties and virgin asphalt contents. The RC test was able to detect RAP source and virgin asphalt content, but was not able to capture potential differences in mechanical response due to differences in specimen mixing temperature.

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***Key words**: Asphalt mixtures; Dynamic shear rheometer; RAP; Repeated creep; WMA.*

Introduction and Background

In recent years, use of reclaimed asphalt pavement (RAP) and warm mixed asphalt (WMA) have been at, or near the, forefront of issues considered by the flexible pavement community (either used individually or together). At least 45 states either actively use WMA or have investigated its use via trial projects [1]. Hansen and Newcomb [2] presented RAP material availability data from a survey that included over 1,000 asphalt plants in 47 U.S. states. Approximately 85% of the RAP obtained in 2010 was used in hot mixed asphalt (HMA) or WMA, and less than 0.1% was land filled. Most of this RAP is used in HMA or WMA where the RAP content is 50% or less. Copeland [3] performed a survey in 2009 that indicated fewer than half of U.S. states used more than 20% RAP in HMA. RAP use below 20% (typically 10 to 15%) has a long history and does not appear to require detailed characterization of the RAP (total asphalt content and aggregate gradation appear sufficient to describe the mixture). RAP use between 20 and 50%, however, is an area where notable amounts of field production have occurred and characterization techniques that provide the designer more detailed information related to the RAP binder behaviour in a given application are more useful.

Limited projects have made use of RAP contents over 50% for plant produced applications. The most notable example found by the authors was reported by Mallick et al. [4] where 100% RAP with rejuvenators was plant mixed. A plant capable of producing 75 to 150 tons of 100% RAP per hour was described, and the 100% RAP material was used to pave city streets in Queens, New York City in 2002. The mixtures were placed with conventional equipment and were performing well in 2009 after seven years of service. The study's conclusion was that it is possible to obtain good performing 100% RAP that is plant mixed. A laboratory study was performed by the same lead researcher [5] where 100% RAP mixtures were tested for workability, compactability, resilient modulus, moisture sensitivity, and indirect tensile strength with generally favorable assessments.

A few additional documents have at least made mention of equipment that could accommodate mixtures where RAP is the dominant component. Howard et al. [6] provides information on a heated auger plant that transfers heat to the RAP through hot oil lines in the auger flights. No case studies were available but the equipment was intended for high RAP content mixture production.

Tools suitable for developing characterization guidance for RAP materials could serve the paving community well for many high RAP applications (i.e., 25 to 100% RAP). A review of literature and practice indicates characterization tools suitable for providing guidance on RAP behavior in mixtures with 25 to 50% RAP would be the biggest area of potential improvement. However, characterization tools for 100% RAP mixtures would be useful, as projects such as the one described by Mallick et al. [4] could benefit from them.

As an example of a useful characterization tool, Doyle et al. [7] used the same RAP sources tested in this paper to investigate the relative effectiveness of RAP surface asphalt after predicting the amount of asphalt absorbed in RAP aggregate pores. Results were that mixing temperature affected the amount of virgin binder needed to compact 100% RAP specimens to 4% air voids (394 100% RAP specimens were mixed with virgin binder and compacted). When the temperature was reduced from 154 to 138°C, virgin binder demand increased 0.1 to 0.8% depending on RAP source. When temperature was reduced from 154 to 116°C, virgin binder demand increased 0.4 to 1.3% depending on RAP source. Warm mix additives did not have

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consistent effects on virgin binder demand. The analysis methods presented in [7] could be used to evaluate a RAP source and lead a producer to elect to, for example, only use the source with HMA because the RAP binder does not re-liven to an acceptable extent at lower temperatures so the efficiency of the RAP source is maximized at higher temperatures. The reverse could be true for a RAP source that largely re-livens as it would be a preferred WMA candidate.

Another example of a characterization tool for RAP materials is provided in [8]. Therein 100% RAP mixtures using the same raw materials used in this paper were mixed with varying amounts of performance grade (PG) 67-22 virgin binder. Approximately 500 mixture beams were sawn from Superpave Gyratory Compactor (SGC) prepared specimens were and tested in the Bending Beam Rheometer (BBR) from Superpave Gyratory Compactor (SGC) prepared specimens. BBR measured stiffnesses were generally 7 to 21 GPa, which was not radically higher than low RAP control mixtures (9 to 18 GPa) tested under the same conditions. Mixture stiffness slope values (m-values) were on average 0.10 (standard deviation of 0.03) and were noticeably lower than other mixtures tested, indicating relatively brittle behavior. This tendency for brittle behaviour could indicate greater susceptibility to thermal cracking. Recycled mixtures made with 25% RAP had similar predicted cracking temperatures to control mixtures, while 50% RAP mixture data indicated an increased crack potential. In this case, use of BBR mixture beams as a tool to characterize RAP materials provided some insight into 100% RAP behaviour, but not nearly as much as [7].

A final example of research where RAP materials were characterized is provided by [9]. Therein, 100% RAP mixtures incorporating the same raw materials used in this paper were mixed with PG 67-22 virgin binder to create specimens with 4% air voids at design compactive effort of 65 gyrations when mixed at 116^{o}C (1.2 to 2.0% virgin binder was added). Mixture specimens were tested for performance using loaded wheel tracking and the Cantabro durability test. These two test methods were able to provide some useful characterization data for 100% RAP mixtures.

The primary objective of the study presented in this paper was to evaluate the Repeated Creep (RC) test performed on torsion bar mixture specimens in a Dynamic Shear Rheometer (DSR) as a characterization tool and to determine if the test is capable of detecting the interaction of aged RAP binder and virgin binder under different conditions. The secondary objective was to determine if any RC test outputs correlate to rutting of 100% RAP since the test has been observed to correlate to rutting of asphalt mixtures [10]. These objectives were met using the research approach described in the next section.

The RC test was developed by Mathy Technology and Engineering in 2000 [11]. During the general time frame when the test method was developed, Reinke and Dai [12] used the RC test to evaluate mixtures from the MnRoad test site. Traditionally the RC test has been used to evaluate high temperature deformation as the test is a measure of mixture strength due to aggregate structure and binder properties (stiffness and elasticity). The work of Reinke et al. [11] is an example as mixtures were tested at a temperature of 58^{o}C with a 34 kPa stress. The research found differences between mixtures with gravel, limestone, and granite aggregates and made some conclusions related to their ultimate bond failure strengths. The project concluded RC results were influenced to a greater extent by the interaction between input variables than were results from the Hamburg Loaded Wheel Tester (HLWT). Correlations between RC (dry test) and HLWT (wet test) by [11] were mixed (mostly the results did not correlate all that well). Mixture ranking was different between the HLWT and RC test results; i.e., they did not provide the same information about bituminous materials.

Mo et al. [13] tested mortar (bituminous material, filler, and fine sand with mass ratios of 0.34:0.30:0.36) in a DSR. Mortar specimens were heated and poured into circular moulds. The specimens were 6 mm diameter and had an effective length of 10 mm (total length was 20 mm). Test results indicated mortar fatigue characterization can be carried out by means of a DSR.

ASTM D7552-09 uses a version of the RC test to determine the complex shear modulus (G^*) of mixture bars. The method is stated to be appropriate for dense-graded mixtures (coarse or fine graded) so long as the nominal maximum aggregate size (NMAS) is 19 mm or smaller. Frequency or temperature master curves can be generated. Test temperatures can range from 10 to 76^{o}C (± 0.1^{o}C tolerance), frequencies can range from 0.01 to 25 Hz, and strains can range from 0.001 to 0.1% (0.01% is default value). D7552-09 is applicable to stress and strain controlled rheometers (stress controlled rheometers are used in strain controlled mode).

Research Approach

Since the RC test does not appear to have been used extensively to evaluate RAP (in particular the interaction of aged RAP binder with virgin binder), several exploratory items were evaluated to fill this gap in the asphalt users and producers community. The research approach was developed to collect data and perform analyses for the purposes of characterizing RAP for: 1) use in 100% RAP mixtures such as described by Mallick et al. [4], and 2) use in high RAP mixtures (e.g., 25 to 50% RAP). Most of the testing performed was on 100% RAP mixed with virgin binder and then compacted. A modest amount of testing was done on traditional HMA for comparison purposes. The exploratory investigation was divided into three components that are summarized as follows:

1. Investigate RC test variability, with three items being of key interest: a) determining if reasonable specimens can be produced from 100% RAP; b) comparing variability of traditional HMA to 100% RAP; and c) using traditional HMA to evaluate RC test outputs so that the most promising outputs can be evaluated in the remaining components.
2. Evaluate sensitivity of 100% RAP to: a) preparation and compaction conditions; b) aged binder properties and gradation; and c) virgin asphalt content changes.
3. Determine if any RC test parameter correlates to rutting of 100% RAP over a range of conditions.

Experimental Program

Materials Tested

Three RAP sources with different binder grades and rotational viscosities were tested (Fig. 1). R-1 was the stiffest, R-3 had intermediate properties, and R-2 was the least stiff. R-2 had a noticeably finer gradation than R-1 or R-3. One PG 67-22 virgin binder was used throughout. The first of two warm mix technologies used was a wax-based additive (Sasobit®), which was added at 1% of total (virgin plus RAP) asphalt content (AC). The second warm mix technology was a chemical additive (Evotherm 3G™), that was added at 0.5% of total AC. Virgin crushed gravel, limestone, and sand aggregates were sampled from a local paving contractor's stockpiles and used along with the aforementioned PG 67-22 binder to produce virgin control mixtures.

The materials described above were used to produce the 31 mixtures presented in Table 1 (i.e., ID 1 to 31). Laboratory mixing occurred at temperature T_{mix}, and specimens had virgin (i.e., PG 67-22 with or without additives) and total (i.e., Fig. 1 RAP plus PG 67-22) asphalt contents shown. The AC type for each mix indicates whether the PG 67-22 was used neat, with Sasobit®, or with Evotherm 3G™.

Mixture 1 (ID's of 1a and 1b) were conventional laboratory mixed HMA made using the neat PG 67-22 binder and virgin aggregates mentioned previously. Mixture 1 was a control developed with an aggregate gradation similar to or in between the RAP mixture gradations, which could have resulted in somewhat stiffer than normal HMA due to its high dust to effective binder ratio of 1.7. The HMA control had 42% passing the 2.36 mm sieve, and

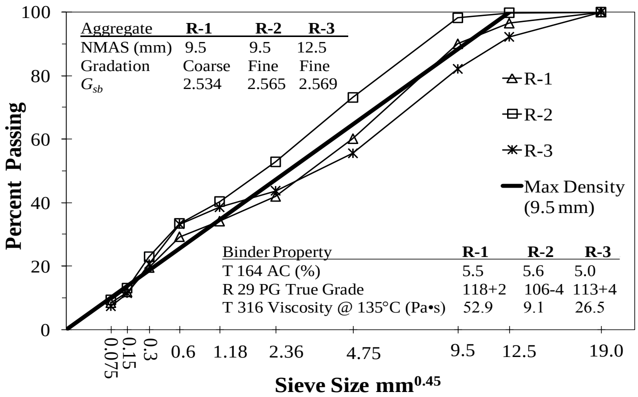


Fig. 1. Properties of RAP Sources Tested.

7.8% passing the 0.075 mm sieve. The gradation consisted of 67% crushed gravel, 22% limestone, 10% sand, and 1% hydrated lime.

Mixtures 2 through 31 were 100% RAP mixed with virgin binder. Mixtures 2 through 25 in Table 1 had relatively high amounts of added virgin binder and total asphalt content greater than 8%. Additional mixtures with the R-3 RAP source (ID's of 26 to 31) were produced with lower amounts of virgin binder (as low as 0.5%) and total asphalt contents as low as 5.5%.

Table 1. Materials and Testing Program.

ID	RAP	T_{mix} °C	$N_{Gyr.}$	T_s kPa	Total %AC	Virgin %AC	AC Type	V_a %	RC n_{RC}	APA n_{APA}
1a	0%	154	65	68	5.7	5.7	A	4.1	9	---
1b	0%	154	65	136	5.7	5.7	A	4.1	9	---
2	100%	116	50	272	8.1	2.8	A	2.5	3	1
3	R-1						B	2.4	9	1
4							C	2.1	9	1
5	100%	116	65	272	8.1	2.8	A	1.6	3	1
6	R-1						B	1.7	9	1
7							C	1.9	3	1
8	100%	116	85	272	8.1	2.8	A	1.2	3	1
9	R-1						B	1.2	3	1
10							C	1.3	9	1
11	100%	138	50	272	8.1	2.8	A	1.0	9	1
12	R-1						B	1.2	3	1
13							C	0.7	9	1
14	100%	138	65	272	8.1	2.8	A	1.0	3	1
15	R-1						B	0.6	3	1
16							C	0.7	3	1
17	100%	138	85	272	8.1	2.8	A	0.6	3	1
18	R-1						B	0.3	3	1
19							C	0.5	3	1
20	100%	138	65	272	8.2	2.7	A	1.6	3	---
21	R-2						B	1.9	3	---
22							C	1.6	3	---
23	100%	138	65	272	7.4	2.5	A	2.2	3	---
24	R-3						B	2.2	3	---
25							C	2.2	3	---
26	100%	138	65	544	6.4	1.5	A	3.5	3	---
27	R-3						B	3.1	3	---
28							C	3.3	3	---
29	100%	138	65	544	5.5	0.5	A	6.1	3	---
30	R-3						B	6.0	3	---
31							C	5.9	3	---

A = PG 67-22-Source 1.

B = PG 67-22-Source 1 with 1% Sasobit® by total AC.

C = PG 67-22-Source 1 with 0.5% Evotherm 3G™ by total AC.

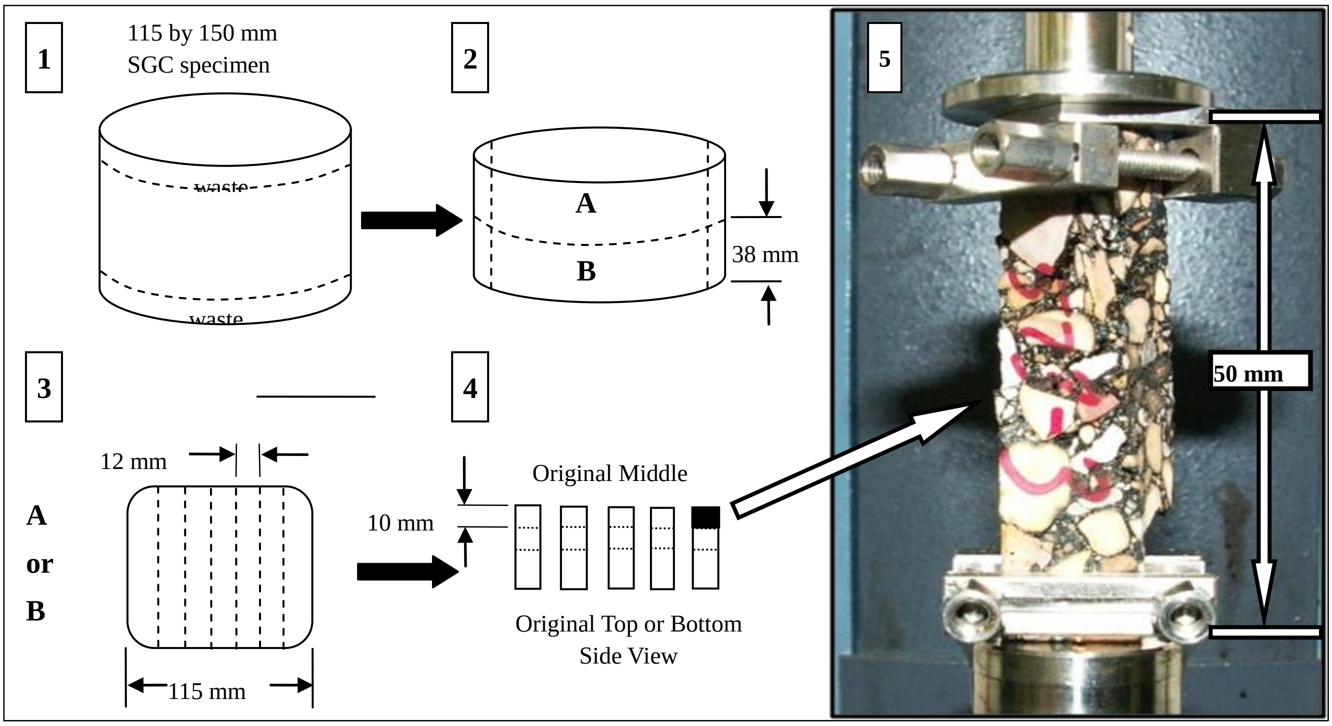


Fig. 2. Schematic of RC Torsion Bar Specimen Preparation Method (Not to Scale).

Specimen Preparation

All mixture specimens were compacted in the Superpave Gyratory Compactor (SGC) using the number of gyrations ($N_{Gyr.}$) shown in Table 1. The air voids (V_a) resulting from gyratory compaction are also shown in Table 1. Air voids were for many of the 100% RAP mixtures very low (less than 1%). Asphalt Pavement Analyzer (APA) testing made direct use of SGC specimens, while Repeated Creep (RC) testing required specimens be sawn to testing dimensions.

RC testing was performed on nominal 10 mm by 12 mm by 50 mm bars prepared from gyratory compacted material. Each compacted specimen was sawn into rectangular blocks then sliced into individual bars from the center only, to obtain consistent air voids. Fig. 2 is a schematic of the specimen preparation method for torsion bars for RC testing.

Test Methods

The APA testing was performed with a test temperature of 64°C, a wheel load of 445 N, and a 690 kPa hose pressure according to AASHTO TP 63. The wheel load and hose pressure were verified once per day and adjusted if necessary. Specimens were preconditioned at the test temperature for a minimum of six hours but not more than twenty-four hours prior to testing. One compacted specimen was considered one test, and the number of replicate tests (n_{APA}) was equal to 1 for all mixes evaluated with the APA (Table 1). The APA tests two compacted specimens in one slot, and typically the average of two specimens is considered one test. In this study, the individual readings from the APA were separated to determine the rut depth of each specimen; readings were verified by manual measurement. Since rut depths were very low as seen later in the paper, this approach was deemed reasonable.

The RC test was performed with a dynamic shear rheometer (DSR) that had been modified to perform the mixture test. The loading sequence consisted of repeated cycles of 1 second of loading followed by 9 seconds of recovery. The DSR control software computed the appropriate force required to produce a desired torsional stress level based on the measured dimensions (not the nominal dimensions) of the test specimen; the control software then recorded the strain history experienced by the specimen during testing.

The stress level used during the test (T_s) was dependent on the mixture properties (Table 1). Values of T_s were selected to produce specimen failure within a reasonable amount of total test time (generally 100 to 990 cycles). The loading sequence was repeated until failure occurred. The effective specimen length during testing is the distance between the two mounting points, which is typically on the order of 37 mm.

ASTM D7552-09 typically tests materials at the high PG grade temperature representative of the climate region as determined by LTPP-BIND v3.1. The same approach was utilized for the testing described herein. The RC test temperature was 64°C.

One torsion bar tested in the DSR was one test. The number of replicate bars tested for each mixture (n_{RC}) is shown in Table 1. Either 3 replicates or 9 replicates were tested for each mixture ID, depending on the desired analysis to be performed.

Test Results and Data Analysis

Table 2 summarizes all test data. A total of 144 RC torsion bars and 18 APA specimens were tested. Average (Avg) and coefficient of variation (COV) values are given for all RC response variables, alongside the result of the single APA test.

Table 2. RC and APA Test Results.

	$\varepsilon(5\%)_T$		$(\Delta\varepsilon/\Delta T)^{-1}$		TFF		F_ε		APA Rut (mm)
ID	Avg	COV	Avg	COV	Avg	COV	Avg	COV	Result
1a	874	24.2	293	29.7	222	31.2	9.8	7.5	---
1b	291	34.4	82	34.7	57	37.8	8.7	20.6	---
2	203	49.8	56	65.0	27	79.0	5.8	20.9	1.5
3	230	56.9	100	42.7	83	37.2	12.0	22.3	1.3
4	304	33.1	164	52.3	154	58.3	12.9	23.2	1.7
5	253	9.9	115	38.1	84	36.5	10.4	15.1	1.2
6	318	47.5	191	58.9	223	61.9	16.0	11.6	1.3
7	304	33.1	164	52.3	154	58.3	12.9	23.2	1.3
8	237	6.5	142	32.1	147	53.8	14.6	28.7	1.4
9	270	26.7	107	48.2	91	36.5	11.6	13.3	1.2
10	240	49.3	169	66.7	174	81.6	14.8	29.5	1.6
11	283	68.7	226	57.2	262	86.0	16.7	23.3	0.8
12	1130	24.4	740	76.8	990	0.0	15.0	7.1	0.9
13	509	52.2	397	70.3	451	72.9	16.1	27.4	1.3
14	437	41.2	230	33.8	267	20.4	15.9	18.5	1.1
15	417	13.2	182	39.6	208	36.3	14.8	8.5	1.5
16	433	47.5	264	64.1	270	72.9	14.4	21.3	1.0
17	640	79.0	410	71.5	473	63.0	16.0	17.9	1.2
18	643	32.0	384	25.6	426	8.6	15.7	19.8	1.4
19	503	33.9	270	16.0	274	19.8	14.2	12.8	0.7
20	33.3	17.3	69	40.4	101	47.5	26.5	9.3	---
21	30.0	0.0	69	31.3	131	46.8	30.6	20.2	---
22	33.3	17.3	79	32.1	158	29.7	32.7	4.2	---
23	213	35.2	193	23.4	297	30.1	22.3	11.7	---
24	177	21.4	186	23.7	343	24.8	26.6	8.1	---
25	170	17.6	258	23.4	544	21.5	30.8	9.5	---
26	343	14.7	108	17.1	85	26.0	10.0	19.3	---
27	327	18.7	94	7.1	66	11.4	8.8	13.6	---
28	283	19.4	98	26.2	80	30.5	10.5	8.3	---
29	793	16.0	193	25.6	100	52.8	5.8	29.9	---
30	1307	24.7	324	24.3	178	24.0	6.6	1.5	---
31	2227	9.4	540	10.6	223	23.7	5.0	16.0	---

Note: For mixture ID 1a, one outlier was identified and omitted from analysis.

Data Analysis Methods

Results for each torsion bar were summarized in the form of a creep test failure curve, divided into three sequential regions (Fig. 3). Primary flow is the region where the strain rate decreases with loading time. The secondary flow region is where the strain rate becomes constant with loading time. The tertiary flow region occurs after the failure point and is differentiated from the secondary flow region in that the strain rate increases with time instead of remaining constant. Throughout the tertiary flow region the specimen starts to fail quickly and experience large permanent deformations.

Four response variables were utilized to describe the behavior of tested RC specimens. They were: 1) time to 5% cumulative strain (denoted $\varepsilon(5\%)_T$); 2) inverse of slope in the secondary flow region (expressed as an inverse for convenience and denoted $(\Delta\varepsilon/\Delta T)^{-1}$); 3) tertiary flow failure (number of cycles to tertiary failure denoted TFF); and 4) cumulative strain at failure (denoted F_ε).

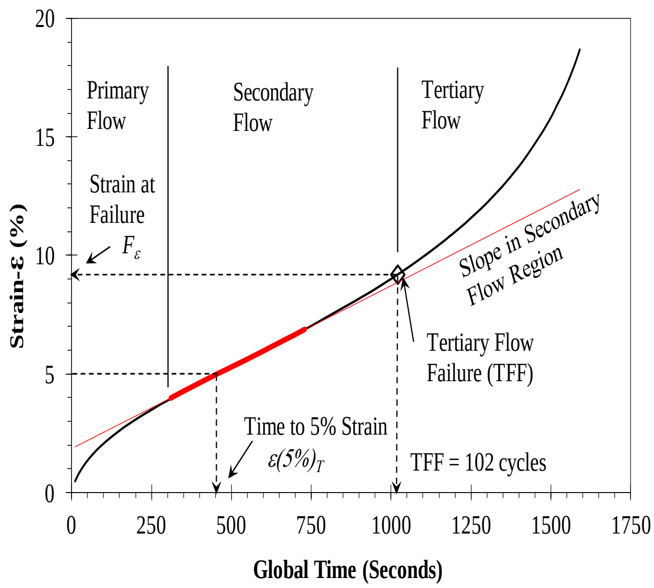


Fig. 3. Example RC Test Data and Associated Terminology.

Component 1 Results: RC Test Variability

Torsion Bar Production and Repeatability

Specimens with lower amounts of virgin binder could not be sawn and tested in some cases due to excessive brittleness resulting in specimens that broke into multiple pieces. Sawing was often the problem, and an example problematic case was R-1 RAP (highest PG grade) with 0.5% added virgin binder. Inability to fabricate specimens over a range of properties of interest was a drawback of this approach for 100% RAP. Dimensions of specimens that could be produced are discussed in the following paragraph.

Specimen dimensions were evaluated with respect to ASTM D7552-09, which requires dimensional tolerances of 12 ± 2 mm and 9 ± 1.5 mm measured with a caliper to the nearest 0.01 mm. The eighteen control specimens (IDs 1a and 1b) had a mean thickness of 9.77 mm (2.9% COV) and a mean width of 12.42 mm (2.3% COV). Fifty-four 100% RAP specimens (nine replicates each of IDs 3, 4, 6, 10, 11 and 12) had a mean thickness of 9.87 mm (3.1% COV) and a mean width of 11.88 mm (7.3% COV). The 95% confidence intervals for all 100% RAP and control specimens were within the D7552-09 tolerances. For 100% RAP and virgin binder combinations that did not break into multiple pieces during sawing, specimen preparation with 100% RAP mixed with virgin binder was feasible, could be performed consistently, and had reasonably low variability.

RC Test Outputs

Variability of the RC test was initially assessed by plotting all data for the no RAP control mixtures (IDs 1a and 1b) in Fig. 4. As expected, specimens tested at the higher stress level (136 kPa) failed quicker than those tested at the 68 kPa stress level. The Fig. 4 horizontal lines indicate the range of failure strains (F_ε) for specimens tested at each stress level. Average failure strains for specimens tested at both stress levels were similar. Interestingly, failure strains for specimens tested at the lower 68 kPa stress level fell within a narrower range than those for specimens tested at 136 kPa. For no RAP control mixtures, COV values for all four response variables are lower for the 68 kPa stress level specimens than for the 136 kPa stress level specimens (Table 2). Failure strain was the least variable RC test output for the control mixtures.

Failure strain was also the RC test output for the 100% RAP mixtures with lowest variability in terms of COV values. Averaging the COV values for mixes 2 to 31 results in a value of 17% for failure strain (F_ε) and values ranging from 31 to 42% for the other response variables. Failure strain COV values for 100% RAP were generally comparable to the HMA controls; 17% is within the two COV values measured on the control specimens (Table 2). The highest failure strain COV for a 100% RAP mix was 29.9%, and 11 of the 30 100% RAP mixes had COV values in the 20 to 30% range. The highest failure strain COV for a no RAP control mixture was 20.6%, so two-thirds of the 100% RAP specimens were below the upper bound COV value of the control mixture. The lowest failure strain COV for a no RAP control mixture was 7.5%, so one-tenth of the 100% RAP specimens were below the lower bound COV value of the control mixture.

Using all the no RAP mixture data, a Pearson correlation analysis between the four response variables was performed (Table 3).

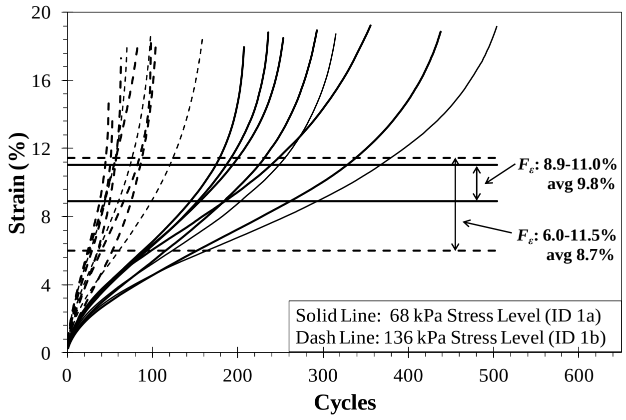


Fig. 4. Variability Assessment of RC Test Data (Mix IDs 1a and 1b).

Table 3. Correlations Between Response Variables (Mix ID 1).

	$\varepsilon(5\%)_T$	$(\Delta\varepsilon/\Delta T)^{-1}$	TFF	F_ε
$\varepsilon(5\%)_T$	0			
	0			
$(\Delta\varepsilon/\Delta T)^{-1}$	0.971	0		
	< 0.001	0		
TFF	0.960	0.993	0	
	< 0.001	< 0.001	0	
F_ε	0.298	0.404	0.485	0
	0.245	0.107	0.049	0

Note: Top number in each cell is the Pearsoncorrelation coefficient and bottom number is the p-value.

High correlations are indicated between the $\varepsilon(5\%)_T$, $(\Delta\varepsilon/\Delta T)^{-1}$, and TFF variables. However, the F_ε variable is not strongly correlated with the other response variables. One-way analyses of variance (ANOVAs) were performed for each variable to investigate their relationships to test stress level; results are not shown for brevity. At a 5% significance level ($\alpha = 0.05$), the $\varepsilon(5\%)_T$, $(\Delta\varepsilon/\Delta T)^{-1}$, and TFF variables were all dependent on stress level (p-values <0.001). However the relationship between the F_ε variable and stress level was not significant at the 5% significance level (p-value = 0.122). Overall, the F_ε response variable is considered most appropriate for use in further analysis of 100% RAP RC test data due to lower variability, lower correlation with other variables, and relatively low sensitivity to test stress level.

Component 2 Results: Sensitivity Investigation for 100% RAP

Sensitivity to Preparation and Compaction Conditions

An ANOVA was performed to assess sensitivity of the response variable F_ε to preparation and compaction conditions using the data for mixture IDs 2 to 19, which are 100% RAP with relatively high virgin binder quantities. For mixture IDs with nine replicates, only the first three replicates were used for this analysis to provide a consistent replication level. Factors of RAP source, asphalt content and T_s were held constant for this dataset. Based on the 100% RAP compaction study results of Doyle et al. [7], the factors of gyration level and AC type will both affect compaction and final specimen volumetric properties; the effects of these factors are captured by changes in specimen air void levels. Therefore, the factorial design investigated the factor of preparation temperature (T_{mix}) at two fixed levels (116 and 138℃) while V_a was treated as a covariate.

ANOVA results (Table 4) indicate the effect of specimen compaction on F_ε results was significant. On the other hand, mixture preparation temperature did not significantly affect F_ε results. The overall assessment based on this data is that the RC test is sensitive to differences in specimen volumetric properties due to compaction, but that it was unable to capture any potential differences in mechanical response due to differences in blending between RAP and virgin binder at different T_{mix} values.

Sensitivity to Aged Binder Properties and Gradation

An ANOVA was performed using the data for mixture IDs 14 to 16 and 20 to 25 to assess the effect of RAP source (i.e., aged binder properties and gradation) on F_ε. Factors of N_{Gyr}, T_{mix} and T_s were held constant for this data subset; asphalt contents varied slightly due to the different RAP sources but the relative proportions of RAP binder and virgin binder were similar for each mixture.

The factorial design considered the factor of RAP source, while V_a was treated as a covariate to represent changes in compaction. To represent variation between RAP sources as a factor in the ANOVA, the base 10 logarithm of recovered binder high PG temperatures for each RAP source were used as the factor levels; e.g., Log_{10} (118), Log_{10} (106) and Log_{10} (113) were used to represent R-1, R-2 and R-3, respectively. This is consistent with common binder characterization philosophies.

ANOVA results (Table 5) indicate that for this data subset, RAP source was a significant factor. Specimen air voids was not a significant factor. A main effects plot for RAP source (Fig. 5) indicates a large difference in F_ε for the R-1 RAP source relative to R-2 and R-3, which have similar failure strains. These results indicate that stiffer binder properties correspond to lower failure strains.

Sensitivity to Virgin Asphalt Content

Three levels of virgin binder were investigated that results in compacted specimens that bracketed 4% air voids. Virgin binder contents were as low as 0.5% and as high as 2.8%. The data in Table 1 for mixtures 2 through 25 are for the highest amount of virgin binder added and always resulted in specimens with less than 4% air voids. As discussed earlier in this paper, specimens with lower amounts of virgin binder could not be sawn and tested in some cases due to excessive brittleness. RAP source R-3 was successfully sawn and tested at three virgin asphalt contents, and as a result the effect of virgin binder content was assessed solely using R-3.

A 272 kPa stress level was required to obtain meaningful responses from mixes 23 to 25 (high virgin binder content), while a 544 kPa stress level was required for mixes 26 to 31 (low and intermediate virgin binder contents). These stress levels are higher than typically used for asphalt mixtures (e.g., [11] used a 34 kPa stress level and the control mixes in this paper used 68 and 136 kPa stress levels). Recall that F_ε did not appear to be particularly sensitive to stress level based on investigation reported earlier in this paper. As a result, an ANOVA was performed for mixtures 23 to 31 neglecting stress level (T_s) differences to assess the effect of changes in virgin asphalt content on F_ε. Virgin binder content was considered as a factor while V_a was treated as a covariate; other factors were held constant.

ANOVA results (Table 6) indicate that effect of virgin binder content was significant at the 5% level. Specimen air voids were not a significant factor. Based on the results from this partial data subset, the effect of virgin binder content was distinguished from the other sources of variance.

Table 4. ANOVA Results for Mix IDs 2 to 19.

Source	df	SS	Adj. SS	Adj. MS	p-value	Sig?
V_a	1	250	45.1	45.1	0.032	Yes
T_{mix}	1	10.9	10.9	10.9	0.285	No
Error	45	476	476			
Total	53	737				

Note: Significance testing performed at 95% level (α = 0.05).

Table 5. ANOVA Results for Mix IDs 14 to 16 and 20 to 25.

Source	Df	SS	Adj. SS	Adj. MS	p-value	Sig?
V_a	1	690	5.98	5.98	0.584	No
RAP ($\log_{10}$PG)	2	380	380	190	0.001	Yes
Error	23	447	447	19.4		
Total	26	1517				

Note: Significance testing performed at 95% level (α = 0.05).

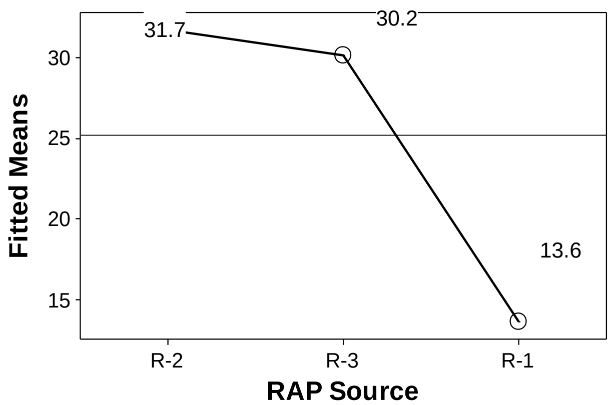
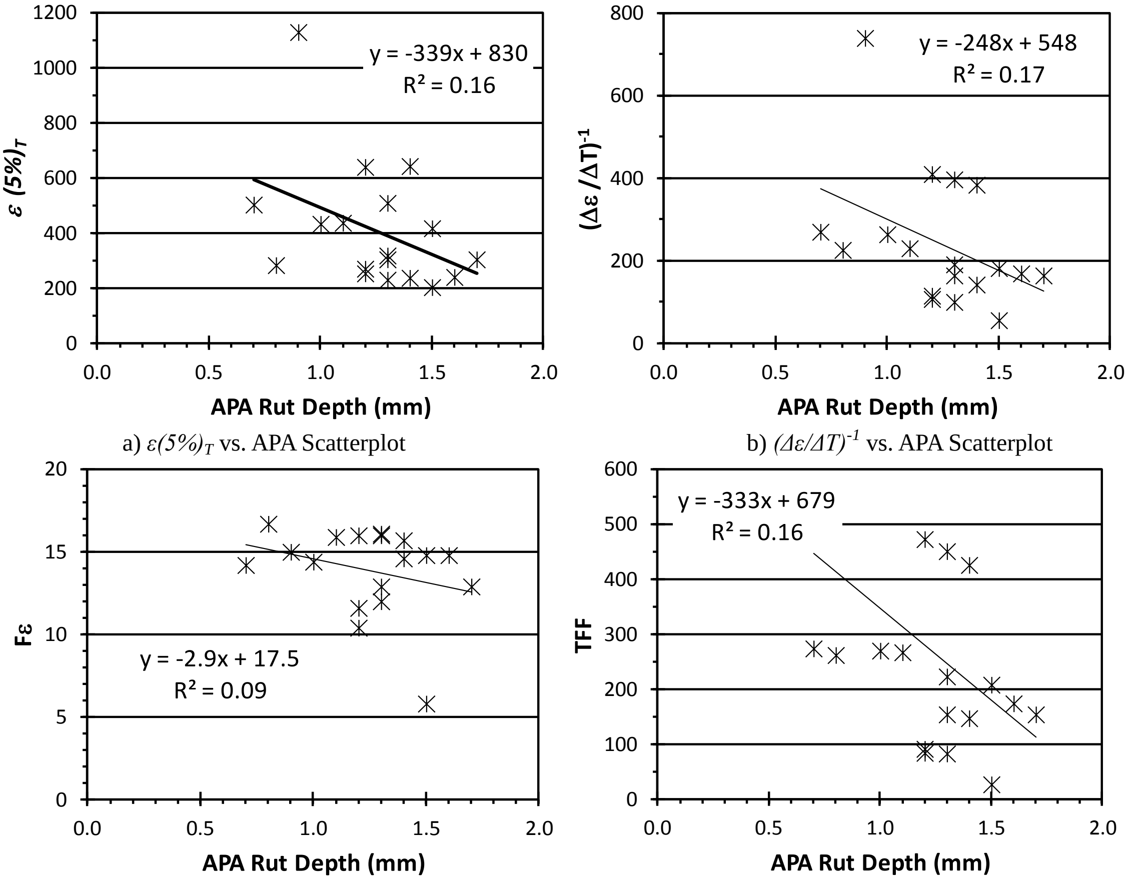


Fig. 5. Main Effects Plot for F_ε by RAP Source (Mix IDs 14 to 16 and 20 to 25).

Table 6. ANOVA Results for Mix IDs 23 to 31.

Source	df	SS	Adj. SS	Adj. MS	p-value	Sig?
V_a	1	1686	3.23	3.23	0.563	No
Virgin %AC	2	795	795	397	<0.001	Yes
Error	23	216	216	9.37		
Total	26	2696				

Note: Significance testing performed at 95% level (α = 0.05).
Note: Effect of stress level (T_s) was neglected.



a) $\varepsilon(5\%)_T$ vs. APA Scatterplot

b) $(\Delta\varepsilon/\Delta T)^{-1}$ vs. APA Scatterplot

c) F_ε vs.APA Scatterplot

d) TFF vs. APA Scatterplot

Fig. 6. Comparison of RC and APA Test Parameters for 100% R-1 RAP Mixes.

Component 3 Results: Comparison of APA and RC Measured Parameters

Fig. 6 plots all RC determined parameters versus APA rut depths. Rut depths were very low (< 2 mm), which was expected for 100% RAP mixes. None of the RC measured parameters correlated to rut depths. Failure strain values were fairly tightly grouped, while the other three RC measured parameters varied a noticeable amount (APA rut depths did not).

Summary and Conclusions

Performing the RC test with the DSR requires a fairly expensive equipment set-up, with key items being the compaction equipment, saw of adequate precision, and the DSR with appropriate fixtures. Nearly all asphalt laboratories have compaction equipment, while a smaller number would have an adequate saw or a DSR with appropriate fixtures. There is a noticeable amount of labor and equipment time involved in preparing the needed torsion bars and subsequently testing them in the DSR. Total DSR equipment time is from 45 to 195 minutes per torsion bar when pre-conditioning times are considered. The amount of labor, equipment types, and equipment time were considered when making the following conclusions.

This paper had a primary objective of determining if the RC test is capable of detecting the interaction of aged RAP binder and virgin binder. The result of the investigation is that the test method does not appear optimal for this purpose when both test results and investment required to obtain the test results are considered. The paper had a secondary objective of determining if any of the RC test outputs correlated to rutting of 100% RAP. None of the RC measured parameters correlated to APA measured rut depths for 100% RAP mixed with virgin binder when the APA test was conducted with typical settings. Specific conclusions from the research effort are as follows:

- 100% RAP specimens with lower amounts of virgin binder could not be sawn and tested in some cases due to excessive brittleness. When specimens did not break, adequately dimensioned specimens could be produced consistently. Generally speaking, specimens required relatively high virgin asphalt contents resulting in low air voids to facilitate sawing and testing in absence of excessive brittleness.
- Average failure strains of the HMA control specimens were similar when tested at two stress levels. Failure strain had the lowest COV of the four RC test variables investigated for the HMA controls and also for 100% RAP. Overall, failure strain (F_ε) was considered the most appropriate RC test output for analyzing 100% RAP due to lower variability, lower correlation with other variables, and relatively low sensitivity to stress level. Stress levels must be varied to test 100% RAP from different sources and with different amounts of virgin binder.

- Using F_{ε} as the response variable, results of 100% RAP testing presented in this paper revealed the RC test is: a) unable to capture any potential differences in mechanical response due to differences in specimen mixing temperature; b) able to detect RAP source when represented by a base 10 logarithm of recovered binder high PG temperatures; and c) able to detect virgin asphalt content based on a partial data set where stress level changes during testing were not considered.

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