

Recommendations for Seal Treatment Rejuvenation Specifications Based on Bending Beam Rheometer Testing of Mixture Beams

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Recently, use of pavement preservation technologies, such as bituminous seal treatments, has increased. Seal treatments are often used to rejuvenate aged asphalt pavements and can decrease permeability and retard oxidation, cracking, and raveling. Many factors affect rejuvenation, and current specifications governing how rejuvenation is characterized could be enhanced. Viscosity testing of asphalt binder extracted and recovered from a pavement's near surface is the predominant means of characterizing rejuvenation (e.g., a product must reduce viscosity by 40% to be classified as a rejuvenator). This paper presents data that suggest other rejuvenation approaches are worth considering because (a) extraction and recovery can adversely affect viscosity results, (b) viscosity testing cannot be conducted without forced and unrealistic blending of aged binder and rejuvenator, (c) high test temperatures may not be the most informative for distresses of interest (e.g., cracking), and (d) viscosity could not detect rejuvenation behaviors of some proprietary products. Alternatively, this paper suggests rejuvenation specifications be developed with bending beam rheometer (BBR) testing of mixture beams sawn from laboratory-compacted asphalt surfaces (e.g., a product must increase the *m*-value by 0.040 to be classified as a rejuvenator). This approach has shown promise for viscosity testing, and many concerns about viscosity testing are alleviated with BBR testing. A specification approach that uses BBR testing of laboratory-compacted asphalt is described and recommended for rejuvenation characterization.

As agency budgets are increasingly allocated to pavement preservation, engineers should evaluate preservation-related specifications, some of which likely could benefit from enhancement. Many existing specifications have remained largely unchanged since their inception, which often would have been before pavement preservation became a major focus. When preservation items were of less concern, preservation projects were likely fewer; therefore, financial losses associated with less than optimal specifications would be smaller relative to an agency's total budget. Overall budget consequences could become more severe because preservation techniques are being used more. As an integral component of pres-

ervation strategies, bituminous seal treatments are one such area for which specification enhancements would be beneficial.

Seal treatments that employ emulsions or other products are often used to rejuvenate asphalt binder in aged pavements by restoring maltene fractions. Although benefits can be numerous (e.g., decreased permeability; retarded oxidation, cracking, and raveling), rejuvenation is dependent on many factors, such as penetration depth and chemical and physical properties. Existing specifications may not appropriately consider these factors and therefore may not consistently provide comprehensive assessment of rejuvenation.

Traditionally, rejuvenation has most commonly been characterized by viscosity testing of asphalt binder extracted and recovered from the pavement's near surface (1–6; U.S. Army Corps of Engineers CEGS-02599, UFHS-32 01 22). For example, a specification may require that a rejuvenator be able to reduce viscosity by 40%. Although viscosity reduction appears to be the most widely used approach to rejuvenation characterization, potential concerns should not be overlooked. For example, variability within asphalt extraction and recovery processes increases uncertainty in results (7); binder softening or hardening during extraction and recovery can affect viscosity (8–11); extraction and recovery leads to forced blending of aged binder and rejuvenator, which is not representative of field conditions; and high testing temperatures may not provide the best information about distresses of interest in aged pavements (e.g., cracking). These factors, coupled with viscosity research presented in this paper, indicate alternative measurement approaches are worth considering.

This paper's first objective is to present an alternative to viscosity that showed promise during companion research and to evaluate this alternative against rotational viscosity testing. A second objective is to provide performance-related specification guidance. This alternative method involves bending beam rheometer (BBR) testing of emulsion-treated asphalt mixture beams sawn from the surface of field-aged pavements or laboratory-compacted specimens. Beams can be sawn and tested with manageable variability, effort comparable to that of viscosity testing, and reasonable success rates, and, using the *m*-value, BBR testing can detect emulsion rejuvenating effects as well as distinguish desirable from undesirable emulsion behavior (12–14).

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LITERATURE REVIEW

Viscosity Testing

Viscosity and penetration testing have been used to evaluate rejuvenation. Viscosity testing is more heavily documented and generally

is reported to be a more consistent and fundamental rejuvenation indicator than penetration (1, 2). Therefore, the focus of this discussion is viscosity, which can refer to kinematic (AASHTO T201), vacuum capillary (AASHTO T202), or rotational (AASHTO T316) viscosity, all of which are documented in the literature.

Sample preparation methods in the literature are similar. Generally, thin slices (e.g., 6.3 or 9.5 mm) are trimmed from field-aged core surfaces. Slices are dried and broken into pieces, and then the binder is extracted, recovered, and tested.

Early studies investigated aged pavement viscosity (untreated) as a function of depth (3, 4). Simpson et al. tested 32-month and 35-month field cores (3, p. 52), and Coons and Wright tested field cores from 1 to 13 years old (4). Viscosity was largely unaffected by long-term aging 12.5 mm from the pavement surface or deeper. Most viscosity increase occurred in the upper 6.3 mm (3). Coons and Wright found that viscosity within the upper 6.3 mm was approximately 50% greater than viscosity between 9.5 and 15.9 mm (4). For treated pavements, Glover et al. determined fog seal penetration depth was approximately 6.3 mm, indicating rejuvenation investigations should focus on this layer (15).

Brown and Johnson evaluated five rejuvenators at three airfields (application rates from 0.23 to 0.69 L/m²) (1). The upper 9.5 mm was removed from cores cut before treatment and approximately 1, 6, 12, 24, and 36 months after treatment. Viscosity reduction [$V_{D(\%)}$] was calculated with Equation 1. At 1 month, three materials effectively softened the aged pavement [$V_{D(\%)}$ ranging from 16% to 83%]. Rejuvenation effects decreased over time [1% to 40% $V_{D(\%)}$ at 36 months]. Shoenberger evaluated 11 rejuvenators at two airfields (application rates from 0.23 to 0.91 L/m²) (2). The upper 9.5 mm was removed from cores cut before treatment and 1 and 12 months after treatment. $V_{D(\%)}$ at 1 month ranged from 18% to 76%. Again, rejuvenation effects generally decreased with time. Sholar et al. treated an in-service Interstate shoulder with a coal tar product (0.23 L/m²) and performed posttreatment viscosity testing at approximately 1 month (5). No $V_{D(\%)}$ was observed in tests of the upper 12.5 or 19 mm.

$$V_{D(\%)} = \frac{V_U - V_T}{V_U} \times 100 \quad (1)$$

where V_U is untreated viscosity and V_T is treated viscosity.

On the basis of Brown and Johnson (1), the U.S. Army Corps of Engineers rejuvenation specification requires 40% $V_{D(\%)}$ in the pavement's upper 9.5 mm to classify as rejuvenation (U.S. Army Corps of Engineers CEGS 02599, UFGS-32 01 22). Other specifications require only a certain application rate (2, 6). Because rejuvenators differ in performance and an emulsion's performance can vary with climate and pavement conditions, fixed application rates cannot ensure desired performance; therefore, performance specifications are preferred (2, 6).

Asphalt Extraction and Recovery

Extraction and recovery are essential in $V_{D(\%)}$ determination and should be considered as they can affect results and may introduce variability. Cipione et al. cited nationwide extraction coefficients of variation (CVs) of 25% as recently as 1989 (7). Many solvents do not completely remove strongly adsorbed asphalt from aggregates (7, 8). This material, however, could be deemed inactive and

of little concern because rejuvenation is likely to affect only active, or effective, binder.

Of greater concern are the binder hardening effects with solvent contact and the softening effects produced by postrecovery solvent residuals (8–11). Hardening and softening effects can cause up to 15% viscosity increase and 50% viscosity decrease (9). Although this can be minimized by proper practices, extraction and recovery effects on viscosity should be considered in evaluations of viscosity's relative merits.

BBR Testing

Testing asphalt mixture beams with BBR instead of asphalt binder beams is a relatively recent development (16–20). To control variability, beams are often sawn from the center of gyratory-compacted specimens (16–20). Zofka et al. tested three replicates of multiple asphalt mixtures at various test conditions (16). CV values ranged from 4% to 19%, which was considered acceptable for low-temperature mixture testing. Marasteanu et al. found that neither the BBR cooling bath medium nor moderate variations in air voids significantly affected BBR results (i.e., stiffness and m -value) (19).

For normal mixtures, BBR beam width and thickness dimensions can be less than the mixture's nominal maximum aggregate size (NMAS), which violates the concept of relative volume elements. However, this concept is largely irrelevant at low temperatures (17, 21). As temperatures decrease, binder stiffness increases such that the difference between binder and aggregate stiffness is much less significant; therefore, aggregate size and distribution have less effect on bulk mixture properties. Velasquez et al. confirmed this theory by testing mixture beams that were one, two, and three times the size of standard BBR beams (18). Although it considerably advanced test practices for BBR mixture beams, research discussed in this section did not evaluate surface-sawn beam testing, which is needed for rejuvenation characterization.

Companion Research

Companion research investigated the feasibility of using the BBR within rejuvenation specifications. Braham et al. investigated the feasibility of sawing and testing BBR mixture beams from a specimen's surface (more than 1,000 were attempted) and the ability of the BBR to detect emulsion rejuvenating effects (only one emulsion was tested) (12). Procedures were successfully developed for quickly and uniformly fabricating beams from surfaces of both laboratory-compacted specimens and field-aged pavements. Average CV values were 0.6% to 1.1% for within-beam width and 2.2% to 2.8% for within-beam thickness. Beams were successfully sawn and tested at an average rate of 9 of 10 for laboratory-compacted specimens and 5 of 10 for field-aged cores. For all pavements tested, treatment with emulsion was detected by BBR in that stiffness decreased and m -value increased, suggesting rejuvenation.

Braham et al. furthered that work by evaluating seven emulsions used statewide in Mississippi (identical to those presented in this paper) (13). The objective was to determine whether BBR could discriminate between emulsions of varying rejuvenation potential based on either percent decrease in stiffness [$S_{D(\%)}$, calculated similarly to $V_{D(\%)}$ in Equation 1] or increase in m -value (Δm -value, calculated with Equation 2).

$$\Delta m\text{-value} = m\text{-value}_T - m\text{-value}_U \quad (2)$$

where $m\text{-value}_U$ is untreated $m\text{-value}$ (i.e., $m\text{-value}$ without emulsion) and $m\text{-value}_T$ is treated $m\text{-value}$ (i.e., $m\text{-value}$ with 0.91 to 1.81 L/m² emulsion). Application rates investigated were 0.91, 1.36, and 1.81 L/m² (0.2, 0.3, and 0.4 gal/yd²).

Statistical analyses were performed with analysis of variance tests with factorial arrangements of treatments and multiple comparison t -grouping procedures. This technique is described by Howard et al. (14); it allows all factors (emulsion, application rate, and BBR test time) to be considered simultaneously and then ranked according to rejuvenation potential. A summary of key findings is presented in this paper.

Evaluating emulsions according to $\Delta m\text{-value}$ was recommended over $S_{D(\%)}$ because $S_{D(\%)}$ results were erratic and inconclusive. Generally, t -group emulsion rankings based on 60-s $\Delta m\text{-value}$ indicated that most, but not all, emulsions could provide a 0.060 $\Delta m\text{-value}$ or better at a 1.81 L/m² application rate (denoted R1.81) or 0.050 or better when all application rates were averaged. Increasing the application rate generally, but not necessarily statistically, increased $\Delta m\text{-value}$. R1.81 was recommended (alongside the $\Delta m\text{-value}$ at a 60-s test time) in specification use to give a product the greatest chance for rejuvenation.

Braham et al. established expectations for $\Delta m\text{-value}$ potential and general trends as well as provided several practical recommendations moving toward a performance-related specification (13). However, their work did not evaluate $\Delta m\text{-value}$ after some duration of aging, address minimum testing replication needed, or recommend an implementable method for approving materials as rejuvenators. This paper extends their findings (12, 13) and addresses these aspects.

MATERIALS TESTED AND TEST METHODS

Materials Tested

Seven emulsions (Table 1) were selected to represent available products for seal treatments in Mississippi as of January 2009. Multiple emulsion samples were needed for a project of this size; therefore, average properties are shown. AASHTO T59, T72, and T200 were performed on emulsion, and remaining tests were performed on emulsion residue. Emulsions are denoted by E (e.g., E3 is Emulsion 3).

Three asphalt pavements were tested (Table 2). Two field-aged pavements were tested: a frontage road adjacent to MS-25 in Starkville, Mississippi, and an abandoned portion of US-45 in Crawford, Mississippi. Field-aged pavements were selected because they had different functional classifications and permeabilities. Plant-mixed, laboratory-compacted asphalt was also tested. All cores and gyratory specimens tested were 150 mm in diameter.

Specimen Fabrication and Testing

Figure 1 illustrates key steps in emulsion treatment, BBR sawing and testing, and viscosity slicing and testing. These processes are summarized briefly here; full descriptions are provided elsewhere (14). To characterize rejuvenation effects, BBR and viscosity testing were performed with untreated and emulsion-treated mixtures. Fabrication and testing procedures for either BBR or viscosity testing were similar regardless of emulsion presence or absence.

Emulsion was applied to specimen surfaces at application rates of 0.91, 1.36, and 1.81 L/m² (0.2, 0.3, and 0.4 gal/yd²); mass was determined through specimen surface area (Figure 1a). After application,

TABLE 1 Average Properties of Tested Emulsions

Property	E1	E2	E3	E4	E5	E6	E7
Type	CRS-2	CRS-2P	PASS-CR	CHFRS-2P	CRS-2P	CRS-EE	CFS-2HP
Polymer	No	SBR	Yes	Latex	SBS	Yes	Yes
T200 pH	3.94	3.81	2.35	2.53	2.54	2.13	2.90
T72 SFS (s) ^a	283	207	98	101	126	172	155
T59 sieve (%)	0.01	0.02	0.02	0.02	0.00	0.04	0.01
T59 demulsibility (%)	93	78	46	72	60	101	89
T59 oil by volume (%)	0.17	0.09	0.63	0.25	0.05	0.27	0.37
T59 24-h storage (%)	0.07	0.11	0.52	1.27	-0.01	0.02	0.21
M208 residue (%) ^b	68.7	67.6	66.6	69.1	67.6	71.4	71.7
T49 penetration (dmm) ^c	130	116	232	111	137	77	70
T51 ductility (cm) ^d	102	81	59	120	148	107	79
T301 elastic recovery (%) ^e	6	63	60	53	67	66	64
T315 Unaged DSR (°C) ^f	59.3	67.0	59.5	75.3	66.2	77.2	78.8
T315 PAV-aged DSR (°C)	8.8	10.3	9.8	10.2	8.3	15.1	15.8
T313 PAV-aged S (°C) ^g	-36.5	-35.8	-36.9	-35.7	-39.2	-32.9	-31.7
T313 PAV-aged $m\text{-value}$ (°C)	-37.3	-33.7	-37.0	-32.4	-38.7	-32.5	-30.8

NOTE: E = emulsion; SBR = styrene-butadiene rubber; SBS = styrene-butadiene-styrene; dmm = decimillimeter.

^aAASHTO T72 SFS performed at 50°C.

^bAASHTO M208 was conducted with CRS-2 protocols because no polymer-latex-modified emulsion specification exists in M208. CRS-2 distillation was conducted at 260°C, and polymer-modified emulsions were distilled at 177°C.

^cAASHTO T49 penetration was performed at 25°C with 100-g mass and 5-s duration.

^dAASHTO T51 ductility was performed at 25°C.

^eAASHTO T301 elastic recovery at 10°C was performed on specimens elongated 20 cm and held 5 min.

^fAASHTO T315 unaged material was obtained via oven evaporation (110°C). PAV material was further aged with R28 (100°C). Critical failure temperatures (T_c) from the dynamic shear rheometer (DSR) are shown. No rolling thin film oven testing was performed on the recovered emulsions.

^gAASHTO T313 material was obtained in the same manner as T315 PAV-aged material. Values shown are critical failure temperatures (T_c) for BBR stiffness (S) and $m\text{-value}$ (m).

TABLE 2 Properties of Tested Asphalt Pavements

Property	Frontage Road	US-45	Plant Mix
Asphalt content (%)	5.8	6.8	6.0
PG grade	98-10	95-10	67-22 ^a
Viscosity, 135°C (Pa*s)	10.6 ^b	9.2 ^b	<3
<i>k</i> (10 ⁻⁵ cm/s)	66	<1	4
<i>G</i> _{mm}	2.380	2.382	2.358
<i>G</i> _{mb}	2.084 to 2.160	2.181 to 2.252	2.169 to 2.217
Air voids (%)	9.2 to 12.4	5.4 to 8.4	6.0 to 8.0
NMAS (mm)	9.5 ^c	9.5	9.5
Passing 4.75-mm sieve (%)	56	63	58
Passing 2.36-mm sieve (%)	39	42	36
Passing 0.075-mm sieve (%)	10.9 ^d	9.6	6.0

NOTE: A blend of 85% toluene and 15% ethanol was used for extraction; binder performance grade was performed with AASHTO M 320; rotational viscosity was performed according to AASHTO T 316; permeability (*k*) was measured with ASTM PS129-01; specific gravity—bulk (*G*_{mb}) and maximum theoretical (*G*_{mm})—was measured by T 331 and T 209, respectively; *G*_{mb} for frontage road and US-45 was measured on blocks taken from cores with surfaces sawed smooth; and gradation and NMAS were performed with C 117 and C 136.

^aProperties of supplied binder, not extracted and recovered properties.

^bViscosity of binder extracted from material within ~6.3 mm of pavement surface.

^cFrontage road variable could be defined as 9.5-mm or 12.5-mm NMAS because 99% passed the 12.5-mm sieve and 91% passed the 9.5-mm sieve.

^dPossible causes of high fines content: test variability, dust filling voids during service, and particle breakdown.

specimens were undisturbed at room temperature for 4 days, left until constant mass was achieved, and then left undisturbed 4 more days. Next, excess emulsion was removed from each specimen because this excess would likely serve some function other than rejuvenation (e.g., aggregate retention in a chip seal). Specimens were heated for 1 h in a 60°C oven, scraped with a putty knife, then sanded until at least 10 aggregates were visible. Oven heating was conducted to slightly soften emulsion for removal ease but was minimal to avoid aging. Heating, scraping, and sanding were not performed on untreated specimens.

Specimens exposed to room temperatures only were considered unconditioned. Comparison testing between BBR and viscosity (Objective 1) used unconditioned specimens. BBR testing oriented toward specification development (Objective 2) also included 7-, 30-, and 60-day laboratory conditioning (60°C oven) and nominal 90-day (May to August; 92 days) and 180-day (February to August; 182 days) outdoor field conditioning. Specimens conditioned outdoors were fully exposed to rain and sunlight. Specimens were conditioned before excess emulsion was removed; following conditioning, specimens were processed identically to unconditioned specimens.

For BBR testing (Figure 1*b*), beams nominally 7.7 by 12 by 115 mm were sawn from emulsion-treated specimen surfaces. Five dimension measurements made with calipers were averaged for width and thickness for use in calculations. Material availability and sawing and testing success rates generally yielded five to 10 replicates per mixture combination. Target replication was greater in some cases (e.g., untreated control sets); greater replication clarity is provided in the results section. Once fabricated, beams were tested (emulsion-treated surface facing upward and in compression to represent field conditions) at -12°C for 1,000 s with a constant 4.9 N load. In total, 691 successfully tested BBR beams are used in this paper.

For viscosity testing (Figure 1*c*), 6.3-mm slices were sawn from specimen surfaces, dried under fans, and heated 1 h in a 60°C oven to so they could be broken into pieces. Binder from multiple broken-up

slices was extracted and recovered in general accordance with AASHTO T319-08. Only two solvent washes (85% toluene and 15% ethanol blend) were used so that only nonabsorbed binder was extracted. Two centrifuges were used, the first to separate particles >0.075 mm and the second to separate particles <0.075 mm. Binder was recovered with rotary-vaporation equipment, ice-chilled water was circulated through condenser coils to facilitate condensation, and recovered binder was placed in a 165°C oven for 10 min to ensure full solvent removal. Following recovery, binder was poured into viscosity cups and tested at 135°C with an S27 spindle in accordance with T316-04. For each mixture combination tested, one replication was conducted, yielding 44 total viscosity tests.

RESULTS AND ANALYSIS

Comparison of BBR and Viscosity Results

Unconditioned US-45 and frontage road data are presented in this section (450 BBR and 44 viscosity tests). For 42 combinations of field-aged pavement, emulsion, and application rate, 321 BBR beams were tested (an average of seven replicates per combination). For untreated control sets, 64 and 65 replicates were tested for US-45 and frontage road, respectively. One replicate viscosity test was conducted for all 42 mixture combinations and both untreated controls.

Figure 2 presents US-45 and frontage road Δm -value and $V_{D(\%)}$ results. Δm -value and $V_{D(\%)}$ generally increase with application rate; however, this trend appears more defined for $V_{D(\%)}$. For Δm -value, emulsion and application rate appear to interact, but statistically they do not (13). Effects of application rate are likely more defined for $V_{D(\%)}$ because emulsion is forcefully blended with aged binder during extraction and recovery. Scraping and sanding are intended to remove excess emulsion but may not result in an equal amount of remaining surface emulsion for all specimens (i.e., within surface texture). $V_{D(\%)}$ may increase more with application rate because more surface emulsion is blended with the aged binder, not because of greater pavement



FIGURE 1 Specimen fabrication and testing procedures: (a) emulsion treatment procedures, (b) BBR beam sawing and testing, and (c) viscosity slicing and testing.

rejuvenation. In contrast, Δm -value responses appear mostly influenced by the asphalt mixture and emulsion properties; application rate has less influence.

According to statistical analyses used by Braham et al., E3, E5, and E6 generally provide the most desirable Δm -value response, and E1, E2, E4, and E7 generally provide the least desirable (13). $V_{D(\%)}$ and Δm -value largely agree with one exception: E6. When results are averaged across application rate, E6 ranks seventh and sixth for US-45 and frontage road $V_{D(\%)}$, respectively, and ranks first and second for Δm -value.

To further investigate these differences, specifically with regard to E6, $V_{D(\%)}$ and Δm -value were compared with Table 1 emulsion

residue properties (elastic recovery was excluded). Correlation analyses evaluated which properties were significantly correlated with $V_{D(\%)}$ or Δm -value ($p < .05$). Correlations with pavement properties (e.g., permeability, asphalt content) were also investigated but are not shown because no correlations were found ($p = .5$ to $.9$).

Figure 3 shows that Δm -value correlated poorly to most residue properties except pressure aging vessel (PAV) m -value failure temperature (T_c). The relationship improved significantly with E6 removed. The common perception that softer base asphalts produce better rejuvenating emulsions is supported by Δm -value but is not universal to all emulsions. Although E6 residue is harder (T_c is higher) than most other residues, it provides one of the highest

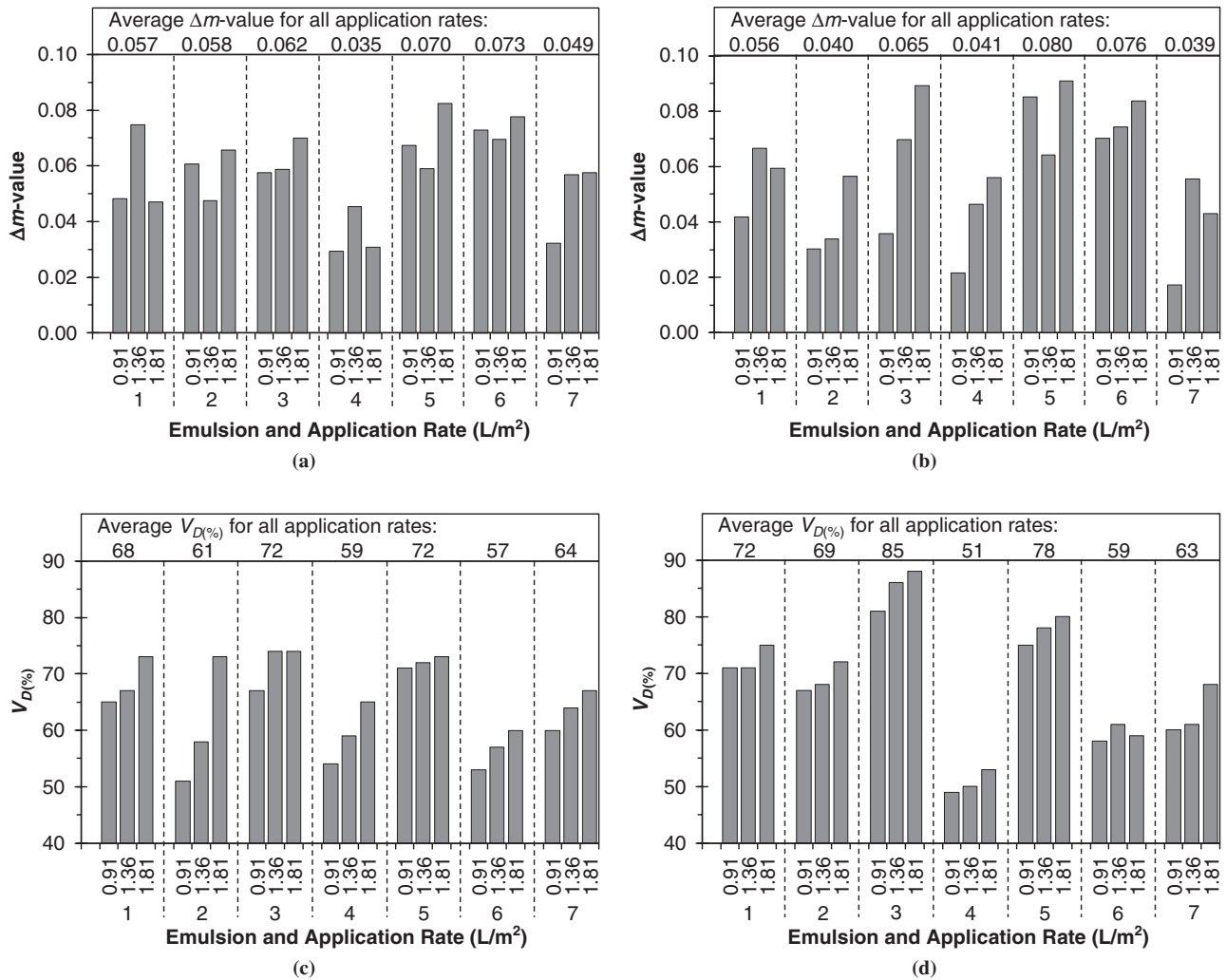


FIGURE 2 BBR and viscosity results: (a) US-45 60-s Δm -value results, (b) frontage road 60-s Δm -value results, (c) US-45 $V_{D(\%)}$ results, and (d) frontage road $V_{D(\%)}$ results.

Δm -values. This suggests rejuvenation depends on more than base binder properties (e.g., interaction with existing aged binder) and implies that buying and selling emulsions based on actual desired performance properties (e.g., Δm -value) instead of material properties (e.g., PAV-aged m -value T_c) has merit.

Figure 4 shows $V_{D(\%)}$ reasonably correlated to most residue properties, especially PAV-aged m -value T_c . Although $V_{D(\%)}$ exhibits stronger relationships to residue properties than Δm -value, this is not beyond reason because $V_{D(\%)}$ tests the recovered blend of residue and binder; Δm -value tests the actual mixture treated with emulsion absent unrealistic, forced blending. Also, $V_{D(\%)}$ does not detect E6's behavior, as does Δm -value.

Although $V_{D(\%)}$ and Δm -value are similar, they are clearly not identical. $V_{D(\%)}$ requires unrealistic blending of emulsion and aged binder and does not test entire mixtures. These attributes result in $V_{D(\%)}$ values that are perhaps better correlated to residue properties but are not necessarily representative of rejuvenation.

Another issue is the testing temperature. Viscosity testing is conducted at 135°C; however, issues that rejuvenation is used to address are associated with lower in-service temperatures (e.g., -22°C to 64°C in Mississippi). This is a deficiency of the $V_{D(\%)}$ system. A rejuvenator that favorably affects low to intermediate temperature properties may exhibit desirable $V_{D(\%)}$; however, other materials may exist

that decrease viscosity but do not favorably affect lower-temperature properties. With $V_{D(\%)}$, it would be difficult to distinguish between these two cases (this was one of the pitfalls of binder grading systems before the PG system). In contrast, BBR testing directly measures properties at temperatures of interest (e.g., -12°C, +10°C warmer than PG low grade as specified by AASHTO M320).

$V_{D(\%)}$ likely can be informative for rejuvenation, but it appears to be limited. Without proper controls and perhaps even additional testing, $V_{D(\%)}$ can be misleading, possibly approving poorly performing materials or vice versa. Viscosity has been heavily studied, so most major areas of improvement likely have been explored, leaving less room for further development. BBR testing, however, shows promise relative to viscosity testing, and there is likely room for future improvement. Data presented in this section suggest that Δm -value is more appropriate than $V_{D(\%)}$ for rejuvenation characterization, and disparities between these will likely increase with BBR improvements.

Specification Development with BBR

US-45 and plant mix BBR data are presented in this section (335 tests, 94 of which were used previously). Emulsion-treated testing was conducted with 1.81 L/m² of E3. Presented US-45

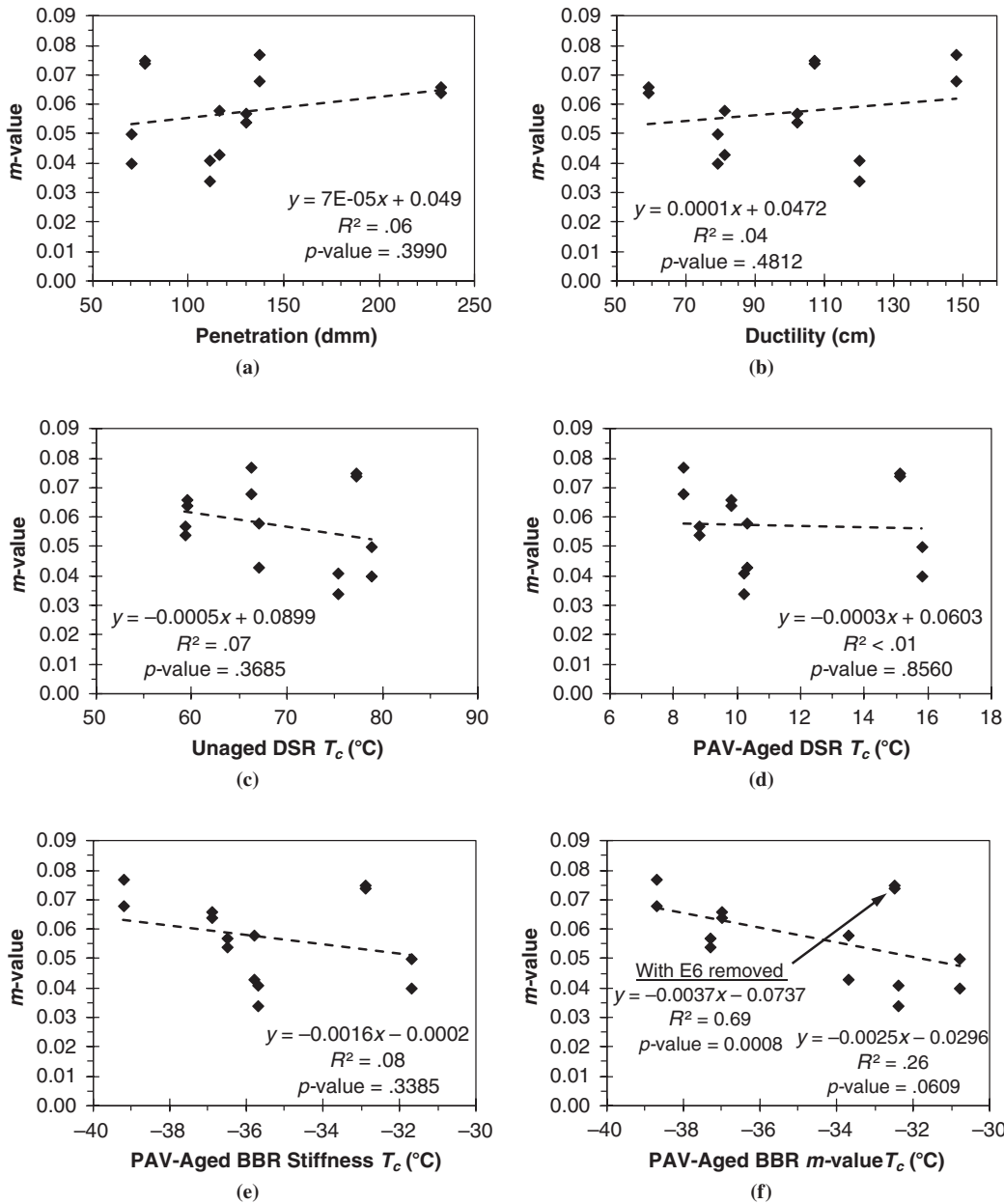


FIGURE 3 Δm -value correlation with various emulsion residue properties: (a) penetration, (b) ductility, (c) unaged DSR T_c , (d) PAV-aged DSR T_c , (e) BBR stiffness T_c , and (f) BBR m -value T_c .

data include (a) untreated control testing (64 replicates) and (b) emulsion-treated testing of unconditioned, 90-day, and 180-day field-conditioned beams (30, 26, and 33 replicates, respectively). Presented plant mix data include (a) untreated control testing of unconditioned, 7-, 30-, and 60-day laboratory-conditioned specimens (27, 26, 10, and nine replicates, respectively) and (b) emulsion-treated testing of unconditioned, 7-, 30-, and 60-day laboratory-conditioned specimens (30, 29, 27, and 24 replicates, respectively).

Replication varied slightly depending on sawing and testing success rates. Due to insufficient materials, fewer replicates (10 and 9) of untreated 30-day and 60-day plant mix were tested so that 30 replicates could be targeted for all other plant mix data sets. Therefore, 30-day and 60-day untreated results are intended to provide general information regarding longer conditioning times but may not be as reliable as other results.

Figure 5a demonstrates that unconditioned (0-day) Δm -value does not provide maximum Δm -value ($\Delta m\text{-value}_{\max}$). As 90-day data indicate, rejuvenation may continue progressing for some material combinations as time and temperature aid emulsion and aged binder interaction. The 180-day data show rejuvenation effects tapering, which agrees with the results of Brown and Johnson (1) and Shoenerger (2).

Figure 5b displays characteristics similar to those in Figure 5a. In this case, the mixture itself (plant mix) had not been previously aged like US-45, so effective Δm -value ($\Delta m\text{-value}_{\text{eff}}$) at a given conditioning time should instead be evaluated (emulsion-treated Δm -value minus untreated Δm -value). $\Delta m\text{-value}_{\text{eff}}$ increases considerably from 0 to 7 days and tapers by 60 days (30-day untreated data are questionable).

Field-conditioned results support findings in the literature. The most appropriate rejuvenation characterization approach might account for

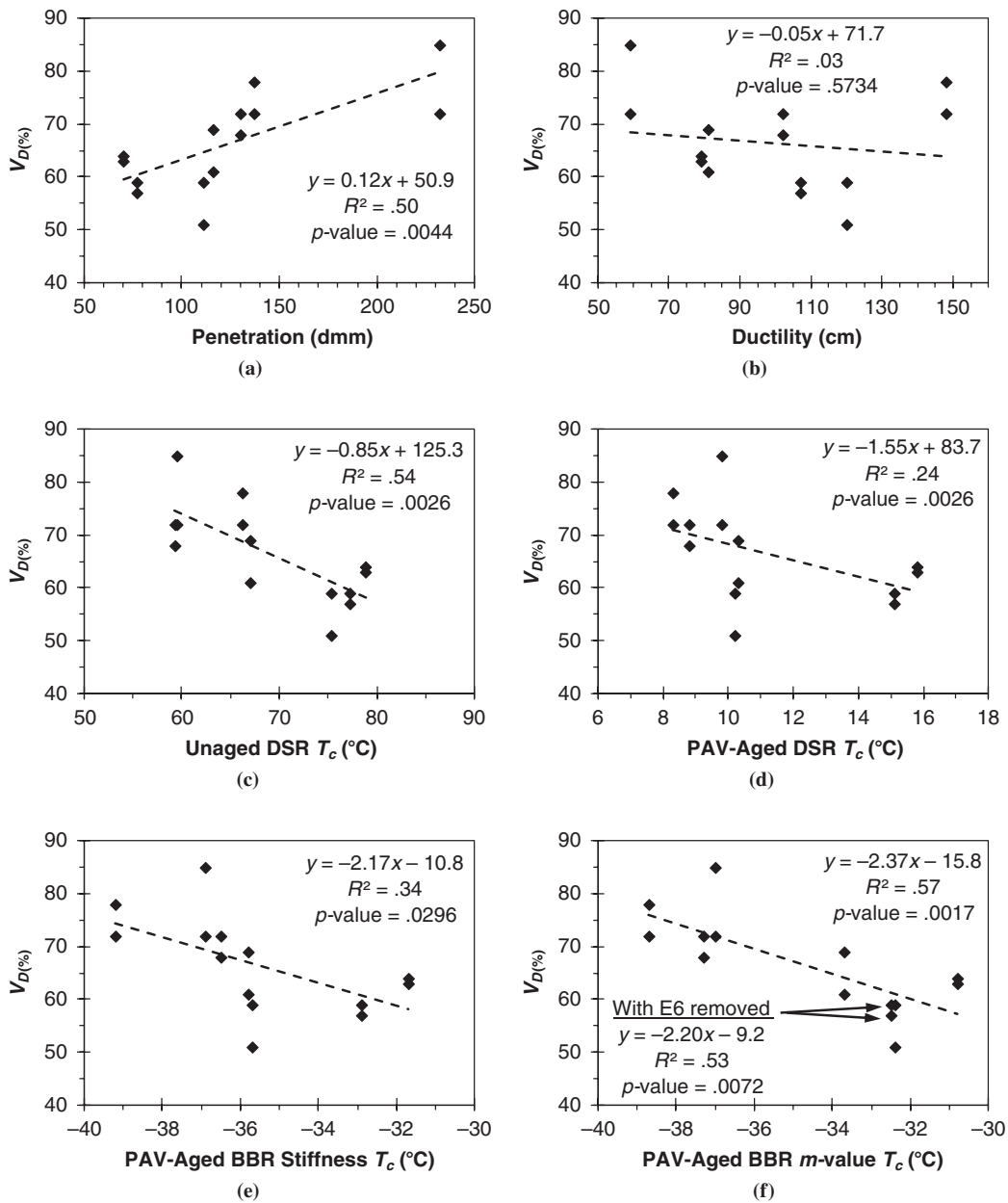


FIGURE 4 $V_{D(%)}$ correlation with various emulsion residue properties: (a) penetration, (b) ductility, (c) unaged DSR T_c , (d) PAV-aged DSR T_c , (e) BBR stiffness T_c , and (f) BBR $m\text{-value } T_c$.

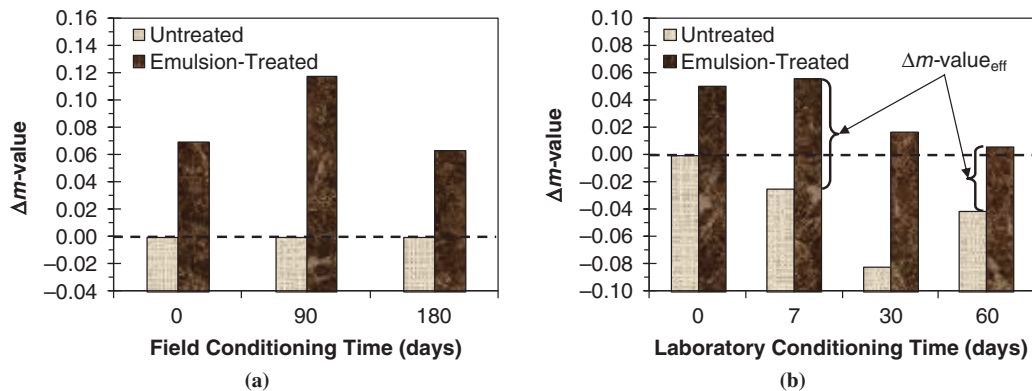


FIGURE 5 $\Delta m\text{-value}$ response as function of conditioning time: (a) US-45 and (b) plant mix.

TABLE 3 Recommended Replication for Given Margin of Error and Confidence Level

Plant Mix	Number of Replications								
	ME = 0.005			ME = 0.010			ME = 0.012		
	75% CL	85% CL	95% CL	75% CL	85% CL	95% CL	75% CL	85% CL	95% CL
Treated	12	19	35	3	5	9	3	4	7
Untreated	21	33	61	6	9	16	4	6	11

Δm -value_{max} and time to reach Δm -value_{max}. However, this concept is beyond the scope of this research and is a possible area for future study. Meanwhile, testing of unconditioned specimens appears sufficient.

E3 provides a 0-day Δm -value of 0.070 for US-45, although it provides only 0.051 for plant mix. This is expected because plant mix has experienced less aging and volatile loss; therefore, rejuvenation potential is less. This suggests minimum Δm -value criteria within specifications should be a factor of mixture type (i.e., field aged versus laboratory compacted). Braham et al. suggested a minimum 0.060 Δm -value for field-aged mixtures in conjunction with a 1.81-L/m² application rate (13). For E3 data, this corresponds to approximately 0.040 for plant mix. As Braham et al. stated (13), these values are for initial specification consideration; if future data warrant, the values should be adjusted according to agency goals and field performance results.

Field-aged or laboratory-compacted specimen testing could be specified. In cases in which agencies maintain approved products lists, laboratory-compacted specimens are likely more practical. Plant mix sawing and testing success rates were approximately 90% (versus 50% for field aged), and CV was approximately 20% on average (versus 28% for field aged). These rates correspond to time, cost, and labor efficiency. Further, raw materials or plant-mixed asphalt can be acquired and stored relatively easily, which allows multiple products to be evaluated on a single mixture. Field-aged pavements could be tested on a project-by-project basis, but this may be unnecessary because little interaction between pavement and emulsion was observed in Figure 2, which indicates rejuvenation potential is likely not project specific to an extent that prohibits use of laboratory-compacted specimens. Because of these factors, specifications that use laboratory-compacted mixtures appear more efficient and are the focus of the remaining discussion.

To account for test variability and for reliably determining Δm -value, recommendations are needed regarding minimum replication levels. Equation 3 was used to determine the required number of replicates based on test variability, desired margin of error, and confidence level (CL):

$$ME = z_{\alpha/2} \left(\frac{SD}{\sqrt{n}} \right) \quad (3)$$

where

- ME = margin of error of the estimate;
- $z_{\alpha/2}$ = critical z -score for two-tailed test: 1.15 for the 75% CL, 1.44 for the 85% CL, and 1.96 for the 95% CL;
- SD = standard deviation; and
- n = number of replicates.

All plant mix data sets where $n \approx 30$ were used in this analysis because sample standard deviations of 30 replicates reasonably approximate the population standard deviation. To prevent extreme

outliers from artificially skewing replication requirements, several outlier removal techniques were explored. Trimming 10% of the data was found to be the most effective approach (e.g., the three highest and the three lowest extremes are removed from a 30-replicate data set). Reliability-based replication recommendations using plant mix are provided in Table 3. For example, the minimum replication for plant mix should be nine to ensure 95% confidence that the true population mean is ± 0.010 of the 10% trimmed sample mean tested.

Recommended Specification Procedure

For an implementable specification, results from the previous section led to the following recommended approach. First, establish a relatively large untreated control data set (i.e., low margin of error, high confidence level). For instance, 35 replicates are required for 0.005 margin of error and 95% confidence level. Therefore, six specimens should be compacted from the standard mixture and five beams sawn from each face of each specimen. With 90% sawing and testing success, this yields 54 test results. Trimming 10% (discarding the highest six and the lowest six results) produces 42 data points used to calculate untreated m -value (rounded to three decimal places), which satisfies minimum replication requirements.

Second, determine the Δm -value of an emulsion, probably with less confidence and higher margin of error since emulsion-treated variability was slightly greater. This would also facilitate routine testing. For instance, 16 replicates are required for 0.010 margin of error and 95% confidence level. This implies three specimens are compacted, treated with 1.81 L/m² of emulsion on each face, and tested. After trimming 10% of the successfully tested results, 21 remaining data points are used in emulsion-treated m -value calculations (rounded to three decimal places), which satisfies minimum replication requirements. If Δm -value, calculated by Equation 2, is greater than the minimum criteria (e.g., 0.040), then the product is a rejuvenator and can be placed on the agency's approved products list.

CONCLUSIONS AND RECOMMENDATIONS

Historically, viscosity reduction has been the predominant means of specifying rejuvenation. As suggested by the literature and the research presented here, this approach is limited in usefulness and potential for further development. A summary of the appropriateness of the viscosity approach is as follows:

- Extraction and recovery processes can have meaningful effects on viscosity.
- Forced blending of aged binder and rejuvenator is required for testing but is not realistic for field conditions.

- High test temperatures may not be the most informative about distresses that rejuvenation seeks to address for aged pavements (e.g., cracking). There is no guarantee that products that favorably affect high-temperature properties (viscosity) will favorably affect lower-temperature properties.

BBR 60-s Δm -value results for emulsion-treated mixture beams appear to be a viable and appropriate rejuvenation specification alternative to viscosity testing. The presented research encourages consideration of the recommended specification procedure. A summary of BBR rejuvenation characterization is as follows:

- BBR beams can be sawn from specimen surfaces and tested with reasonable success and variability.
- Test specimens and conditions are more representative of field conditions in that (a) the asphalt mixture is tested instead of the binder only, (b) the loading configuration simulates field conditions, and (c) testing is conducted at lower temperatures.
- Results support general relationships with emulsion residue PAV-aged m -value T_c (i.e., softer emulsions provide more rejuvenation) but also acknowledge exceptions such as some proprietary products (e.g., E6).
- Plant mix testing demonstrated that Δm -value concepts extend to unaged laboratory-compacted mixtures although Δm -value for a given emulsion is likely less. A 0.040 Δm -value criteria appears reasonable for initial consideration.
- Laboratory-compacted fabrication and testing procedures can be conducted efficiently and with reasonable variability such that reliable Δm -values can be obtained with manageable replication.
- The BBR approach appears promising relative to the viscosity approach. Since the BBR approach likely has more room for further improvement than viscosity, disparities between the two are likely to increase in favor of the BBR.

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