TTI: 0-6747

Evaluation of Seal Coat Construction Materials

Technical Report 0-6747-1

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE

COLLEGE STATION, TEXAS

in cooperation with the
Federal Highway Administration and the
Texas Department of Transportation
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16. Abstract

Researchers conducted a laboratory test program to evaluate the durability and wear characteristics of aggregates commonly used for seal coat construction. They also sampled commonly used seal coat binders from construction projects and tested the binders in the laboratory to evaluate their propensity for flushing characteristics. Field test sections consisting of many of the commonly used binders were evaluated for performance in terms of bleeding and aggregate loss. Some of the limestone aggregates, which normally perform poorly in terms of Micro-Deval, performed better than expected in the new test methods employed in this study. While the polymer modified binders overall performed at a higher level, the test section with the highest score happened to be an unmodified binder (AC-10). There are many factors that can influence the performance of seal coats, and material selection is only one. If constructed properly and if the roadway is a good candidate, unmodified binders may perform very well. For higher volume facilities, it still seems that polymer modified binders are likely to give better success. For lower volume facilities, most of the laboratory and field data point to polymer modified materials ensuring better performance. To assist in selecting materials, 0-6747-P1, *Guidelines for TxDOT in Selecting Seal Coat Materials* was developed as part of this project.

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Cindy Estakhri, P.E. #77583.

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CHAPTER 1: INTRODUCTION

BACKGROUND

The Texas Department of Transportation (TxDOT) administration has provided direction on the types of seal coat binders that can be used on a particular facility based on traffic through the use of the Seal Coat Material Selection Table (SCMST) (Table 1). The more expensive modified binders are reserved for use on higher volume facilities while the very low volume facilities may be sealed with unmodified binders. Given the cost-cutting needs the department faces, this guidance is justified. However, it is just as important (economically) to get the maximum life out of a seal coat. For example, on a very low volume, rural road, a Grade 3 aggregate placed with a polymer modified asphalt may provide a surface that needs no maintenance for 12+ years.

Table 1. SCMST.

Texas Department of Transportation

Form 2388
(Rev. 09/13)
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Seal Coat Material Selection Table		
Tier I: Heavy Use - Use only the selected materials.		
Type	Asphalt Rubber (A-R) A-R Only	Asphalt Cement (AC) AC Only
Asphalt	A-R Ty II A-R Ty III SP 300-	AC-20-5TR AC-20XP AC-15P SP 300-
Tier II: Moderate Use - Use these materials or any selected Tier I material combinations of the allowed types.		
Type	Asphalt Cement (AC) AC Only	Asphalt Emulsion Emulsion Only
Asphalt	AC-10-2TR AC-15P AC-20XP AC-10 w/2%SBR AC-5 w/2%SBR SP 300-	CHFRS-2P HFRS-2P CRS-2P SP 300-
Tier III: Light Use - Use these materials or any selected Tier I or Tier II material combinations of the allowed types.		
Type	Asphalt Cement (AC) AC Only	Asphalt Emulsion Emulsion Only
Asphalt	AC-10 AC-5 SP 300-	CRS-2 CRS-2H HFRS-2 SP 300-
Districtwide Seal Coat Project Seasons: Refer to Item 316 for temperature and weather restrictions.		
Season 1:	AMA, CHS, LBB	May 15 to Aug 31
Season 2:	ABL, ATL, BWD, DAL, FTW, LFK, ODA, PAR, SJT, TYL, WAC, WFS	May 1 to Aug 31
Season 3:	AUS, BMT, BRY, ELP, HOU, SAT, YKM	May 1 to Sept 15
Season 4:	CRP, LRD, PHR	Apr 1 to Sept 30
Note: Seal coats on routine maintenance contracts must be completed by August 31 unless otherwise shown on the plans.		

Performance of seal coats is highly dependent on workmanship and correct application rates for binder and cover stone. However, districts have discovered that using polymer-modified binders can be like buying insurance against workmanship issues. Rock loss typically occurs in the first few weeks after construction and polymer modified materials aid in holding rock even when too little asphalt may have been applied. Flushing/bleeding is usually caused by application of too much asphalt, but polymer modified binders can minimize the severity of the flushing. TxDOT's responsibility to maintain serviceability of almost 80,000 centerline miles of roadway is an ever-increasing challenge. Public pressure to reduce traffic congestion and delay times in urban areas has forced reductions in funding available for preventive maintenance. As TxDOT invests over $250 million annually in its seal coat program statewide, selecting the right materials for the right roadway is very important.

Texas has long been a leader among state departments of transportation (DOTs) in the use of seal coats. Unlike the majority of other states, seal coats are a major staple of TxDOT's strategy to provide and maintain the vast number of lane-miles of pavement in the state. Seal coats have been successfully used in Texas on every type of state-maintained roadway, including interstate highways. But the 41,000 centerline miles of Farm and Ranch to Market roads is the most common application location.

The primary functions of a seal coat are sealing and protecting underlying pavement layers while providing an abrasive surface with adequate skid resistance. Many factors affect the performance of seal coats, including properties of the asphalt and aggregates, strength and condition of the existing pavement, construction techniques, and the amount and types of traffic. Useful service life of a seal coat generally ends due to cracking or loss of skid resistance. Loss of skid resistance can be the result of aggregate polishing, loss of macrotexture from aggregate reorientation, or asphalt flushing. Loss of macrotexture is sometimes due to the use of softer aggregates, which polish, wear, and break down under traffic.

When the correct materials and application rates are used for a seal coat, TxDOT should expect a service life of at least 7 years or more. When incorrect materials and/or application rates are used, or when poor construction practices are used, the life of the seal coat can be a matter of months or weeks. Because seal coats are one of the most visible types of maintenance treatments performed by TxDOT, the public can be easily exasperated when things go wrong. Figure 1 shows a poorly performing seal coat on RM 12 in the Austin District.

Figure 1. Poorly Performing Seal Coat on RM 12.

The seal coat was placed late in the season (early October) using an AC-20-5TR and Grade 4 precoat. Initially performance was fine but area residents were complaining about noise. When cold weather set in, rock loss began to occur and neighborhood complaints surmounted. The

Texas A&M Transportation Institute (TTI) was asked by TxDOT to provide independent evaluation and recommendations. In summary, there were several problems contributing to the distresses shown in Figure 1 such as insufficient asphalt application rate with embedment depths about 25 percent, rock rate too heavy, clogged nozzles, and late season sealing. The bigger problem for TxDOT, however, was the pressure exerted by this very active neighborhood organization and the resulting negative publicity. The neighborhood group successfully solicited the involvement of state politicians, county commissioners, and multiple media outlets. A website (Fixranchroad12.com) was created to exert pressure on TxDOT. While the goal of this group was to get an overlay on RM 12, their ultimate goal was to have no more seal coats at all in the Austin District, which is absolutely not an option for TxDOT. Seal coats are an integral part of TxDOT's preventive maintenance program and the use of proper materials and construction procedures are essential to avoiding the types of failures described above and all of the ramifications that can follow from a disgruntled public.

The potential for poor performance of seal coats resulting from the use of lower quality materials is very significant for TxDOT given the importance of the seal coat program. Poor performance of seal coats (which equates to rock loss or flushing in the wheel paths) is a safety issue due to the loss of friction and is a maintenance nightmare, especially when soft binders are used in the seal coat. No matter what is placed to cover up the problem, the soft binder manages to migrate through to the new surface.

RESEARCH APPROACH

Researchers conducted a laboratory test program to evaluate binders and aggregates commonly used for seal coat construction. For aggregates, Micro-Deval and Aggregate Imaging System (AIMS) testing were conducted on the aggregate samples. In addition, two new procedures were employed. Asphalt binders were sampled from field projects and test sections and tested to evaluate their propensity for flushing characteristics. Three tests were conducted in this task of this research: the Dynamic Shear Rheometer (DSR) Strain Sweep Test on asphalt binder, Multiple-Stress Creep-Recovery (MSCR) Test on asphalt binder, and Pull-Out Test on Aggregate Embedded on Asphalt Binder. The strain sweep and MSCR tests are standard American Association of State Highway and Traffic Officials (AASHTO) tests, and the pull-out test was developed at Texas Tech University. The non-recoverable creep compliance values calculated from the MSCR test for commonly used seal coat binders.

Field test sections consisting of many of the commonly used binders were evaluated for performance in terms of bleeding and aggregate loss. Most of the unmodified binders (CRS-2, AC-10) were used on low volume roadways. Fourteen test sections were on moderately trafficked roadways, Binders used here included AC-20-5TR, AC-15P, CRS-2P, CRS-2H, and AC-10. Twelve test sections were constructed on high traffic roadway.

CHAPTER 2: INFORMATION SEARCH

Based on the information gathered from the recent TxDOT seal coat construction plans in terms of materials used, TxDOT districts were contacted to obtain the following information:

- Seal coat materials selection process prior to introduction of the SCMST.
- Overall assessment of performance (aggregate loss, bleeding) before and after the SCMST was introduced.
- Field sections that experienced early life performance problems (rock loss, flushing).

Table 2 and Table 3 summarize these results. Table 4 summarizes pertinent literature.

Table 2. Summary of District Responses to Survey.

District	What materials (both asphalt and aggregate) do you select for use from the table for each tier for the District-Wide Seal Coat Program?		
	Asphalt Type	Aggregate Type	Aggregate Grade
ABL	2011: AC-20 5TR for Tier I, AC-10 2TR for Tier II. 2013: AC-20 5TR and AC-20 XP. Emulsions were tried but did not work.	Limestone; Eastern half of district uses Vulcan Black Lease and Zach Burkett Graham aggregates; Western half uses aggregate from Price Construction and Trans Pecos Hoban.	PB Grade 4 with no contractor option.
ATL	Tier 1: Ac-20-5tr, AC-20Xp, AC-15; Tier II: Ac-10-2tr, AC-20xp, AC-15p Contractor will usually use one binder for the whole seal coat contract. This year it will be AC-20-5tr.	Only SAC A, PL or PB (Usually from Martin Marietta Sawyer, but this year it will be a crushed gravel from Hanson Little River.)	Grade 4
BMT	Tier 1: Ac-20-5tr, AC-20Xp Tier II: Ac-10-2tr, AC-20xp Tier III: CRS-2p, CHFRS-2p		Tier I and II: Grade 4 Tier III: Grade 3
BWD	Tier I: AC 20-5TR, AC 20-XP, AC15-P (contractor option); Tier II: AC 10-2TR (not used much by contractor), CRS-2P (typical); Tier III not used since 2012. Sources: Emulsion from Ergon Waco, AC from Valero Houston or Alon Big Spring; 2013 will be the first summer there will be no emulsion used in BWD.	Limestone	Gr 4, used Gr 3 on IH-20 in Eastland County. When AC is used, precoated aggregate is used.
BRY	Hot ACs: AC-15p, AC 10-2TR, AC 20xp, AC-20-5tr. No unmodified ACs allowed because we are concerned with our lower volume roads having to last longer with the limited money we have. So based on my engineering judgment, it's not cost effective to use unmodified binders.	Either lightweight or crushed stone.	Gr 4
CHS	AC20-5TR, AC20-XP, AC-10	PB & PL, SAC-A	Gr 4 Mod
CRP			
DAL	Tier 1 AC-20-5TR, AC-20XP Tier 2: AC-10-2tr, AC-15p	Tier 1 and 2, PB or PL	Tier 1: Grade 3, Grade 4s Tier 2: Grade 3, Grade 4, Grade 4s
ELP	Neat AC asphalts, some emulsion, AC 10-2TR, asphalt rubber (AR)	Western part of district: Jobe Concrete Granite (volcanic), East: Trans Pecos Hoban Pit, other pits mostly volcanic	Gr 4 for high traffic, Gr 3 for low traffic
LBB	AR or AC20-5TR	All precoated aggregate except when	Gr 4 and sometimes Gr 5

		emulsion is used.	(moved away from 4S due to higher cost)
LFK	Tier 1: AR, AC-20-5tr Tier II: AC-10-2tr, AC-15p, CRS-2p	PB, PL	Tier 1: Grade 3 and 4 Tier 2: Grade 4 and 5
ODA	Tier I for IH-20: AR with Grade 3 rock (Cox usually blends at fixed plant, also in 2012 Cactus Company blended at site and both worked out to be OK). Also, AC-20 5TR with Grade 4 modified rock with SAC A or B; AC-10 2TR can be substitute with AC-15P or AC-20XP.	Capitol Aggregate (Hoban Pit is the only SAC A aggregate in the District. Also use aggregate from Jones Brothers (Rankine Pit).	Grade 3, Grade 4 Modified
PAR*	Tier 1: AC-20 5tr, AC-20xp, AC-15p Tier II: AC-20xp, AC-15p, CRS-2p Tier III: CRS-2p Last year accidentally called for CRS 2 instead of 2p and eastern part of the district was with 2 and western part with 2p. Would like for us to review performance.	Tier I and II: Type PB and PL for ACs and B and L for emulsions Tier II: Type B and L	Tier 1 and II: Grade 4 Tier III: Grade 3
SJT	AC 20-5TR, AC10-2TR for Tier II roads, AC15-P, CRS-2, AC-5 and AC-3 neat asphalt for cool weather sealing; Binder Sources- Alon Big Spring (50%), Valero (50%).		
SAT	AC-15P is the most commonly used Tier I binder. Also use AC-20 5TR, AC-20XP and AC 10-2TR. Did not have good luck with XP and 2TR. Not much emulsion is used due to bad experience in the past. Sometimes use CHFRS-2P from Ergon Pleasanton Plant.	PB including limestone rock asphalt (LRA), PD excluding LRA, Sanstone from Capitol Aggregate in Marble Falls.	Uses Grade 3 in rural low volume roads because it is more forgiving and provide better constructability. Grade 4 is used for suburban district. Grade 5 at a rate of 140 sy/cy rate for bicycle routes, for noise reduction in suburban areas and in rural roads without shoulders. State forces used heavy Grade 5 (rates of 110-120 sy/cy) on IH-10 west of San Antonio and created no problems!!
WFS	Tier 1: AC-20-5TR, AC-20XP Tier 2: AC-15p, AC-10-2TR, AC-20XP	Tier 1, 2: PE	Tier 1: Grade 4 and 5 Tier 2: Grade 4
YKM	Tier 1: AC-20-5TR, AC-15P Tier II: AC-10-2TR, AC-15P, AC-20XP	Type: PB Source is usually a crushed limestone or LRA	Tier I: Grade 4 Tier II: Grade 3 or 4

District	What materials are used for seal coats placed by maintenance forces?	What materials are used for underseals applied on existing asphalt surfaces?
ABL	In-house crews use PB Grade 4 or uncoated Grade 4 aggregate; Binder: CRS 1P or 2P; Dis not shoot AC binders due to lack of equipment, but now using boosters to shoot AC-20 5TR or AC-20 XP.	Underseals are used always when overlays are used and on black base. Base bid of AC-20 5TR with AR alternate bid (Spec ITEM 318). Aggregate is typically precoated when it is dusty and soft. AR being a premium seal option is only used in jobs where existing pavement has cracked.
ATL	We do very little in-house sealing, But we would use a CRS-2p.	CRS-2p, Grade 4 no performance issues.
BMT	Not enough maintenance personnel to do in-house sealing.	CRS-2p (Use under PFCs or under level-ups, especially on concrete)
BWD	This needs to be verified. Perhaps CMS was used in Comanche County.	Underseal: One or two projects, Gr 4 rocks with either CRS-2P (covered up same day), AC-10 with precoat, or AC-20 5TR (for heavy traffic). Usually covered with 1.5 inch thick Type D hot mix using PG 70-22 or PG 76-22.
CHS	Ty B Gr4, Ty B Gr5, Ty L, Gr 5, CRS-2, CRS-2P, CHFRS-2P	Have not placed under seals in years, but when we did, we used the above materials…really no different than seal coat other than we did not precoat aggregate
ELP	Very little in house sealing (<25 miles in 2012, <30 miles planned for 2013)	Essentially same as preventive maintenance seals.
LBB	In Lubbock County, AC20-5TR. Elsewhere CRS-2p.	Does a lot of underseal using AC20-5TR with Gr 4 rock. Sometimes use aggregate with no precoat. Have used lower quality binders in underseal but started tracking.
LFK	CRS-2p and lightweight	
ODA	ODA has a substantial in-house program for full-width sealing ($6million in-house and $8million contract). 2013: $8million construction contract, $6million contract maintenance, $1million in-house; 2012: AC-10 2TR, AC-15P, AC-20XP but no emulsion.	AC-10 2TR or AC-10 (unmodified) with Grade 4 rock. Cover up seal in 4-5days with hot mix; That way a tacking agent (tack coat) is not needed.
PAR	CRS-2p and Grade 4 RC-250 and Grade 5	Spray paver or CRS 2p, or AC-20-5tr
SJT	First tried significant in-house sealing in 2012 (200,000 gallons of asphalt shot compared to 1 million gallons for contract seal; AEs like to do it again, but do not have the money to seal significant quantities.	Used fabric underseals sometimes, but now regular seals are used for underseals; Would like to use AC20-5TR because traffic may be on the seal for 3 days to several months before covering with hot mix.
SAT	CHFRS-2P with precoated aggregate has worked in San Antonio.	Underseals are done on base with prime coat. Ask AEs for how long underseal will be used before paving hot mix. Outside of Bexar County, RC-250 with Grade 5 at 0.2gal/sy is used and inside Bexar County, MC-30 is used.
YKM	CRS-2p, Grade 4	Same as preventive maintenance seal coats.

District	Do you think the table is a good tool?
ABL	The concept of the Table is good and it can be made to work by allowing flexibility for Districts to customize for unique local situations. ABL exercises flexibility. In 2011, Tier I, II, and III binders were specified, but the contractor only used Tier I and II binders. In 2012, only Tier I and II binders were specified. In 2013, only Tier I binders will be specified.
ATL	We were providing options to the contractors prior to the introduction of the table. Didn't change anything for us.
BMT	It is good in that it gives us a basis of where to start from. Gives a lot of pertinent information in one place (i.e., groups the rock with the oil, gives seasonal information). But it also tries to box up everything to fit all conditions. You have to understand the dynamics of where you are in the state. What is a viable option for where you're located and what asphalts are available in the area?
BWD	The Table has a place in TxDOT seal coat work. Problems in seal coats are not due to the Table. It took BWD a few years to get it right.
BRY	No. It has design guidance and we don't like putting design guidance in the plan set. It conflicts with the plans and can cause controversy with the contractor.
CHS	Mixed feelings. Our district was already using letting strategies for maximizing competition and getting lower bids.
ELP	The Table is based on a good concept but districts should have the flexibility to make adjustments based on local conditions.
LBB	No. Its use has not made much of a difference in Lubbock District. Some contractors opt to use Tier I asphalts in all roads; Unit Cost: 2010-$1.96/sy, 2011-$1.73(had more competition this year), 2012-$1.95, 2013-$1.99.
LFK	In a district that has typically specified one material, then it's a good tool. In a district like Lufkin, we didn't really change anything because we always had more than one option on medium and lower volume roadways. With the table, we played the game of selecting AR along with AC-20-5TR so that we would get the latter.
ODA	The Table is not a good tool. May be for new hires. Prior to the Table, Districts had bid items that allowed more flexibility on binder options. The Table does not give a measure of binder quality. The use of the Table has evolved accommodating more flexibility to account for road conditions. Also pushes up a Tier for heavy vehicles.
PAR	No. We need to be able to specify the particular asphalt we want for a particular roadway.
SJT	The Table is a good guidance tool, but not a good idea to mandate.
SAT	The Table is a good idea and is helpful in some ways. It may be better suited for rural districts because urban districts have high traffic levels. The Table also helps the designers but needs to be more fine-tuned to use engineering judgment. Need to add more binder options to the Table, develop a pamphlet for new designers, teach them to not use the Table blindly, and consider SAC rating of aggregate as well.
WFS	Would prefer to be able to specify desired materials based on engineering judgement.
YKM	Yes, overall. We elect not to include the table in the set of plans but specify the binders to be used in the general notes.

District	How has your practice changed since the introduction of the table?	Without the table, what would you do differently?
ABL	Had significant problems with 2010 seal coat program because the AC-10 2TR binder tracked easily much like an unmodified binder. Prior to implementing the Table, used a base bid with a couple of alternatives.	Would like to use base bid and an alternate bid. Before Table, used AC-20 5TR or AC-20 XP.
ATL	None.	Nothing.
BMT	No significant change as a result of the table.	Nothing
BWD	Not a lot of change as a result of the Table. Earlier, Engineer decided, but the Table encourages more competition between emulsion and AC suppliers. Used it as a guidance tool beginning in summer 2009. First summer the Table was used, everything was decided based on ADT as the Table stipulated. Now BWD uses the Table as a guide and uses engineering judgment. BWD has no mandate. Also, there is no need to break-up Tier II into sub-ADT levels.	The Table has merit. BWD was already trying to work with alternate binders at the time the Table was implemented.
BRY	Not much. We always tried to allow more than one option. For high volume roads we allowed AC-20-5Tr and then when AC-20xp came along we allowed it to compete. When we dropped to lower volume, we used AC-15p or AC-10-2TR. Allowed all 4 binders on the lower volume.	Nothing.
CHS	Not really. As mentioned above, we offered choices in our bids prior to the table.	Nothing. We would continue our previous practice of setting up asphalt and aggregate choices for contractors
ELP	Check with Chris Webber.	Take the ADT part out of the table and give districts flexibility to select materials based on experience.
LBB	Not a lot. The District specified different asphalts from the Table, but the contractor opted to go with Tier I binder (AC20-5TR) for all due to convenience.	Would use AC20-5TR exclusively on contract seal coat.
LFK	None.	Nothing.
ODA	The Table has taken the District a little bit away from having the ability to make good judgment calls. Now, moving back to that comfort zone with more flexibility.	Picking the binders based on experience at the District level.
PAR	We've been in a state of continuous change in recent years. We have ended up with asphalts that seem to be too soft on tier II or tier III roadways. We've changed the traffic requirement for the different tiers. We've allowed CRS 2p to be used as a tier 2 material (but if that one is selected, application rate needs to be greater so probably not saving any money).	Would specify a particular binder for a particular roadway.
SJT	Started using an earlier version of the Table as a guide in 2008. Contractor used AC20-5TR; After the mandate, District had some of the worst seal coats when using Tier III binders and using Tier II binders up to 1000 ADT; Hot 2011 summer generated a lot of flushing; Had one job using Tier II binder (AC10-2TR) that raveled, perhaps because it was shot when nights were cool in early May; May shift to a May 15 seal coat season start.	Would use the experience-based approach as before while making effective use of the TxDOT Seal Coat Manual combined with training; Table as guidance can help.
SAT	Prior to using the Table, SAT had problems with binder suppliers. In 2013 contract, SAT will include notes on plan sheets and try to get better aggregate.	Use SAC effectively and fine tune aggregate selection. May bump up one level for binders.
WFS	We've allowed less expensive binders to save money, and performance has suffered. We've since decided we can justify no Tier 3 roadways in our district.	We would specify the binders needed for a particular roadway based on our experience and history of performance.
YKM	None.	Nothing.

District	Describe seal coat performance prior to and since the introduction of the table.
ABL	Check with AEs for possible test sections. 2010 and 2011 sections would be good. 2011 contract had problems with Tier II binders (AC-10 2TR). DOC had a document prepared for the maintenance conference. Will try to locate and share that with us.
ATL	Very satisfied with our seal coat performance. We only allow Tier 1 and 2 binders and we don't allow emulsions. Used emulsions on about 30% of our roads up until about 6 years ago. But we found we couldn't keep traffic off of the roadways long enough for the binder to cure. These emulsions would end up on our lower volume roads but they also happened to be the roads where we had logging traffic and oilfield service roads. We would routinely end up having an entire seal "roll-up" on us.
BMT	Performance is fine as long as the application is done properly. We need to do a better job at rating our roads to determine what we need…..need to get more eyes on the ground.
BWD	
BRY	No difference, if we get the rates right. What we do see over time is excessive wear of the aggregate causing it to become flush with the AC. Looks flushed but it's not. I don't think AC-15p should be allowed for higher traffic roads. It strings and flushes and doesn't work well at the higher temperatures with lots of traffic. On tier 2 we have a note that says it can only be used on certain roads (depending on the cracking and existing flushing).
CHS	Prior to Table, we typically experienced shelling in winter months, mainly due to applying harder asphalts. With the Table, and most of our roads being Tier 3, we started getting soft, unmodified asphalts (mainly AC-10) and for the first 2 summers suffered severe bleeding. This upcoming summer, which will be our 3rd under the Table, we eliminated Tier 3 binders from the Table to get back to receiving modified asphalts.
ELP	Prior to table: no problems. After Table: significant problems in two projects, one with high level of truck traffic and the other on mountainous terrain.
LBB	No difference was observed.
LFK	No difference.
ODA	Some quality control has diminished due to consistency of work. Ex: bid on three different kind of asphalts will results in reduced cost, even without the Table. Don't see aggregate as a value to Table because it is driven more by local availability, and lowest bid will always govern.
PAR	AC-20 5TR seals are good. Had some problems with unmodified materials, which were change-ordered in on late sealing projects (not district wide seal coat program). These roadways bleed when it gets hot. We think anything AC-10 with or without TR is too soft and maybe even the AC-15p. We've had really good success with the CRS-2p/Grade 4 seals placed by maintenance which is why we've gone to them for Districtwide; however, we used the CRS2p with Grade 3 for Tier 3 (last year) and had rock loss. Thinking maybe Grade 3s should not be used with emulsions.
SJT	Observed problems with seals using Tier III and some Tier II binders. Will not use Tier III binders any more.
SAT	20XP had issues. Quality is influenced by the quality of contractor and the selection of binder by contractor. Cost: just under $2/sy Table has helped set costs to some extent. Material selection should be based on value engineering that suits the roadway. LRA, which is soft and cannot see 7 years of life, is only used in rural Tier II and III roads.
WFS	In the past, we could get as much as 12 years on low volume roads with Grade 3 and AC-20-5tr. We've had significant performance problems since the introduction of the table, primarily with the Tier 3 materials. Another problem, which has exacerbated the problem is in recent years, the seal coat program has started later in the summer and when the temperatures are 100+ during the seal coat construction, tend to have flushing problems. Most of the problems we've had have been on the roads that have more than 1000 ADT. We would like to do a life cycle cost of the different binders. If we can get just one additional year of life from the more expensive polymer modified binders, they pay for themselves.
YKM	No difference as a result of the implementation of the table.

Table 3. Bid Tabs for Statewide Seal Coat.

FY 2012 Statewide Seal Coat Summary	Low Bid	Tier I	Tier II	Tier III	Tier I	Tier II	Tier III
District		$/gal	$/gal	$/gal	$/cy	$/cy	$/cy
Abilene 295-2-26	$ 3,244,327.88	2.85	2.75		70	70	
Amarillo 41-2-12	$ 9,915,291.50	3.4	2.7	2.4	56	40	35
Atlanta 10-11-68;6227-47-001	$ 3,919,749.30	3	3		56	56	
Beaumont 28-5-50 200-4-23	$10,599,125.90	3.21	3	2.7	68	68	68
Brownwood 0007-03-084 (tierII alt in tierIII column)	$ 7,641,701.66	2.73	2.73	2.52	56.65	59.76	40.13
Bryan49-9-67;204-5-36;6226-11-001	$ 5,324,879.71	2.78	2.78		75.48	76.38	
Bryan49-9-67;204-5-36;6226-11-001	$ 1,254,880.97	2.9	2.82		62	62	
Childress 31-4-48;6227-2-001							
Corpus Christi 100-5-71	$ 9,565,612.62	3.228	3.228	2.978	43.64	44.06	41.29
El Paso924-0-71;358-01-025	$ 5,763,239.52		3.12	2.72		49.96	59.18
Fort Worth 8-13-224;6239-26-001(gr3-t1,gr4-t2)	$ 7,751,942.98	2.64	2.65		50	48	
Laredo 160-5-45;483-1-42;1229-1-55;6238-98-001	$ 3,038,981.50	3.478	3.478		37.74	33.05	
Laredo 160-5-45;483-1-42;1229-1-55;6238-98-001	$ 1,160,705.76	3.28	3.28	3.28	35	37	36
Laredo 160-5-45;483-1-42;1229-1-55;6238-98-001	$ 2,305,783.72		3.18	3.18		50.97	44.92
Lubbock 52-1-39	$10,574,174.82	2.96	2.75		59	55	
Lufkin 59-2-13	$ 8,597,338.04	2.97	2.76		63	60	
Odessa 228-6-80	$ 5,871,577.62		3.105			58.05	
Paris 45-2-31	$ 7,539,782.11	2.9	2.9	2.45	60	57.5	45
Pharr 696-3-14;1941-1-10	$ 2,882,782.05	3.378	3.378	3.078	50.36		
Pharr 696-3-14;1941-1-10	$ 2,659,227.47	3.25	3.25		51		
San Angelo 0076-08-025;35-2-35	$ 4,444,282.08	2.85	2.77	2.45	57		
San Antonio 17-4-40;25-3-93	$ 3,846,831.88	2.64	2.64		58.87	42.21	
San Antonio 17-4-40;25-3-93	$ 5,500,240.56	2.63	2.63	2.52	59	49	43
Tyler 123-3-20	$ 9,627,226.87	2.79	2.69		72.51	68.35	
Waco 183-4-47	$12,369,778.75	2.86	2.86	2.7	27.25	55.25	32.6
Wichita Falls 13-13-004	$ 4,957,929.90		2.8	2.42		48	48
Yoakum YKM 266-3-28;241-1-44;6228-11-001	$ 3,656,256.98	3.07	3.07		45	45	
Yoakum YKM 266-3-28;241-1-44;6228-11-001	$ 3,825,669.06	2.87	2.87		56	56	
average		2.985391	2.932926	2.722769	55.19565	53.73083	44.82909
min		2.63	2.63	2.4	27.25	33.05	32.6
max		3.478	3.478	3.28	75.48	76.38	68

Table 4. Summary of Pertinent Literature.

Reference	*Summary of Findings*
Newcomb, D., R. Lenz, R., C. Estakhri, 2012. ***Evaluation of the Texas Tier System for Seal Coat Binder Specification***. Report 0-6798, Texas A&M Transportation Institute, Texas A&M University, College Station.	In this study, researchers held meetings in several districts and generally included district engineers, area engineers, maintenance and operations engineers, designers, materials engineers, construction engineers, planners, seal coat supervisors, and maintenance supervisors. The districts interviewed seemed to have very clear ideas about why the table was developed. Most believed that it was intended to increase competition between contractors while some mentioned lowering costs, increasing contractor flexibility, improving the uniformity of contracting practices statewide, and finally matching the binders to the appropriate roadways. There is not a consensus among districts of whether the tier system is saving the department money. From an administrative point of view, the table appears to have made contract management generally easier. When asked if binders within a given tier were equivalent, there was not a consensus among the various districts, although most believe that within a given tier there are problems in equating performance among binders. Findings include the following: • Tier system is working as it was intended for the most part. It has spurred competition among binder suppliers. • There is a general sense of satisfaction with the current tier system although at least one district and one contractor expressed negative opinions about the system. The binder suppliers expressed appreciation of the system so long as it is being used as it was intended. • The tier system is saving money as calculated by TxDOT. Over a 2.5-year period, it is estimated that the system has saved more than $33 million. • There are opportunities for the tier system to be improved.
Vijaykumar, A, E. Arambula, T. Freeman, A. Epps Martin, 2012. ***Revision and Further Validation of Surface-Performance Graded Specification for Surface Treatment Binders.*** Texas Transportation Institute, Texas A&M University, College Station.	TxDOT's design and selection of surface treatment binders in service is currently based on specifications that only account for the penetration and ductility of emulsion residues or the penetration and viscosity of hot-applied asphalt cements. These specifications consider neither the entire range of temperatures that the binders may be subjected to during production and in service nor long-term aging behavior. A surface performance-graded (SPG) specification for the selection of surface treatment binders, which takes into account the physical properties and performance of the binder at the temperature ranges in which the material will be used, was developed as part of previous TxDOT and National Cooperative Highway Research Program (NCHRP) projects. In the current study, the SPG specification was revised and further validated. This was accomplished by standardizing the emulsion residue recovery method through the evaluation of two warm oven methods, exploring the exclusive use of the DSR for determining performance-based properties, and further field validating the thresholds for these properties. The laboratory and field results were used to revise the SPG specification for surface treatment binders in service. Moreover, the results obtained from the MSCR and DSR frequency sweep tests were compared with field performance to evaluate additional criteria for the specification. This study is limited to producing a revised SPG specification for properties that address stiffness and aggregate retention in service; the effects of construction and quality control processes are beyond the scope of this study.
Senadheera, S. R. Tock, M. Shabbir Hossain, B. Yazgan, and S. Das, 2006. ***A Testing and Evaluation Protocol to Assess Seal Coat Binder-Aggregate Compatibility***, Research Report 0-4362-1, Texas Tech University, Lubbock. Senadheera, S., R. Tock, M. Shabbir Hossain, B.	For seal coat work, highway agencies such as TxDOT need to have an approach to measure and evaluate the performance of an aggregate-binder system in the laboratory. In this research study, a performance-based test protocol was developed to address this need. Two test protocols were developed in this research. The primary test protocol was the performance-based seal coat aggregate-binder compatibility test, which can be used for all types of binders, and the other was the modified net adsorption test to be used for non-precoated aggregate and hot asphalt binders to determine the affinity of aggregate to the asphalt and its resistance to stripping. The researchers also studied the construction processes in 15 projects and collected data, sampled materials, and evaluated performance. Approximately 300 tests were conducted using this performance-based test protocol. But before these tests were conducted, seal coat specimens brought in from the 15 seal coat projects visited during the first year of the study were tested using the protocol to assess the accuracy with which it predicts field performance. The field performance in these sections and the test results for field specimens collected from the same test sections using the new test protocol compared very well. In addition to this performance-based test protocol, a second test protocol was recommended by researchers to evaluate the bond between non-precoated aggregate and hot asphalt binders under ideal field conditions. The second

Yazgan, and S. Das, 2005. ***Draft Test Procedures for Seal Coat Aggregate-Binder Compatibility***, Research Product 0-4362-P1, Texas Tech University, Lubbock.	protocol recommended is the modified net adsorption test developed by the Strategic Highway Research Program and later modified by the National Roads Authority of Ireland to evaluate the bond between seal coat aggregates and binders. This test method provides a good assessment of the affinity of an aggregate to a particular asphalt binder and also the resistance of that aggregate-binder combination to stripping. Both test protocols proved to be very effective in predicting the field performance of aggregate-binder combinations for seal coats. The performance-based seal coat aggregate-binder compatibility test showed very good promise for prediction of field performance under a variety of field conditions. The test protocol was able to distinguish between the good and poor material combinations classified as such based on years of field performance. The performance-based seal coat aggregate-binder compatibility test also showed sensitivity to all key experimental parameters investigated for hot asphalt, emulsified asphalt, and precoated aggregates.
Senadheera S., Prozzi J, Smit A.,Bannerjee A, Tubb A, Niu L., ***Laboratory Evaluation of Constructability Issues with Surface Treatment Binder*** Research Report 0-5893-1, *2012.*	This research project was conducted jointly by TechMRT and CTR with TechMRT as the lead institution. The work done by TechMRT focused on a field constructability review that included eight test project sites to help identify parameters for the laboratory testing program. These test sections were later monitored as a part of the performance evaluation at the end of the study. The stiffness development of the binder when in contact with different aggregate surfaces was investigated using the DSR Strain Sweep Test. Additional tests were conducted using the ASTM D7000 Sweep Test on laboratory-prepared seal coat specimens. Laboratory test data clearly showed that some binder-aggregate combinations were ready for opening to traffic and/or brooming sooner than others. This time delay between material applications also depends significantly on the climatic conditions. The ASTM D7000 Sweep Test, used in other states to determine the effectiveness of binder-aggregate combinations for seal coats, was also conducted. The DSR strain-sweep test, using the aggregate substrate and environmental conditioning, was found to be a very effective tool in the seal coat planning and design stage to identify the best emulsion-aggregate combinations for different climatic conditions. Results from this test also provide information on the rate of stiffness gain in the binder, under different geographic and environmental conditions. This type of performance-based test method can be used to rank material combinations for use in roadways with different traffic levels and functional classifications. Even though the ASTM D7000 Sweep Test has been used by other states to evaluate seal coat material effectiveness, it was not recommended for use by TxDOT in its current form due to several limitations. However, since then, modifications to this test has been developed by Colorado State University, it may show promise for further research.
Shuler, S., A. Lord, A. Epps Martin, and D. Hoyt, 2011. ***"Manual for Emulsion-Based Chip Seals for Pavement Preservation***," NCHRP Report 680, National Cooperative Highway Research Program, Washington, D.C.	NCHRP Project 14-17 *Manual for Emulsion-Based Seal coats for Pavement Preservation* produced a manual that describes the best methods to use for designing and constructing emulsion-based seal coats on hot mix asphalt pavements. As part of this project, the SPG specification developed in TxDOT Project 0-1710 was used and further developed and field validated. In addition, three emulsion residue recovery methods (Stirred Can, Hot Oven, and Force Draft Oven [ASTM D 7497]) were evaluated toward standardization of a method for use with the SPG specification. Eight emulsions including CRS-2, CRS-2P, RS-2, RS-2P, HFRS-2P, and LMCRS-2 were used in this project. Five of the emulsions were provided along with their corresponding base binders by emulsion suppliers and evaluated only in the laboratory. The other three emulsions were obtained during construction of three field sections in Utah Arches National Park; Frederick, Colorado; and Forks, Washington. All three emulsion residue recovery methods were used for the five laboratory emulsions, but only two methods (Stirred Can and Hot Oven) were used for the three field emulsions. Each recovered emulsion residue and the available base binders were characterized by both the standard PG system and the original SPG system and some additional DSR and chemical tests. Shear strain sweeps in the DSR were investigated in this project as an addition to the SPG system for evaluating strain tolerance and resistance to raveling of emulsion residues during curing (before opening to traffic) and at early ages based on work by Kucharek et al. (2007) that ties measured binder properties to sweep test results (ASTM D7000). Further development of the SPG specification including additional comparison of emulsion residue recovery methods produced the following significant results and recommendations: • Properties of the base binders were different at high temperatures, but the same at low temperatures as compared to the recovered emulsion residues. These differences were not enough to change the PG grade. • The gel permeation chromatography chromatograms from all of the emulsion residues

	recovered from both the Stirred Can and Hot Oven recovery methods indicated that water was absent, but the emulsion residues recovered from the Force Draft Oven method did show a small detectable amount of residual moisture. • The carbonyl areas calculated from FT-IR spectra for the emulsion residues indicated that the recovered binders were all slightly more oxidized than the base binders. • The full scale test pavement at Fredrick, Colorado, was assessed visually after one year and good performance was indicated. • A modified SPG emulsion residue specification based on that developed in TxDOT Project 0-1710 was recommended with DSR shear strain sweep thresholds to reflect the significantly different performance of one of the laboratory emulsions and the Utah Arches emulsion. The Stirred Can emulsion residue recovery method was recommended for use with this proposed specification.
Gransberg, D., D, James, 2005. ***Chip Seal Best Practices***. NCHRP Synthesis 342, National Cooperative Highway Research Program, National Academy of Sciences, Washington, D.C.	This synthesis report provides an overview of successful chip seal practices in the United States, Canada, and overseas. Although not meant to be an exhaustive study, it covers the spectrum of chip seal practice and presents, where possible, the state of the art, as reported in the literature and survey responses. The report presents ways to assist in the development and implementation of pavement preservation programs by identifying the benefits of using chip seal as part of a preventive maintenance program. Innovative and advanced chip seal programs from around the world were identified with respect to critical factors that can be incorporated by other transportation agencies. Approximately 40 best practices were identified in the areas of chip seal design methods, contract administration, equipment practices, construction practices, and performance measures. The increased use of chip seals for maintenance can be a successful, cost-effective way of using preventive maintenance to preserve both low-volume and higher-volume pavements. For this synthesis report of the Transportation Research Board, 92 survey responses were received from state DOTs; U.S. cities and counties; Canadian provinces, cities, and territories; Australian and New Zealand provinces; and other public agencies. In addition, a comprehensive review of the literature covering nearly 80 years of research was undertaken, and more than 120 articles on chip seals and preventive maintenance identified. Case studies that illustrate trends found in best practices, taken from those respondents who routinely achieve good results from their chip seal programs, are also presented. In addition, two innovative and emerging technology cases that address areas of concern for the future implementation of chip seals are provided. For materials selection, the following conclusions were presented. The aggregate should be checked to ensure that electrostatic compatibility is met with the type of binder specified. Also, precoating of the aggregate appears to be required for use with hot asphalt cement binders to ensure good adhesion after application. Finally, it appears that the use of geotextile-reinforced chip seal is promising and should be considered for those roads that have more than normal surface distress and for which an overlay is not warranted. Therefore, several best practices can be extracted from the foregoing discussion: 1. Conduct electrostatic testing of chip seal aggregate source before chip design to ensure that the binder selected for the project is compatible with the potential sources of aggregate. 2. Specify a uniformly graded, high-quality aggregate. 3. Consider using lightweight synthetic aggregate in areas where post-construction vehicle damage is a major concern. 4. Use life-cycle cost analysis to determine the benefit of importing either synthetic aggregate or high-quality natural aggregates to areas where availability of high quality aggregate is limited. 5. Use polymer-modified binders to enhance chip seal performance.

CHAPTER 3: ASPHALT BINDER STIFFNESS DEVELOPMENT AND BONDING CHARACTERISTICS OF SEAL COAT BINDERS TO AGGREGATES

BACKGROUND

TxDOT relies greatly on sprayed seals for new road construction (surface treatments) and for preventive maintenance (seal coat). Procedures for pavement maintenance and preservation using seal coats have shown to be successful and effective when done properly. TxDOT specification Item 316 defines a surface treatment as one or more applications of asphalt binder covered with a single layer of aggregate. No matter what materials are used, the success of seal coats and surface treatments depend to a significant extent on the construction process and the field conditions that often necessitate critical field adjustments.

A typical sprayed seal involves a simple and straightforward process. However, monitoring of their performance over the years has highlighted some significant premature failures in the form of flushing and aggregate loss (raveling). These can be attributed to complexities arising from factors such as material selection, quality of materials, application of materials under undesirable conditions, and unforeseen climatic events during construction and post-construction conditions. Senadheera et al. (2006) presented a comprehensive constructability review of seal coat and surface treatment practices in research projects 0-1787, 0-4362, and 0-5169 and highlighted the factors that contribute to seal coat and surface treatment failures.

Modified binders are often used by pavement agencies because of their ability to improve performance over conventional binders. In general, modified binders cost more than conventional binders. The Asphalt Academy (2007) identified the following benefits from using modified binders:

- Improved consistency.
- Reduced temperature susceptibility.
- Improved stiffness and cohesion.
- Improved flexibility, resilience, and toughness.
- Improved binder-aggregate adhesion.
- Improved resistance to in-service aging.

The benefits gained from using modified binders are good for the pavement but because of their higher cost, they may not always be the optimal choice for all situations. Modified binders often have much improved material properties, but that will have to be evaluated along with characteristics of the aggregate, climatic conditions, constructability, and the quality management plan.

The Asphalt Academy (2007) also divided modified binders into two broad compositional groups:

- Homogenous binders: a blend of polymer and bitumen where two distinct phases cannot be detected on a microscopic level (i.e., the material behaves as a single-phase material). Examples of such binders are those modified with elastomers and plastomers.

- Non-homogenous binders: have two distinct, detectable phases and there will be localized differences in properties depending on at what stage a test on the binder is performed. An example of such a binder is crumb rubber modified asphalt.

There are two types of polymers: elastomers and plastomers. An elastomer has a flexible rubber backbone and large side chains in its structure making it elastic and along with that, an ability to recover its shape when unloaded. Some common elastomers are styrene-butadiene-styrene (SBS), styrene-isoprene-styrene, styrene-butadiene-rubber (SBR), polybutadiene (PBD), and natural rubber. SBR is a softer and more adhesive polymer than SBS and is sometimes used in combination with other polymers. PBD modified binders generally have good adhesion characteristics and are used in applications where cohesion and a moderate level of flexibility are required. Some of the earliest modified binders had low levels of natural rubber added to provide enhanced adhesion, but are now rarely used in hot bitumen sprayed sealing applications. However, it is used in the latex form in some modified emulsion applications.

Plastomers, however, will deform in a plastic or viscous manner at higher temperatures and becomes hard at low temperature (Senadheera et al. 2012). Ethylene vinyl acetate (EVA) copolymer, polyolefin, and polyethylene (PE) are some examples of commonly used plastomers (Senadheera et al. 2012). EVA polymers are easily incorporated into bitumen, and provide increased stiffness and deformation resistance, as well as improved cohesion and toughness. EVAs are also used in some slurry surfacing applications. Various forms of PE can be incorporated into hot bitumen, including recycled materials, to provide improved cohesion in sealing applications. Binder properties such as softening point and viscosity depend greatly on the polymer content in a modified asphalt (Figure 2).

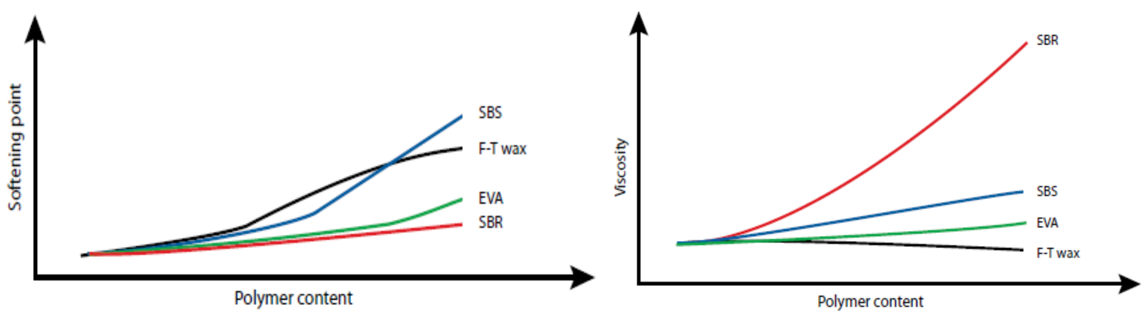

Figure 2. Effect of Various Modifiers on Bitumen Softening Point and Viscosity (Asphalt Academy, 2007).

The polymers are mixed in the pre-blending process, and different quantities of it are added depending on the application. As shown in Table 5, Johnston and King (2008) summarized the work published by several authors on polymer modification of asphalt binders. Surfactants are added in the binder whenever emulsified asphalt is used. Depending on the chemical nature of the emulsifying agents (surfactants), asphalt emulsions can be classified into anionic, cationic, and non-ionic emulsions. Emulsifying agents also help to keep the emulsion in stable condition and controls the breaking and setting mechanism. More details on this topic can be found in TxDOT Report 0-5893-1 (Senadheera et al. 2012).

Table 5. Polymer Modification Methods and Dosages (Johnston and King, 2008).

Type	Method	% Polymer Solids	Application(s)
SBR	Soap pre-batching. NO post or field addition.	3 – 4% of residual asphalt content	Slurry seals
SBR	Not specified	3% of residual asphalt content	Various
SBR (Ultracoat™)	Dilute with water to 15% latex solids and blend with aggregate at collection hopper	15% of total emulsion weight	Polymer anti-strip increases chip seal stone retention
SBR (Butonal LS 198®)	Soap pre-batching. NO post or field addition.	2 – 6% of residual asphalt content, usually 3%	Various
SBR	Soap pre-batching	∃3% of residual asphalt content	Micro surfacing
SBR, NRL, Neoprene, SBS, EVA	Preblend latex solids with bitumen using a high-shear blender. If latex in form, then use soap pre-batching.	2% of residual asphalt content	Micro surfacing
SBR, NRL	Soap pre-batch, co-mill, or post add	3 – 5% of residual asphalt content	Various
SBS	Preblend with asphalt	5 – 12% of residual asphalt content	Various
SBS	Preblend with asphalt binder	> 5% of residual asphalt content (forms continuous polymer matrix)	Various HMA applications
SBS, SB	Preblend with asphalt	6% of residual asphalt content	Various
SBS, SB	Preblend with asphalt	4% by weight of asphalt content	Various low temperature applications
CRM (RG-1)	Post-blended in-line directly with emulsion at plant and remixed before application	5 – 8% of total emulsion weight	Asphalt rubber slurry surfacing
NRL (1497C)	Ralumac Process – Soap pre-batching	4% of total emulsion by weight	Various
EGA (Elvaloy®)	Preblend directly with binder	1.5 – 2.0% of residual asphalt content	Various HMA applications
EVA	Preblend with binder	5% by weight of asphalt content	Various
EVA / EVM	Preblend with binder	6% by weight of asphalt content	Various low temperature applications
EPDM, LDPE, HDPE	Preblend directly with binder	5% of residual asphalt content	Various HMA applications
EVA, LDPE	Preblend directly with binder	4 – 8% of asphalt content by weight	Various
Any Appropriate	Soap pre-batch or preblend with bitumen	3% of residual asphalt content	Micro surfacings
Polyethylene (Tyrin® 2552)	Preblend directly with binder	3 – 5% of residual asphalt content	Various
Various	Various	2 – 10% of residual asphalt content, 2 – 3% most commonly	Various

D'Angelo (2010) indicated that different blending techniques can result in significantly different binder properties despite using the same polymer type and concentration. The three asphalt binder properties, non-recoverable creep compliance (J_{nr}), percent recovery at 3.2 kPa, and the percent elastic recovery (ER) (used by TxDOT for modified binders), were used in D'Angelo's evaluation. The binders LC 4 (with Kraton® 1101 SBS linear polymer) and LOP 4 (with Kraton® 1184 SBS radial polymer) were both used as additives at 4 percent dosage to base asphalt. Results from D'Angelo's MSCR test shown in Table 6 indicate that the LOP 4 binder gives better ER and better performance potential. The addition of 0.5 percent Phosphoric acid (PPA) in the binders LC 4P and LOP 4P showed improved binder properties.

Table 6. Comparison of Different Blending Ingredients and Methods (D'Angelo 2010).

Sample ID	Continuous Grade	Polymer	Acid	Temp (°C)	J_{nr} 3.2 kPa	Percent Recovery 3.2 kPa	Elastic Recovery
LC	66.7–24.1		0	64	3.1	0	5
LC 4	75.7–22.3	4% linear SBS	0	70	1.9	19.2	73.8
				76	4.6	6.0	
LC 4P	81.2–22.2	4% linear SBS	0.50%	70	1.1	28.4	93.8
				76	2.4	20.6	
LOP 4	76.6–25.2	4% radial SBS from concentrate	0	70	1.2	40.3	86
				76	2.4	37.0	
LOP 4P	81.6–24.5	4% radial SBS from concentrate	0.50%	70	0.7	52.1	91.6
				76	1.4	42.5	

Seal Coat Specifications

TxDOT

The selection of asphalt binders for TxDOT seal coat projects is made using the TxDOT SCMST shown in Table 7. This was first introduced as a statewide mandate in 2010. In this table, binder and aggregate choices are presented according to three tiers established based on the traffic level on the highway. An additional factor in the decision making process is the asphalt construction season. Since that time, many districts have adapted to using the table for guidance and incorporating local conditions and experience to provide binder choices to bid for district-wide contract seal coat work.

South Africa

The binder selection practices in South Africa was studied using the guidance documents published by the South African National Roads Agency Ltd and by the Asphalt Academy of the Center for Scientific and Industrial Research. South African binder selection procedure considers factors such as traffic level, average annual temperature and precipitation, roadway location (urban/suburban/rural), road gradient, and maintenance capabilities of the highway agency in the area (The South 2007). Table 8 reproduced from the South African National Roads Agency (2007) show how the traffic volume and climate variables (temperature and precipitation) are factored in the decision-making process.

Table 7. TxDOT SCMST.

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Seal Coat Material Selection Table		
Tier I: Heavy Use - Use only the selected materials.		
Type	Asphalt Rubber (A-R) A-R Only	Asphalt Cement (AC) AC Only
Asphalt	A-R Ty II SP 300- A-R Ty III	AC-20-5TR AC-15P AC-20XP SP 300-
Tier II: Moderate Use - Use these materials or any selected Tier I material combinations of the allowed types.		
Type	Asphalt Cement (AC) AC Only	Asphalt Emulsion Emulsion Only
Asphalt	AC-10-2TR AC-15P AC-20XP AC-10 w/2%SBR AC-5 w/2%SBR SP 300-	CHFRS-2P HFRS-2P CRS-2P SP 300-
Tier III: Light Use - Use these materials or any selected Tier I or Tier II material combinations of the allowed types.		
Type	Asphalt Cement (AC) AC Only	Asphalt Emulsion Emulsion Only
Asphalt	AC-10 AC-5 SP 300-	CRS-2 CRS-2H HFRS-2 SP 300-

Districtwide Seal Coat Project Seasons: Refer to Item 316 for temperature and weather restrictions.	
Season 1: AMA, CHS, LBB	May 15 to Aug 31
Season 2: ABL, ATL, BWD, DAL, FTW, LFK, ODA, PAR, SJT, TYL, WAC, WFS	May 1 to Aug 31
Season 3: AUS, BMT, BRY, ELP, HOU, SAT, YKM	May 1 to Sept 15
Season 4: CRP, LRD, PHR	Apr 1 to Sept 30
Note: Seal coats on routine maintenance contracts must be completed by August 31 unless otherwise shown on the plans.	

Once a binder is selected, controls for temperature and holding time are established for short-term handling, storage, and application to minimize aging of the binder during handling, storage, and construction. Binder acceptance is based on results from numerous tests and supported by a robust quality management plan. For bitumen-rubber, the compression recovery test (@ 5 minutes, 4 hours and 4 days), Ring and Ball (R&B) softening point test, resilience test, flow test, and dynamic viscosity (Haake) test are conducted. For polymer-modified emulsion, tests are conducted on both the emulsified asphalt and the residue. The tests conducted on emulsified asphalt are similar to TxDOT practices. However, the R&B softening point, ER, and force ductility test are conducted on the residue.

Table 8. Recommended Binders (The South 2007).

Traffic (elv/l/d)	Winter : Dry	Summer: Dry	Winter and Rain *(c)	Summer and Rain *(c)
<10 000	(i) 80/100 pen bit + cutter * **(b)** (ii) MC 3000 (iii) Emulsion (80/100 pen base bitumen) (iv) Lowveld - 80/100 pen bitumen (v) Modified hot binder or emulsion *(**d**)	(i) 80/100 pen bitumen (ii) 65% emulsion (80/100 pen base bitumen) (iii) Highveld -80/100 pen bitumen (iv) Modified hot binder or emulsion *(**d**)	(i) Cationic emulsion (quick setting) (ii) MC3000 (iii) Modified hot binder *(**d**)	(i) 80/100 pen bitumen + 2% cutter * **(a)** (ii) Cationic emulsion (iii) Modified hot binder *(**d**)
10 000 - 20 000	(i) 80/100 pen bitumen + cutter *(**b**) (ii) Modified hot binder or emulsion *(**d**)	(i) 80/100 pen bitumen (ii) Modified hot binder or emulsion *(**d**)	(i) Modified hot binder or emulsion *(**d**)	(i) 80/100 pen bitumen + 2% cutter *(**a**) (ii) Cationic emulsion (iii) Modified hot binder *(**d**)
20 000 +	(i) Modified hot binder *(**d**)	(i) Modified hot binder *(**d**)	(i) Modified hot binder *(**d**)	(i) Modified hot binder *(**d**)

*MC 3000: Cutback Bitumen with 3000-6000 cSt application viscosity

Binder-Aggregate Bonding

Bonding Mechanisms

Bahia et al. (2007) indicated that the affinity of aggregate to water is a very important factor that determine asphalt adhesion and its stripping potential. Table 9 illustrates the stripping potential of asphalt based on the affinity of the aggregate to water.

Table 9. Relationship between Aggregate Mineralogy and Moisture Damage (Bahia et al. 2007).

Aggregate Affinity	Definition	Composition	Silica Content	Resistance to Moisture Damage
Hydrophilic	Have a greater attraction for water than for asphalt binder	Acidic	High	Poor
Hydrophobic	Have a greater attraction to binder than water	Basic	Low	Good

There are two type of binder failure: adhesive and cohesive. Adhesive failure occurs at the interface between binder and aggregate and cohesive failure occurs within the binder. Bahia reported that the most common binder failures are of the cohesive kind (Morales et al. 2011).

Based on the field testing conducted for NCHRP 680, Shuler concluded that cationic-anionic attraction does not necessarily improve bonding strength between aggregate and binder (Shuler et al. 2011). The bonding process of aggregate and emulsified asphalt binder consist of several mechanisms: wetting, breaking, and curing.

Wetting

The moment aggregate comes in contact with the asphalt binder, the wetting process begins. Wetting is defined as the process when the binder tries to coat the aggregate surface that touches it. There are several mechanisms related to wetting: spreading, wetting, and dewetting. The effectiveness of the wetting process is dictated by the surface tension at the interface of the materials in contact (Figure 3).

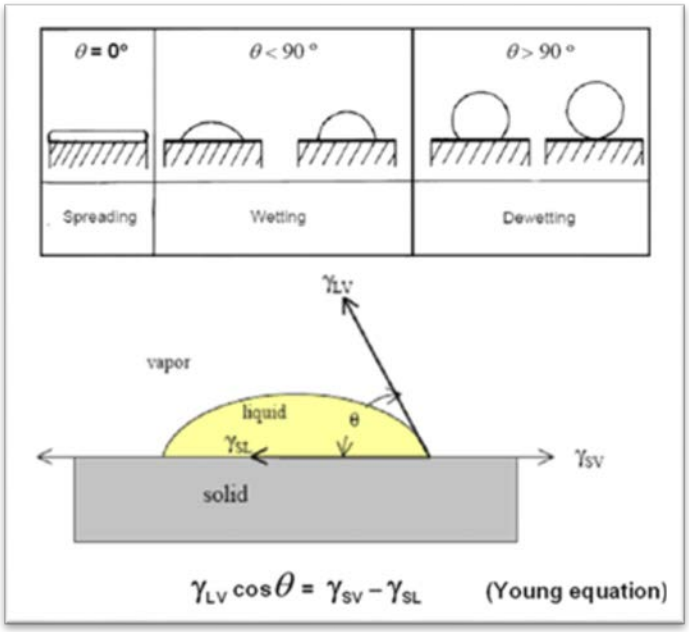


Figure 3. Wetting and Surface Tension.

Complete wetting occurs when the contact angle (θ) is equal to zero, making the surface tension between asphalt and vapor (γ_{Lv}) less than or equal to the surface tension between solid aggregate and vapor (γ_{Sv}). This would mean that the surface tension of binder is much lower than that of the aggregate. Hooleran (1999) indicated that a system with a strong energy difference between surfaces will require extra driving force to remove water, and this is usually achieved using cement.

Breaking and Curing

Breaking is a mechanism in emulsified asphalt, which involves the separation of water from emulsion. It is vital for breaking to happen for the emulsified asphalt to perform its ultimate function as a binder (Senadheera et al. 2006). Curing, however, involves the removal of water from the emulsified asphalt, either by evaporation or through aggregate absorption. According to the Asphalt Emulsion Manual, several factors affect breaking and curing rates of asphalt emulsions: water absorption, aggregate moisture content, weather conditions, mechanical forces, aggregate surface area, surface chemistry, emulsion and aggregate temperature, and the type and amount of emulsifier (Asphalt Institute 1997).

Tests on Seal Coats and Their Constituent Materials

The testing methods will be divided into two categories: tests on binder and tests on seal coats.

Binder Tests

Bitumen Bond Strength Test

Bitumen Bond Strength (BBS) test was developed by Bahia et al. (2007) at the University Wisconsin at Madison. It uses Pneumatic Adhesion Tensile Testing Instrument to measure adhesive and cohesive strength of binder. An asphalt sample is attached to a pull-out stub, which is then attached it to the aggregate substrate. This system is placed in the water bath for several hours for moisture conditioning. Morales found that the pull-off tensile strength value of the asphalt-aggregate bond decreased when samples are conditioned in water, regardless of the aggregate-binder material combination. Statistically analysis showed that the BBS test also yielded good repeatability between different laboratories (Morales et al. 2011).

Results from the BBS test shows that polymers improve the adhesion between asphalt and aggregates as well as the adhesion within the binder (Morales et al. 2011). The bond between the aggregate and binder is highly dependent on the binder modifier and the conditioning time. The failure mechanism does change due to presence of water, cohesive for dry samples and adhesive for wet samples. PPA was found to significantly improve moisture resistance of asphalt aggregate, especially on acidic and granite aggregates. All PPA modified binder have cohesive failure, an indication that bond at the aggregate-binder interface is greater than the cohesive strength of the binder. A workshop held in 2009 that focused on PPA provided evidence pointing to increased moisture damage potential in PPA-modified binder at application rates higher than 1.5 percent (D'Angelo 2010). Field tests conducted in several states have shown that there are no negative effects with PPA modified binder as long as dosage levels stay in the range between 0.25 percent and 1.2 percent.

Frequency Sweep Test

This test was developed as an alternative to the BBS test to specify sprayed seal binders. The test is performed on pressure aging vessel (PAV)-aged binder samples using the 8mm DSR plate and a 2mm gap at frequencies ranging from 1 to 150 rad/s and intermediate temperatures of 15°C, 10°C, and 6°C (Epps Martin et al. 2012). From this test, the complex modulus and phase angle of the asphalt binder can be obtained.

Multiple Stress Creep Recovery Test

This test was developed to be an improvement from the Superpave PG Asphalt Binder specification in AASHTO TP70 and AASHTO MP19. A new high temperature binder specification was developed to more accurately predict rutting in asphalt concrete. Using the DSR equipment, the sample is loaded in shear for one second and then the shear stress is removed allowing it to relax for 9 seconds. This load-unload cycle was repeated nine more times for a total of 10 cycles. The non-oscillating shear stresses of 0.1kPa and 3.2 kPa were applied one after the other for 10 cycles apiece. Two binder parameters, the percent recovery of shear strain and the non-recoverable creep compliance (J_{nr}), are calculated from the results of this test.

Work by D'Angelo (2010) showed that polymer modified binders displayed an increase of ER values at lower stress levels compared to unmodified binders. D'Angelo also indicated that the MSCR is preferred over the ER test because the ER test does not seem to distinguish between different polymer systems.

Golalipour (2011) conducted tests on the MSCR Test and found an extremely high variability results for 0.1 kPa shear stress. The study also found that the current method of averaging the results for 10 cycles at each stress level could give misleading information regarding the binder performance. Therefore, he recommended using 30 cycles and performing the test at 3.2–10 kPa stress level. In addition, he suggested J_{nr} and % Recovery limits should be changed to account for the non-linear relationship between these parameters and the traffic characteristics.

In general, polymer modified binders may cost as much as 30 percent more from unmodified binders. Using the Federal Highway Administration (FHWA) Life-Cycle Cost Analysis software *RealCost v2.2.2*, Lee and Kim found that polymer modified emulsion is a cost-effective solution as long as it gives at least two additional years of service life (Lee and Kim 2009). Therefore, it was recommended to adjust the construction procedures for chip seals that use polymer modified binders in order to get the maximum benefit from it:

- ER measured in the ductility bath can be replaced by ER measured in DSR (R^2=0.97).
- The correlations between ER-DSR and number of cycles to failure from the time sweep at 10 kPa and 20 kPa, and to the linear amplitude sweep results were relatively poor, so using ER as a surrogate to fatigue is not promising.
- Correlation between ER from DSR and ER from MSCR at 0.1 kPa is poor (R^2=0.04) but better at 3.2 kPa (R^2=0.71).

Seal Coat Tests

Shuler's NCHRP 14-17 Report No. 680 recommends several tests method to measure chip seal performance (Shuler et al. 2011):

1. Test for Laboratory Chip Loss from Emulsified Asphalt Chip Seal Samples. This test is a modification of the ASTM D7000 test, where users can adjust initial chip embedment, percent moisture lost from the emulsion, and consistent aggregate application. It was suggested that by doing this test, users can find the percentage aggregate loss at different moisture level of asphalt emulsion by simulating the brooming of chip seal. Significantly higher chip loss percentages were measured for dry aggregates as opposed to saturated-surface-dry aggregates. However, no significant difference in chip loss was observed between cationic and anionic emulsions when used with either calcareous or siliceous aggregates.
2. Test for Measuring Moisture Loss from Emulsion Chip Seals. A close monitoring of an equivalently constructed and cured chip seal specimen is done by getting the chip seal sample from the field. Data are recorded at least once per hour until desired curing level is achieved. Result from this test indicates that when 90 percent aggregates are retained during the sweep test, it is safe to open traffic.
3. Asphalt Emulsion Recovery by Stirred-Can Method. A 1,250 g sample of asphalt emulsion is placed into the testing device. The device will require nitrogen to prevent oxidation and

aging. Results from the test indicated that the test provides a rapid and good simulation of the base asphalt material properties. Recovered emulsion residue was shown to be different from their base binders at high temperature before aging, but similar to the base binders at cold temperature after PAV aging.

4. Strain Sweep Test. This DSR-based test is used to find the complex shear modulus (G*) of the binder. Procedures are as described in AASHTO T315 using 8-mm plates with 2-mm gap except frequency is set to 10 rad/s. The test is conducted on un-aged and PAV-aged materials. A 10 percent reduction in G* indicates that the material is behaving nonlinearly and accumulating damage. Fifty percent reduction in G*, however, defines failure of the material. The percent reduction in G* reduction can be used to indicate when the material will exhibit raveling. Recovered emulsion residue was shown to be different from their base binders at high temperature before aging, but similar to the base binders at cold temperatures after PAV aging.

Modified Vialit Adhesion Test (MB-7) – South Africa

In this test method, the binder is heated in the oven to a temperature of 160°C and then applied to a metal plate placed on a hot plate at 65°C. The specimen on the plate is then removed and the aggregate is rolled three passes perpendicular to one side. The specimen plate is then rotate 90° and another three roller passes are applied. Rolling must be done within one minute of removing the test plate from the hot plate. The specimen is conditioned for one hour at 5°C or 25°C apiece. The plate is then turned upside down within the Vialit apparatus and a steel ball is dropped on the inverted plate. The degree of aggregate retention (*R*) is calculated using the equation:

$$R = (Z-L)/Z * 100$$

Where, *L* is the number of aggregate particles (chips) lost when loaded, and *Z* is the total number of chips applied to the sample.

The primary differences between the Modified Vialit Test and the Standard Vialit Test (California) are that the standard test only requires dropping the ball for three times. Louw conducted a study to find out whether the current Vialit Test gives valid results to predict low temperature failure (Louw et al. 2004) and concluded that the current test is not suitable for evaluating the low temperature performance of polymer modified binders. He also found that adhesion is a function of the texture (smooth or rough) of the test plate.

Lee and Kim (2009) conducted field and laboratory experiments to compare the performance of unmodified (CRS-2) and polymer modified (CRS-2L and CRS-2P) emulsions. They found that CRS-2L emulsion has less aggregate loss and requires less curing time, allowing for pavement to be opened sooner. CRS-2L also improves aggregate retention at low temperatures, making it a suitable binder for winter. Curing temperature is found to be a very important that will dictate adhesion development, especially for CRS-2. They observed that the benefits of using polymer modified binder in chip seals diminish for lightweight aggregate because they display better bonding characteristics due to the porosity and surface texture. They also observed that flushing and bleeding can be reduced by using polymer modified binder.

Mechanistic Model for the Seal Coat System under Traffic Load

One of the primary distresses associated with seal coats is flushing. In Texas, flushing is the predominant form of seal coat distress that reduces pavement surface macro-texture, and as a result, it is wet-weather skid resistance. Therefore, it is important to understand what causes the flushing distress in seal coats and to evaluate seal coat binders in terms of their propensity to cause flushing. Researchers and practitioners generally agree that flushing is caused by the penetration of aggregate particles under traffic loading into the softer asphalt layers below during hot summer days when the pavement temperatures hover in the 140°–160°F range. The extent of penetration of aggregate into the asphalt depends on the load, travel speed of the vehicle, asphalt binder properties, and the degree of support from underlying layer. The lower the degree of support (caused by softer underlying layer) is, the higher the shear stress around the aggregate particle and higher the penetration of the aggregate. With each passing heavy vehicle axle, the aggregate gets pushed-in even more. There will be some rebound of the aggregate once the axle moves away from its location, which will depend on binder properties and the time between loading cycles. Figure 4 shows a schematic of an idealized cylindrical piece of seal coat aggregate embedded in asphalt subjected to a vertical force exerted by a vehicle tire. In this case, two wheels on one side of a standard 18-kip axle is considered equivalent to one circular loaded area with a diameter of 12 inches.

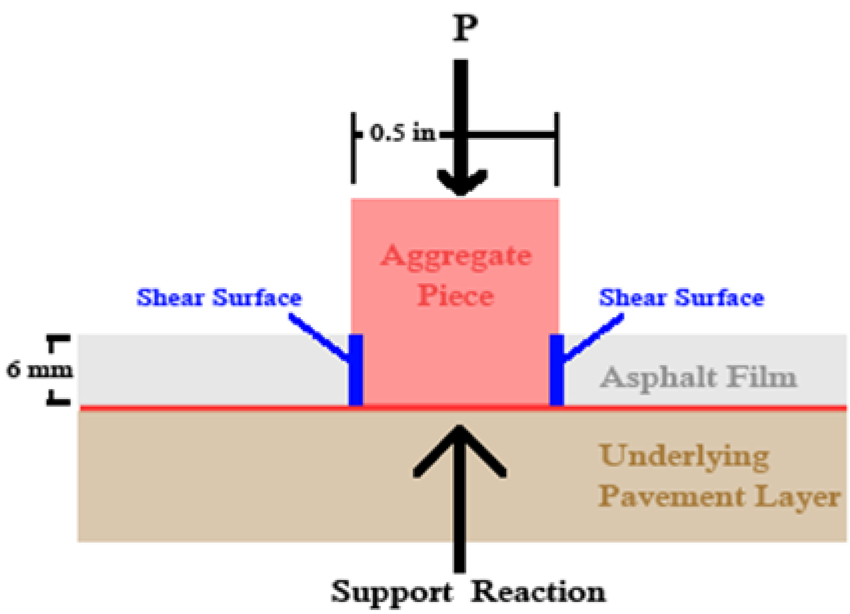


Figure 4. Schematic Showing Loaded Seal Coat Aggregate Piece.

$$\text{Contact Area of the tire imprint} = A = \pi(0.5ft)^2 = 0.25\pi\ ft^2$$

Assuming that 70 percent of the tire contact area on the seal coat is covered with aggregate particles:

$$\text{Area of aggregate pieces under a tire} = 0.25\pi * 0.70\ ft^2$$

For a cylindrical aggregate piece with a diameter of 0.5 inches:

Number of aggregate pieces within the tire contact area is equal to $\frac{0.25\pi * 0.7\,ft^2}{\frac{\pi*(0.25in)^2}{144\,in^2/ft^2}/piece}$= 403 pieces

Assuming that the 900 lb wheel load is uniformly distributed over the circular loaded area:

The vertical force acting on each aggregate particle is equal to $\frac{9{,}000\,lb}{403\,pieces}$= 22.3$\frac{lb}{piece}$

For the case where there is no support on the aggregate from the underlying layer and when the aggregate is embedded 6mm into asphalt (for a 50 percent embedment):

Shear Stress at the aggregate-binder interface due to wheel load =

$\frac{22.3\,lb}{\left(\pi*0.5in*\frac{6mm}{25.4\,mm/in}\right)}$ = 60.1 psi = 413 kPa

This is for the special case of zero support from the layer below. However, in actual situations, the underlying layer provides support to the aggregate, which will reduce the shear stress on the asphalt binder at the aggregate-binder interface around the particle.

Based on the mechanistic model described above, shear stress on the binder can be calculated for various degrees of support on the aggregate particle. Table 10 shows some typical values.

Table 10. Shear Stress on Binder for Different Degrees of Support from Underlying Layer.

Degree of support from underlying layer (%)	Shear Stress on Binder (kPa)
95	20.65
98	8.26
99	4.13
99.9	0.413
99.99	0.0413

In the MSCR test protocol proposed by D'Angelo, the standard shear stress settings are 0.1, 3.2, and 10.0 kPa. Table 11 shows the degree of support values calculated using the mechanistic model that correspond to the three standard shear stress values used in the MSCR test.

Table 11. Shear Stress on Binder for Different Degrees of Support from Underlying Layer.

Degree of support from underlying layer (%)	Shear Stress on Binder (kPa)
97.6	10
99.2	3.2
99.97	0.1

Based on the calculations above, the stresses levels of 0.1 kPa and 3.2 kPa are very small and conservative for summer pavement conditions. The 10 kPa stress will actually give better representation of the support on the field even though it might actually be way smaller when the base is an old pavement seal. It is also found from the loading simulation that the amount of shear one aggregate experienced is way greater than the amount of shear required to pull the aggregate from the pull-out test. This indicates that the support reaction is playing a very significant role in the development of flushing. This idea of support reaction is very promising since it might be the explanations on why a binder is more or less susceptible to flushing. However, more studies and tests need to be done to confirm this idea.

Laboratory Evaluation

The research team collected all the site asphalt binder samples from FY 2013 chip seal construction projects. A total of eight asphalt binders were tested including AC-10, AC-10 2TR (two sources), AC-15P, AC-20 5TR (two sources), and AC-20 XP (two sources).

In this laboratory test program, two tests were conducted on asphalt binders: strain sweep test using the DSR and the MSCR test. The strain sweep test was used to identify the rheological characteristic of the binder under different strain intensities. The MSCR test that was originally developed to characterize rutting potential of asphalt concrete was selected due to its ability to evaluate asphalt binder creep and recovery characteristics. The influence of asphalt binder properties on flushing, which is one of the two primary distresses in seal coats, can be assessed based on results from the MSCR test. These two tests were conducted on both the un-aged and rolling thin film oven (RTFO)-aged binder. The RTFO aging method was used based on historical field observations that indicate the aggregate loss (raveling) to likely to occur during the first winter after the seal is placed, which is typically within a few months from seal coat placement.

Strain Sweep Test

The strain sweep test uses the DSR to investigate the elastic, viscoelastic, and viscous behavior of the asphalt and to identify its linear viscoelastic region. An asphalt binder is considered to be in the linear viscoelastic region when it is dynamic stiffness (G*) is within 95 percent of the G*. The strain sweep test is conducted by calculating the stresses at different shear strains of the specimen at a certain temperature. This test applies an oscillating motion similar to that of the standard DSR test. From there, G* will be recorded. All strain sweep tests in this research were conducted at 64°C and for strains up to 100 percent.

Multiple Stress Creep Recovery Test

The MSCR Test (AASHTO TP 70-12) is used to evaluate the flushing potential of seal coat binders. This test uses the DSR equipment configuration shown in Figure 5. Both un-aged and RTFO-aged binders were tested and each of them subjected to a 10-minute, 64°C temperature conditioning. This temperature was chosen to represent the hottest pavement temperature in Texas during summer. The standard test calls for 10 creep cycles with a duration of 10 seconds each (one second of creep shear stress followed by 9 seconds of recovery under zero stress). The loading was done at three shear stresses level: 0.1kPa, 3.2 kPa, and 10kPa. Several adjustments are made from the standard protocol to investigate the effect of longer recovery periods resulting from longer recovery periods (i.e., low truck traffic volumes). The creep portion was kept one second but recovery period was increased to 59 seconds. The 10 kPa stress level was added to the other two standard stress levels because the researchers believe that higher stress level would better represents the pavement response under summer conditions.

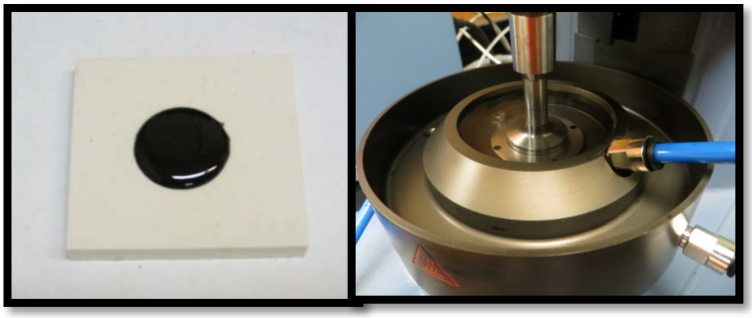


Figure 5. DSR Specimen and Test Setup.

One unique parameter the MSCR test uses is the non-recoverable creep compliance, J_{nr}, and it is calculated:

$$J_{nr} = \frac{\varepsilon_{10}}{\sigma}$$

ε_{10} = un-recovered accumulated strains at the end of 10th cycle.
σ = Shear stress applied.

Figure 6 shows a typical accumulated shear strain curve for one cycle of the MSCR test. A specific shear stress is applied for one second, and then the shear stress is removed causing recovery of the shear strain for a period of 59 seconds.

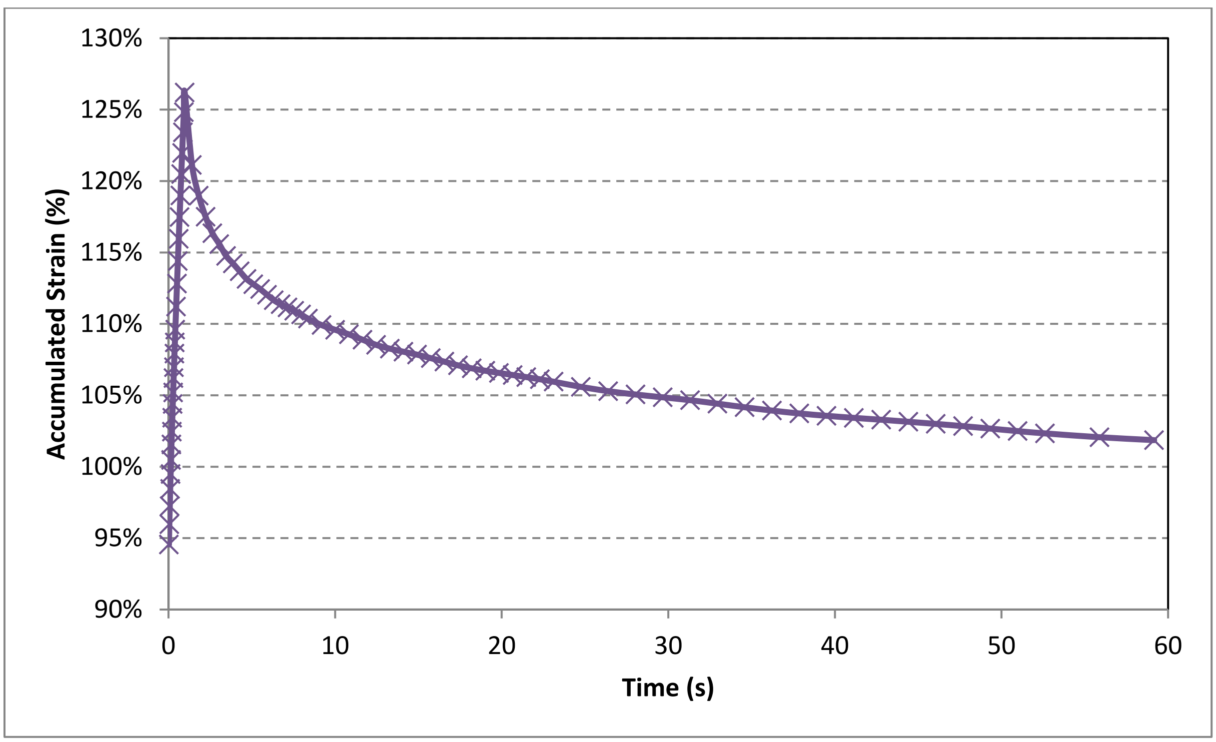


Figure 6. Accumulated Percent Strain for One Cycle of MSCR Test.

Rolling Thin Film Oven Aging Test

Oxidation and hardening occur whenever asphalt binder is either heated or exposed to the environment for long periods of time. For mixing and spray applications, the asphalt binder needs to be heated to temperatures in the region of 300–350°F. In the case of asphalt binders modified with higher quantities of crumb rubber, the heating temperature needs to be in excess of 400°F. These operations create oxidation and hardening, which is referred to as aging. The rolling thin-film oven test (AASHTO T 240 standard test procedure) is used to simulate the short-term aging that occurs during the construction process. An asphalt sample weighing 35 g is placed in a cylindrical glass bottle and the bottle is inserted into the RTFO rack. The oven must be pre-calibrated, and its interior temperature is maintained at 325°F for at least 2 hours with hot air constantly injected into the asphalt bottle at a rate of 4 liters per minute. At the end of this simulated aging process, the sample of asphalt is taken out and tested to determine its various properties. For simulation of long-term aging under service conditions, the PAV is used. However, in this research, since asphalt hardening that leads to rock loss is generally an early phenomenon that occurs during the first winter months, which is often within the first few months of the seal coat life, the research team felt that RTFO is a better way to age the asphalt.

Pull-Out Test

The pull-out test was developed at the Texas Tech laboratories to measure shear strength at the interface of various binder-aggregate combinations. Larger aggregate cobbles or boulders are sliced and then cored to make cylindrical aggregate pieces with 0.5 inches diameter and approximately 0.5 inches high. The cored sample is sliced using a precision saw as shown in Figure 7 to ensure that the flat end surfaces of the cylindrical particle are flat, smooth, and most importantly perpendicular to the axis of the cylinder. One flat end of each aggregate piece is then glued using Super Glue® to the head of a screw nail. Next, a two-inch diameter O-ring is glued onto a steel plate. The cored aggregate specimen, along with the glued screw is then washed-dried and placed flat face down and the screw pointing up at the center of the O-ring. Six grams of asphalt is poured onto the steel plate in the area between the O-ring and the aggregate piece. The O-ring thickness carefully selected to provide the proper embedment depth to the aggregate piece when asphalt is poured around it. The steel plate along with the aggregate piece and the glued nail are then placed in a 325°F oven for approximately 3 minutes to level-off the binder around the aggregate.

The finished specimens are then taken out of the oven and were subjected to different climate-conditioning regimes to simulate different field conditions before they were subjected to the pull-out test. Three replicates were tested for each aggregate-binder-conditioning combination. Table 12 shows the different types of specimen conditioning regimes used.

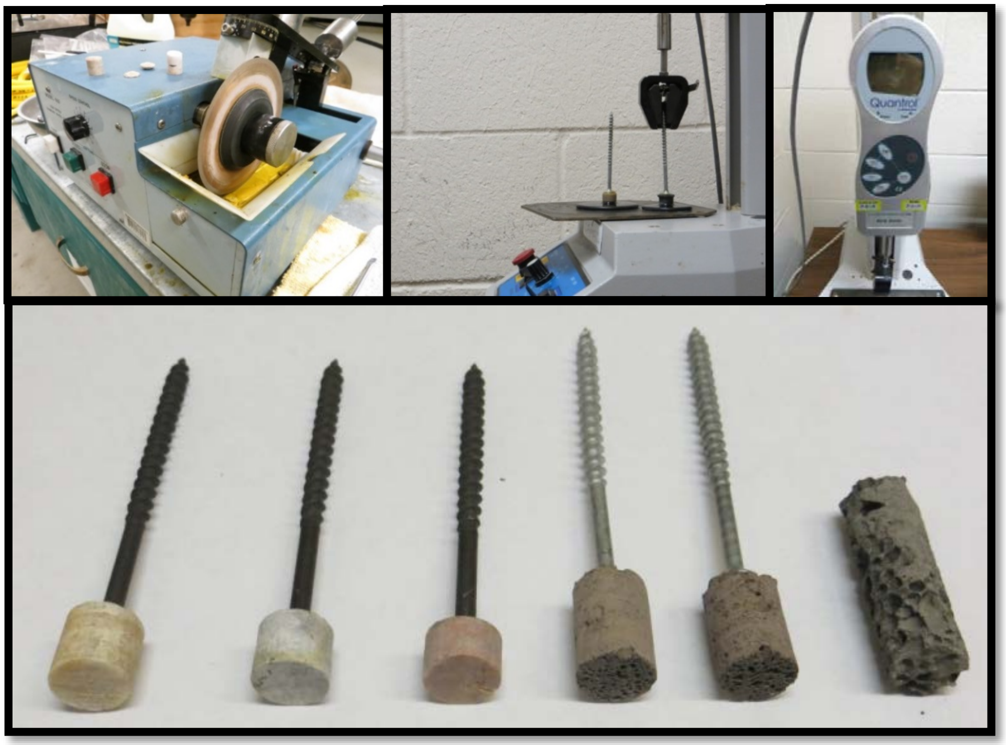


Figure 7. Elements of the Pull-Out Test, (a) Precision Saw to Cut Aggregate Pieces, (b) Test Configuration, (c) Force Gage Used to Measure Pull-Out Force, (d) Pieces of Aggregate Used in the Pull-Out Test.

Table 12. Service Climate Simulation Conditions for the Pull-Out Test.

Conditioning	**Descriptions**
U-ROOM	Specimen is placed in room temperature for 4 hours then it is tested at room temperature
F-ROOM	Specimen is frozen at −10°C for 18 hours then tested at room temperature
F-LOW	Specimen is frozen at −10°C for 18 hours then tested at low temperature
F-T ROOM	Specimen is frozen at −10°C for 18 hours then thawed for 2 hours for 3 times before it is tested at room temperature
F-T LOW	Specimen is frozen at −10°C for 18 hours then thawed for 2 hours for 3 times before it is tested at low temperature
SOAK-ROOM	Specimen is soaked in a room temperature water bath for 18 hours then tested at room temperature
SOAK-F-ROOM	Specimen is soaked in a room temperature water bath for 18 hours then frozen at −10°C for 18 hours then tested at room temperature
SOAK -F-LOW	Specimen is soaked in a room temperature water bath for 18 hours then frozen at −10°C for 18 hours then tested at low temperature
SOAK-F-T-ROOM	Specimen is soaked in a room temperature water bath for 18 hours then frozen at −10°C for 18 hours then thawed for 2 hours; repeat for 3 cycles before testing at room temperature
SOAK-F-T-LOW	Specimen is soaked in a room temperature water bath for 18 hours then frozen at −10°C for 18 hours then thawed for 2 hours; repeat for 3 cycles before testing at low temperature

After conditioning, the test specimen system is mounted onto the pull-out test machine as shown in Figure 7. During the pull-out, the force and time are automatically captured from the testing machine. The time is then converted into elongation using the average pull-out rate setting.

Analysis of Results

This section presents results from three tests. Two tests, the strain sweep test and the MSCR test, were conducted on each binder both at the un-aged and RTFO-aged state. In addition, a laboratory pull-out test was developed to characterize the bond between the asphalt and an embedded aggregate particle. In addition to the various binder-aggregate combinations, specimens were conditioned to simulate field service conditions by combining freezing, soaking, and thawing in various combinations outlined in Table 12.

Strain Sweep Test

Figure 8 and Figure 9 present the results from the strain sweep test conducted on both un-aged and RTFO-aged binders where the asphalt binder complex shear modulus (G*) is plotted against percent strain. As expected, the complex shear modulus increased in the order of lowest (unmodified AC-10) to the highest (AR). For both un-aged and RTFO-aged binder, the increasing order of binder stiffness was AC-10, AC-10 2TR, AC-15P, AC-20 5TR, AC-20 XP, and AR. The percentage increase in G* from un-aged to aged state is lowest for AC-10 and AR binders (less than 100 percent) and higher for the other modified binders (more than 100 percent). The AR binder shows the lowest increase (35–40 percent), and the AC-20 5TR shows the highest (150 percent) increase.

The black square dot in Figure 8 and Figure 9 represents the 95 percent of the zero-strain complex shear modulus (G*) that is used to represent the end of the linear viscoelasticity (LVE) limit for the binder. As expected, the increased stiffness due to aging shifted the LVE range of the binder to the right of the percent strain scale for several binders. For others, it remained roughly the same. The AC-10 binder shifted the most and AR binder the lowest. The higher shift in LVE limit indicates that the binder aged significantly in the RTFO and will likely age more under service conditions. A good binder will have higher un-aged G* for resistance to flushing and a small shift of LVE limit indicating lower aging potential.

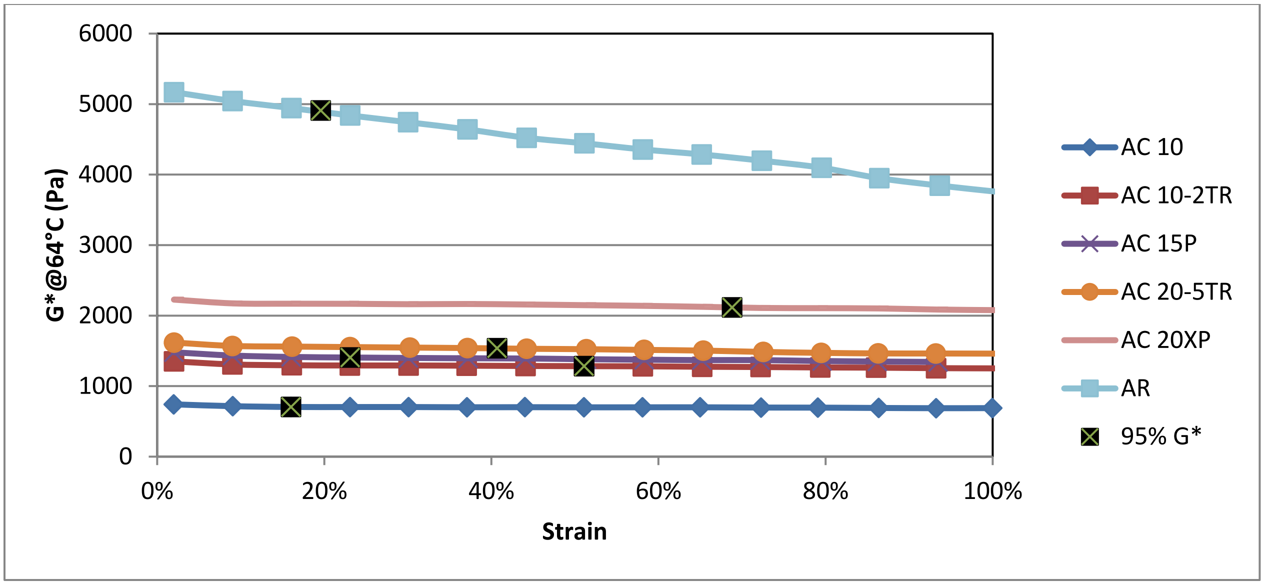


Figure 8. Strain Sweep Results for Un-Aged Binders.

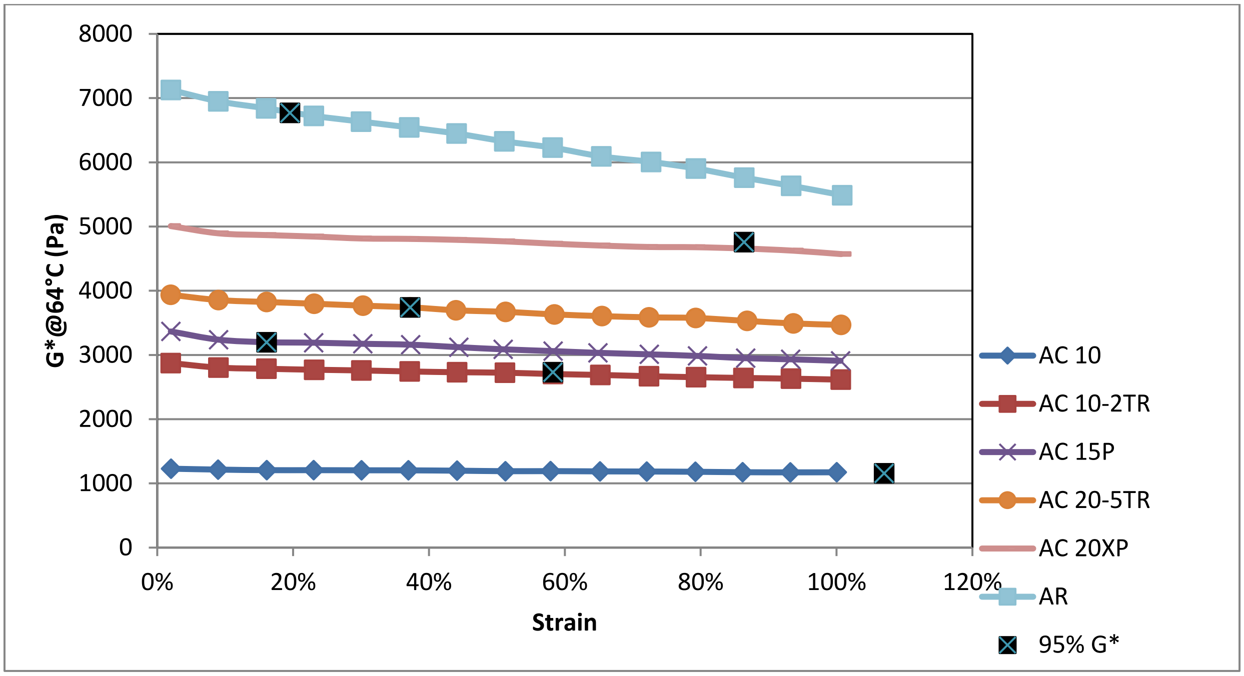


Figure 9. Strain Sweep Results for RTFO-Aged Binders.

MSCR Test

As indicated in a previous section, the MSCR test was run at three shear stress levels: 0.1 kPa, 3.2 kPa, and 10 kPa. The standard DSR binder grading test procedure and the strain sweep test per AASHTO TP 315-12 uses an oscillating motion with an angular frequency of 10 radians/second to mimic the actual traffic speed. The standard MSCR test protocol uses a non-oscillating motion and the angular speed is adjusted for the three stress levels of 10 kPa, 3.2 kPa, and 0.1 kPa to 7.2, 2.1, and 0.1 radians per second, respectively. Many researchers have suggested that applying higher stresses will gives better indications of binder quality and better repeatability of results. The higher stress levels have also been reported to alter the molecular structure of the modifier, and of the asphalt itself.

Table 13 and Figure 10 through Figure 12 show the J_{nr} values for both un-aged and aged binder at 0.1 kPa, 3.2 kPa, and 10 kPa stress levels, respectively, at the end of the 59-second recovery period of the 10th cycle. As expected, the aged binder has lower J_{nr} values indicating higher stiffness, and the J_{nr} values increased as the stress levels increased. A lower J_{nr} value indicates a stiffer binder at higher service temperatures that will perform better in terms of flushing. Different binders showed different degrees of stiffening from the aging process. AC-10 shows the highest J_{nr} values at all three stress levels and the AR binder the lowest. There appears to be a significant difference between the two sources of AC-10 2TR binder with the AC-10 2TR 2 being much softer and more likely to flush compared to AC-10 2TR 1. The J_{nr} values for unmodified AC-10 and the modified AC-10 2TR 2 under RTFO-aged conditions were almost identical for all three stress levels, possibly indicating that the modification may not help much as far as flushing is concerned. There was also a difference in J_{nr} for AC-20 5TR sources, but they were not as pronounced as for AC-10 2TR sources. At the 10 kPa stress level, the AC-20 XP showed somewhat smaller J_{nr} values than the AR binder.

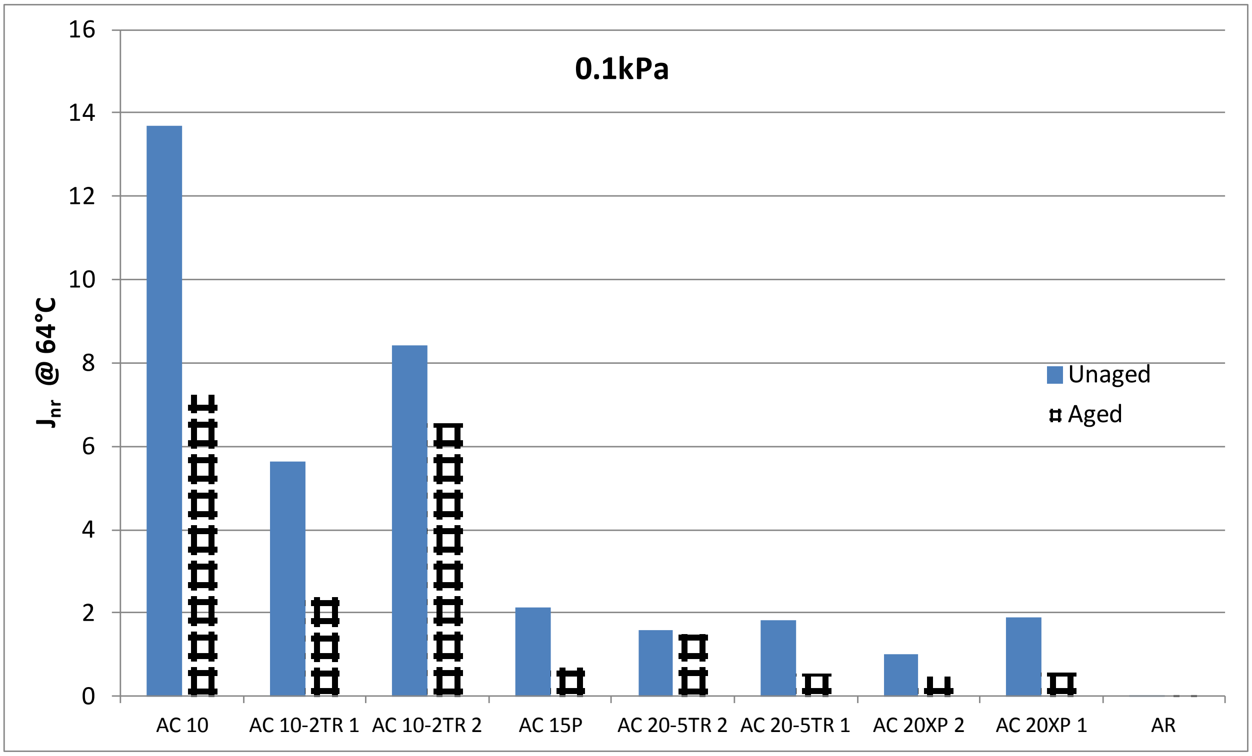


Figure 10. J_{nr} at 0.1 kPa Stress Level.

Table 13. J_{nr} for Un-Aged and RTFO-Aged Binder.

Binder	0.1 kPa		3.2 kPa		10 kPa	
	Un-Aged	RTFO-Aged	Un-Aged	RTFO-Aged	Un-Aged	RTFO-Aged
AC 10	13.67	7.23	14.80	8.37	15.77	8.91
AC 10-2TR 1	5.65	2.48	7.88	3.65	9.10	4.24
AC 10-2TR 2	8.43	6.55	10.25	8.36	11.41	9.22
AC 15P	2.14	0.79	4.61	1.20	7.68	1.91
AC 20-5TR 1	1.82	0.52	4.45	1.03	6.16	1.56
AC 20-5TR 2	1.58	1.49	3.85	2.41	6.57	3.40
AC 20XP 2	1.87	0.55	2.50	0.81	3.64	1.11
AC 20XP 1	1.01	0.47	1.71	0.78	3.23	1.11
AR	0.00	0.00	0.53	0.28	1.99	1.48

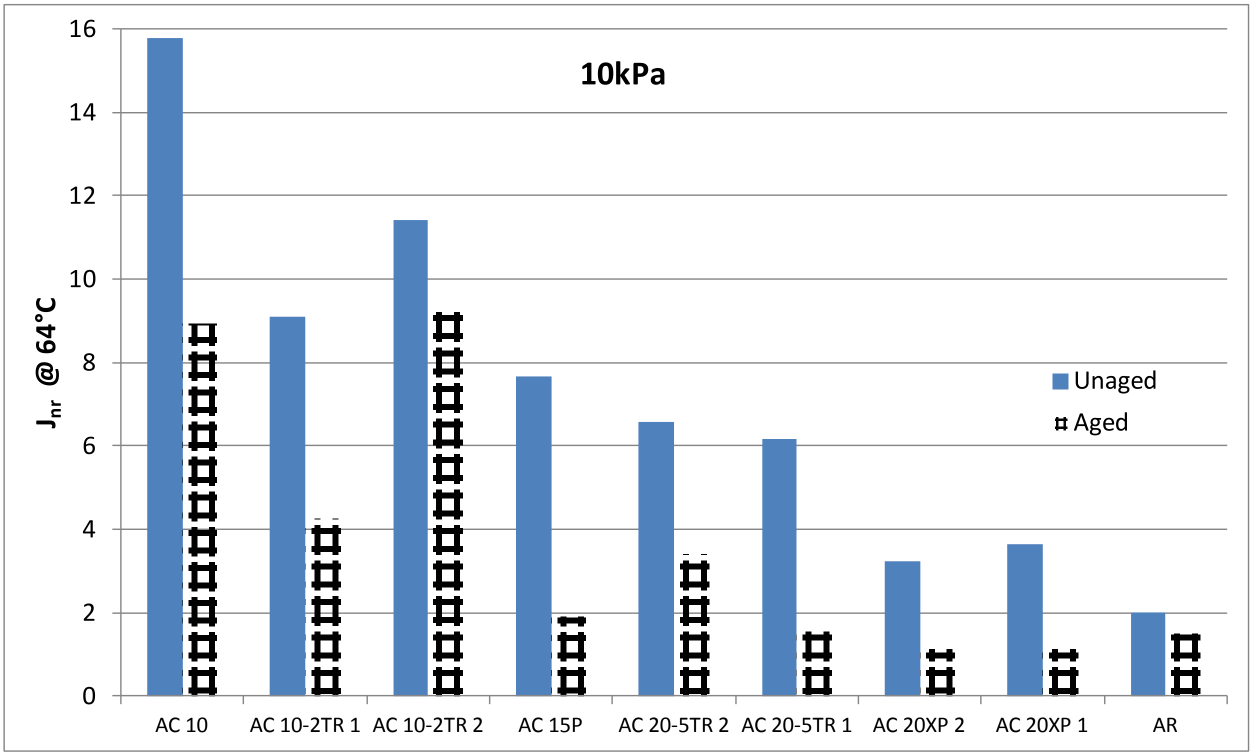


Figure 11. J_{nr} at 10 kPa Stress Level.

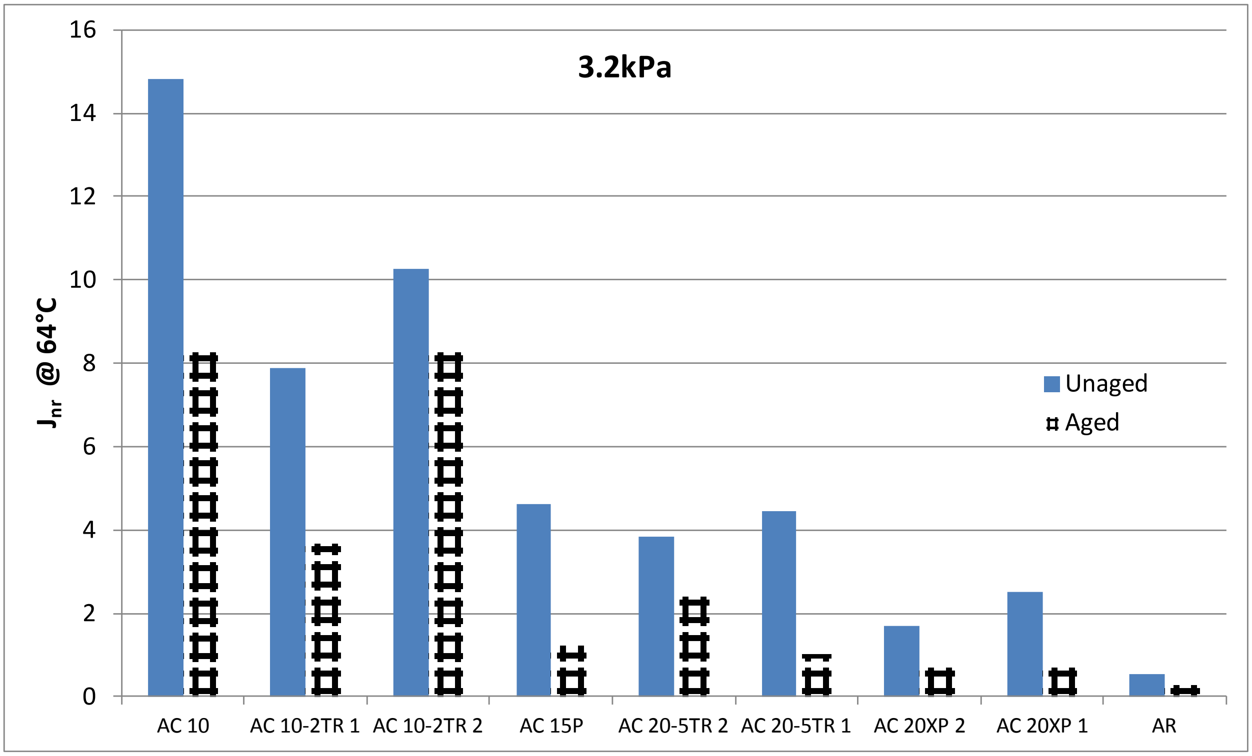


Figure 12. J_{nr} at 3.2 kPa Stress Level.

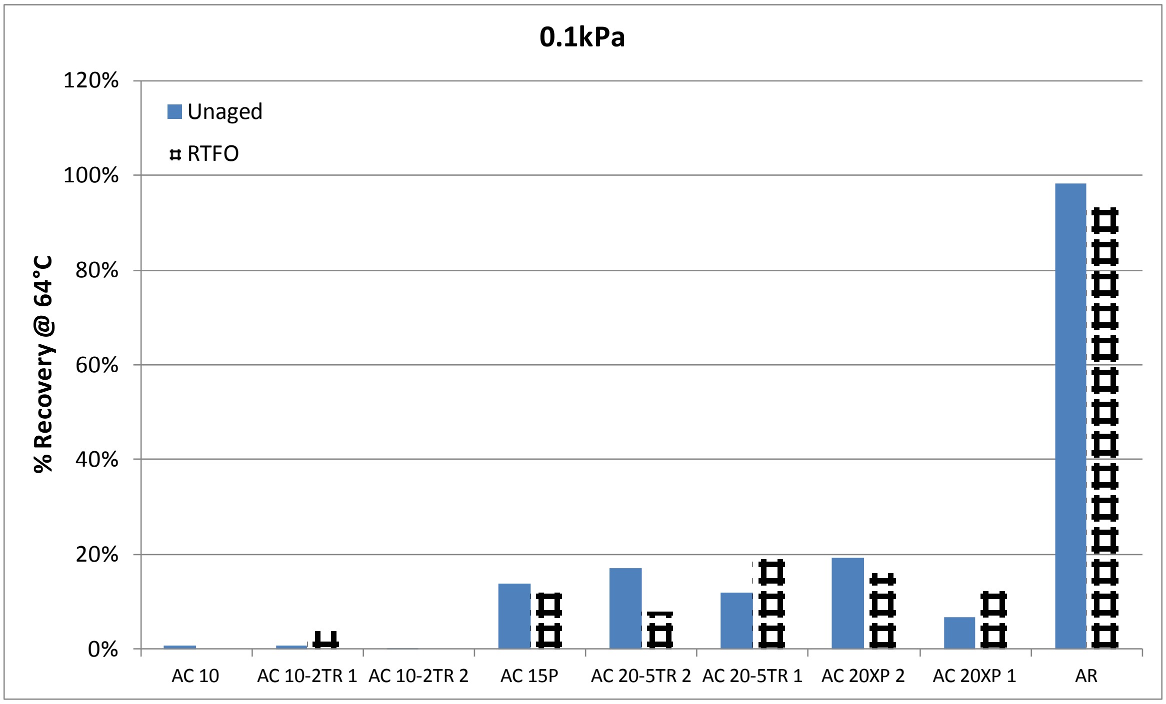


Figure 13. Percent Strain Recovery at 0.1 kPa Stress Level.

Table 14 and Figure 13 through Figure 15 show results of the percent recovered shear strains at the end of the 59-second recovery period of the 10th cycle. This is almost an inverted version of the J_{nr} results, and hence the relative order of the binders stays similar J_{nr} results. Once again, un-aged and aged binders were plotted next to each other with aged binders shows higher percentage of strain recovered. As expected, the binder starts to recover less and less of the strain as the shear stress increases.

Table 14. Percent Recovery of Un-Aged and Aged Binder.

Binder	0.1kPa		3.2kPa		10kPa	
	Un-Aged	RTFO-Aged	Un-Aged	RTFO-Aged	Un-Aged	RTFO-Aged
AC 10	0.00	0.00	0.00	0.00	0.00	0.00
AC 10-2TR 1	0.00	0.03	0.00	0.00	0.00	0.00
AC 10-2TR 2	0.00	0.00	0.00	0.00	0.00	0.00
AC 15P	0.13	0.11	0.03	0.06	0.00	0.01
AC 20-5TR 1	0.11	0.19	0.01	0.07	0.00	0.02
AC 20-5TR 2	0.17	0.07	0.02	0.01	0.00	0.00
AC 20XP 1	0.06	0.13	0.03	0.07	0.00	0.03
AC 20XP 2	0.19	0.16	0.08	0.07	0.01	0.02
AR	0.98	0.93	0.08	0.15	0.00	0.01

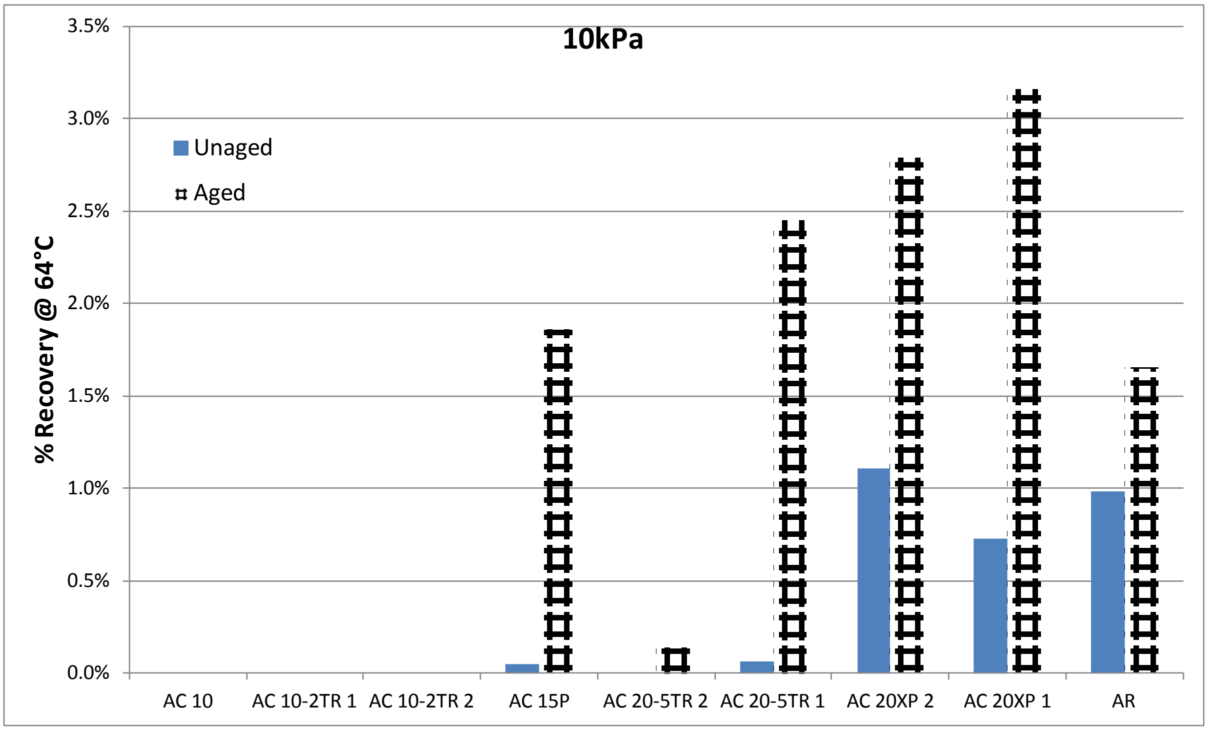


Figure 14. Percent Strain Recovery at 10 kPa Stress Level.

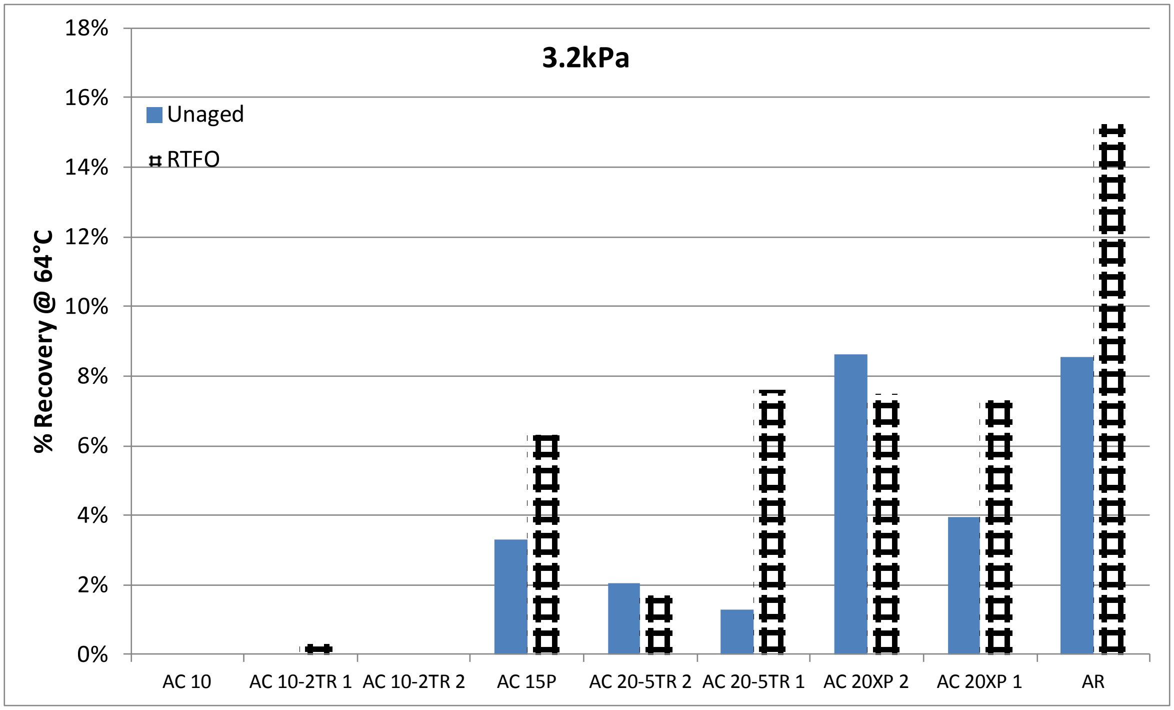


Figure 15. Percent Strain Recovery at 3.2 kPa Stress Level.

Figure 16 shows a plot of accumulated percent strain vs. time for all un-aged binders tested at 0.1 kPa stress. The relative rankings of binders are similar to that from J_{nr} and percent recoverable strain indicated above.

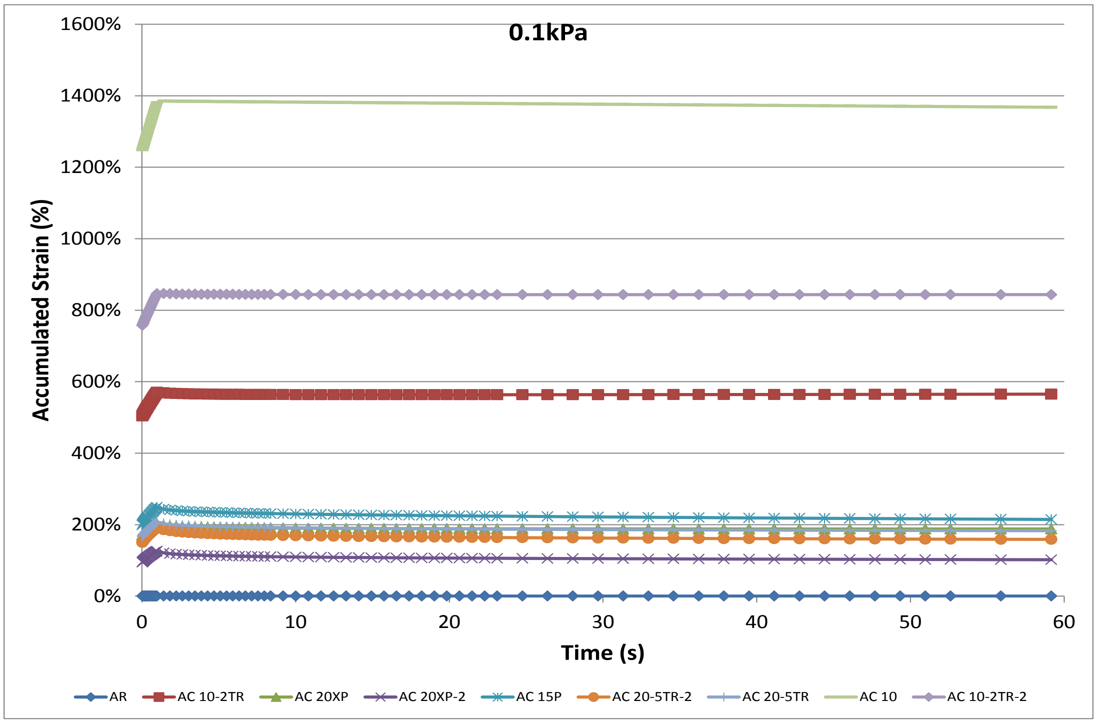


Figure 16. Accumulated Percent Strain at the 10th Cycle for 0.1 kPa Shear Stress.

One interesting observation made from the MSCR test results is that with some binders, the percent accumulated strain recovery curve reversed direction after sometime within the cycle. This was only observed at the 0.1 kPa stress level. A highly polymer modified binder such as AC-20 XP takes an expected gradual strain recovery path as shown in Figure 17, but a relatively softer binder such as AC-10 2TR reversed recovery direction after a short period into the relaxation phase of one cycle as shown in Figure 18. Further investigation is needed to understand this phenomenon. However, one theory for this could be the possibility that the water flow within the water bath may be causing this. The fact that the reversal was only observed with softer binders and with the smallest shear stress (i.e., 0.1 kPa). The manufacturer of the DSR machine was contacted, and they have so far not able to come up with a definitive explanation for this phenomenon.

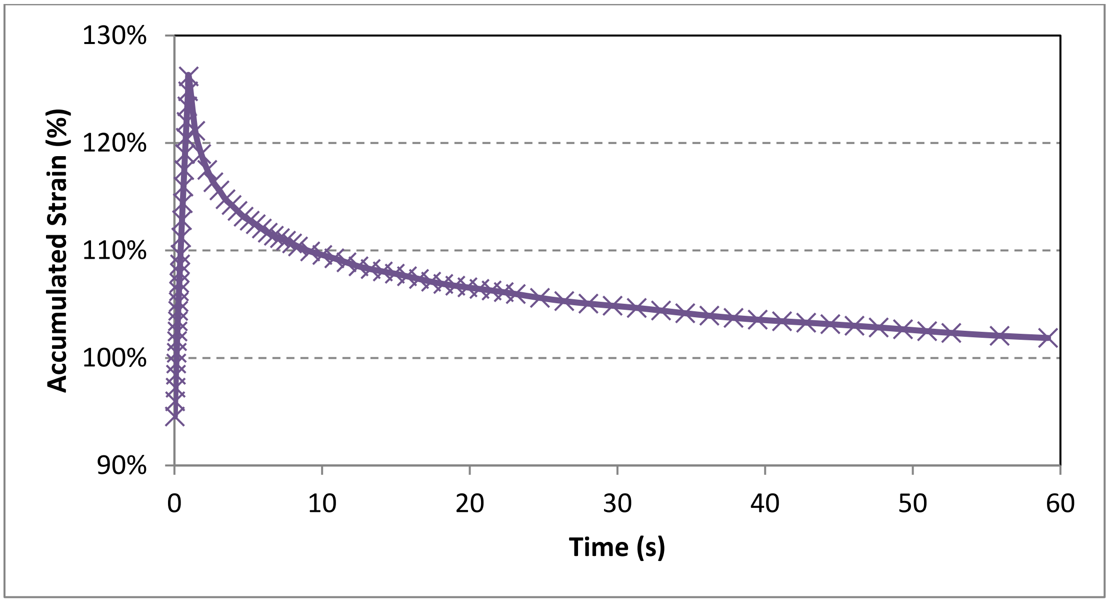


Figure 17. Accumulated Strain Curve for AC-20 XP at 0.1 kPa Stress Level.

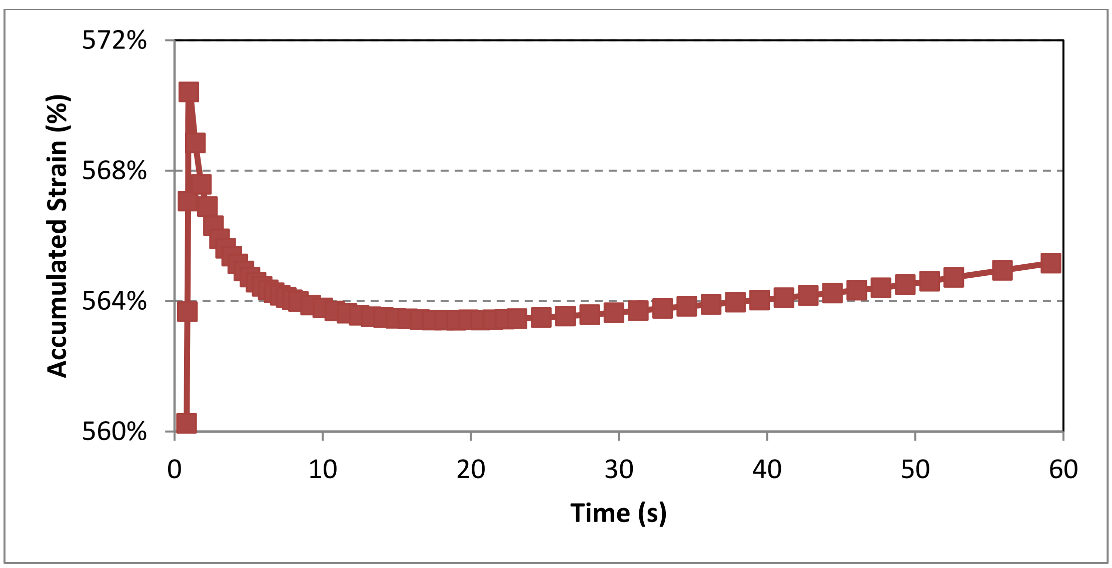


Figure 18. Accumulated Strain Curve for AC-10 2TR at 0.1 kPa Stress Level.

Pull-Out Test

This process first started with the development of a test protocol to provide repeatable results. As described previously, a cylindrical aggregate particle with a diameter of 0.5 inches was pressed onto a flat steel plate and the area around it was filled with asphalt cement so that 50 percent of the height of the aggregate cylinder was covered. Care was taken to ensure that no asphalt was trapped between the bottom face of the aggregate and the steel plate. Once the specimen mounted on the steel plate was ready, it was subjected to a conditioning regime selected for the asphalt-aggregate combination. After conditioning, the pull-out test was conducted. When the aggregate is pulled up using the machine, it creates a shear stress around the aggregate particle in the area covered with asphalt. Asphalt, being a viscoelastic material, gets pulled along with the aggregate up to a certain distance before breaking off. This elongation of asphalt depends on the temperature at which the test is conducted. The force gage attached to the pull-out machine recorded the pullout force. Several aggregate-binder combinations were tested at different climate conditioning regimes. The objective of this test program is to develop a repeatable test that will provide results that are useful to supplement the mechanistic flushing model developed in this study. Additional tests can be conducted to incorporate more binders and aggregates to evaluate a larger spectrum of materials used in TxDOT seal coat projects.

Results from the pull-out test program are presented in Table 15, and they are obtained from three replicate tests of each combinations being tested. Elongation was generally comparable for different combinations expect when volcanic rock was used. The elongation for volcanic aggregate tests reached the maximum distance the aggregate could be pulled up in the testing machine (i.e., 3 inches). Volcanic rock is very porous causing the asphalt to penetrate into the pores of the aggregate, making the asphalt-aggregate bond stronger. Furthermore, it was observed that that volcanic rocks had a high degree of variability in terms of its hardness and porosity. Therefore, three types of volcanic rocks were identified as Volcanic, Volcanic 2, and Volcanic 3. The Volcanic type appeared to be the densest and least porous of the three types, and at the other extreme, Volcanic 3 was highly porous and somewhat friable.

Figure 19 shows the maximum pull-out force for AC-20 XP binder and the three types of volcanic rock. The results are quite variable in this group of tests. This can be attributed to the highly variable nature of the aggregate itself both in terms of its hardness and porosity. When the specimen was subjected to freezing and tested at room temperature, the specimens failed at the interface at high pull-out loads. In two exceptions, (XP-V2-FR and XP-V2-F32), failure occurred not at the interface between the aggregate and the asphalt, but rather within the aggregate itself because the particle was very friable. The harder volcanic rock provided the highest pull-out force when tested at low temperature, which was immediately after it was taken out of the freezer.

Figure 20 illustrates results for the pull-out test using the AC-20 XP binder and siliceous river gravel (SRG) aggregate subjected to different conditioning regimes. One test was conducted for the Limestone 2 of LS2 aggregate as well. The repeatability of this group of tests is better than that of the volcanic aggregate presented in Figure 19. SRG aggregate showed average pull-out failure loads and the specimen that was tested at low temperature (SFT32) providing the highest pull-out force. The limestone specimen showed higher bond strength than the siliceous gravel specimens subjected to the same conditioning regime. Figure 21 compares two types of limestone and siliceous gravel aggregate with the AC-15P binder. In this group of tests, the results were rather unremarkable, but the repeatability was very good with two exceptions. The maximum pull-out load values were in the medium to high range. Additional testing is needed to investigate the bond strength at higher pavement temperatures (140–160°F) at which flushing occurs.

Table 15. Pull-Out Test Results.

Binder	Aggregate	Conditioning	Max. Force (lb)	Elongation (in)	Max. Shear Stress, σ (psi)
AC 20XP-2	Siliceous	U-ROOM (UR)	13.72	1.75	6.81
AC 20XP-2	Siliceous	F-ROOM (FR)	13.54	1.75	6.72
AC 20XP-2	Siliceous	F-T 53°C (SF32)	33.70	0.94	16.73
AC 20XP-2	Siliceous	F-T ROOM (FTR)	16.19	1.42	8.04
AC 20XP-2	Siliceous	SOAK-ROOM (SR)	14.47	1.27	7.18
AC 20XP-2	Siliceous	SOAK-F-60°C (SF32)	18.98	1.25	9.43
AC 20XP-2	Siliceous	SOAK-F-ROOM (SFR)	11.15	1.56	5.54
AC 20XP-2	Siliceous	SOAK F-T 60°C (SFT32)	24.01	1.00	11.92
AC 20XP-2	Siliceous	SOAK F-T ROOM (SFTR)	9.25	1.13	4.60
AC 15P	LS MF	U-ROOM (UR)	9.89	1.56	4.91
AC 15P	LS MF	F-ROOM (FR)	12.69	1.42	6.30
AC 15P	LS MF	SOAK-ROOM (SR)	13.18	1.63	6.54
AC 15P	LS East	U-ROOM (UR)	9.81	2.08	4.87
AC 15P	LS East	SOAK-ROOM (SR)	16.25	1.54	8.07
AC 15P	LS East	F-ROOM (FR)	11.01	1.92	5.47
AC 15P	Siliceous	SOAK-ROOM (SR)	12.10	1.29	6.01
AC 15P	Siliceous	U-ROOM (UR)	16.14	1.88	8.01
AC 20XP-2	Volcanic	U-ROOM (UR)	15.61	3	7.75
AC 20XP-2	Volcanic 2	U-ROOM (UR)	12.64	3	6.28
AC 20XP-2	Volcanic	F-60°C (F32)	26.97	3	13.39
AC 20XP-2	Volcanic 2	F-50°C (F32)	12.3	3	6.11
AC 20XP-2	Volcanic	F-ROOM (FR)	19.07	3	9.47
AC 20XP-2	Volcanic 2	F-ROOM (FR)	8.324	3	4.13
AC 20XP-2	Volcanic 3	F-ROOM (FR)	24.864	3	12.35

Note: LS – Limestone aggregate; F – Freeze; T – Thaw; U - Unconditioned

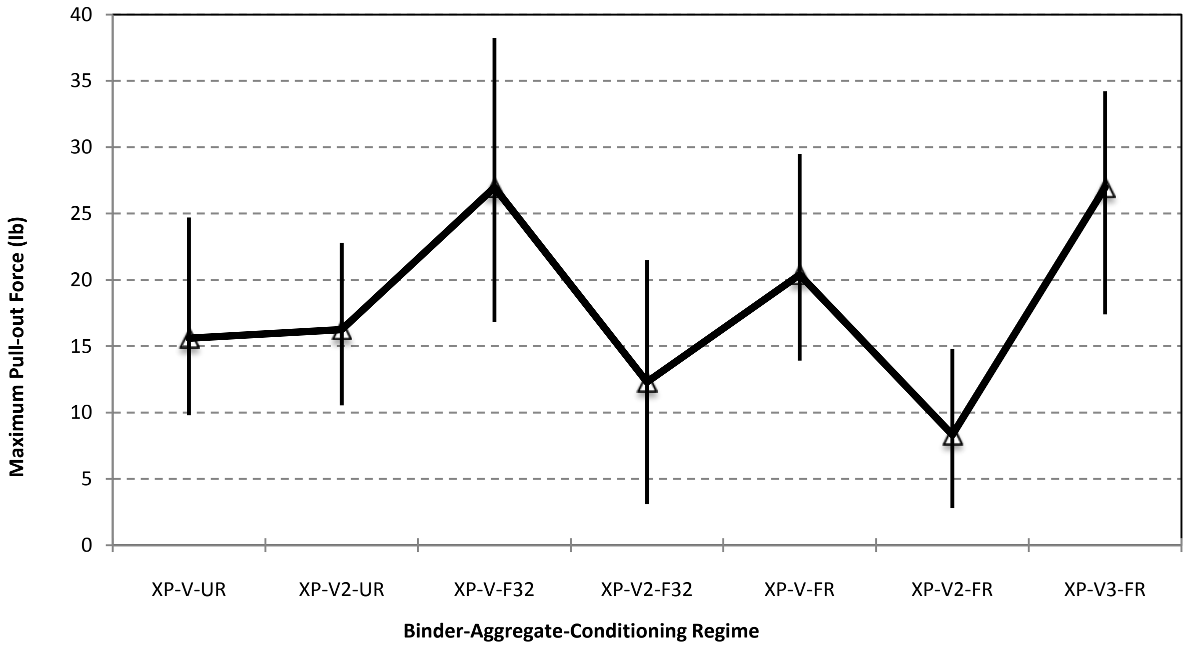


Figure 19. Maximum Pull-Out Force for AC-20 XP and Three Types of Volcanic Aggregates for Different Climate Conditioning.

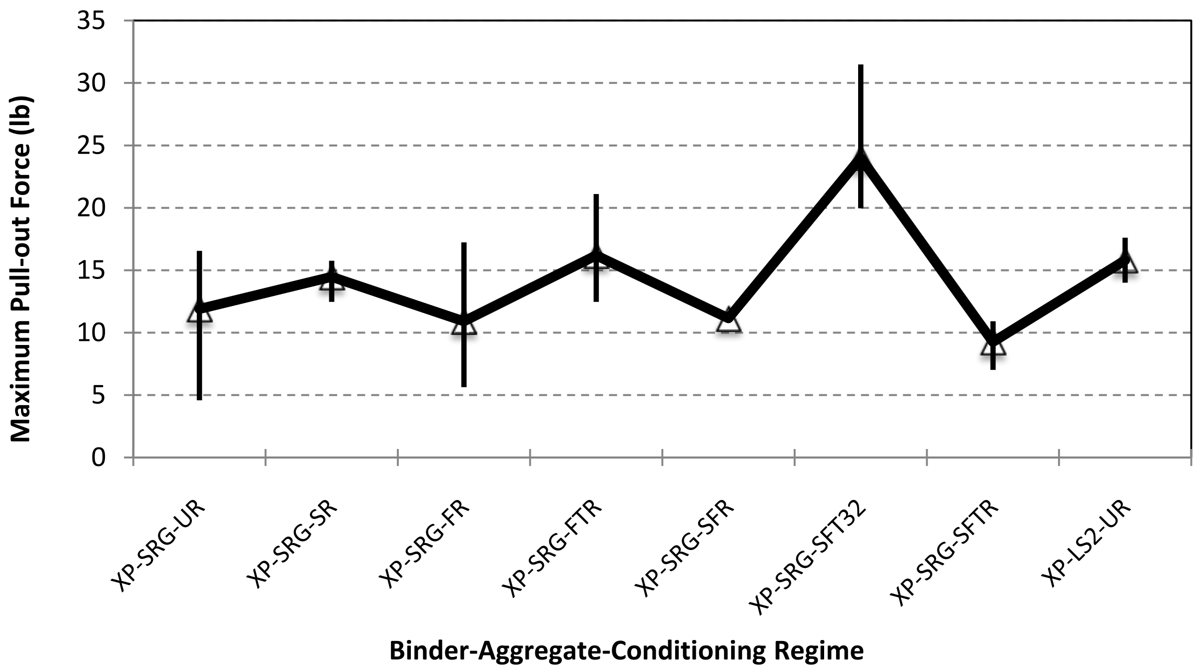


Figure 20. Maximum Pull-Out Force for AC-20 XP with SRG and Limestone Aggregate for Different Climate Conditioning.

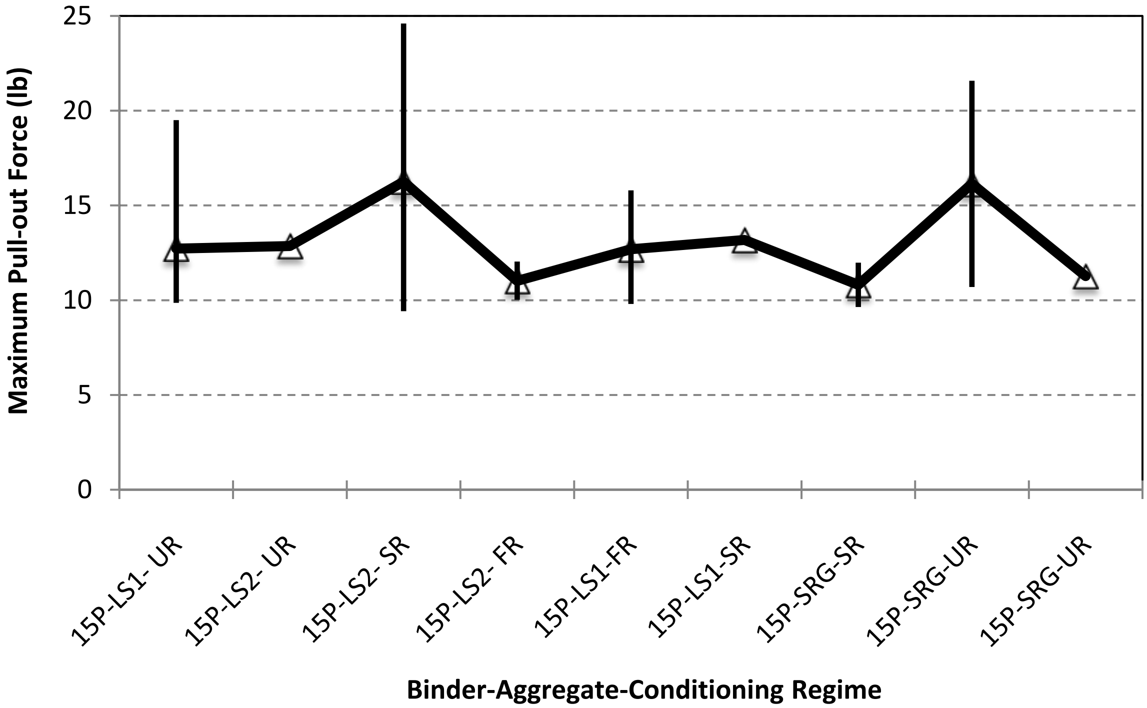


Figure 21. Maximum Pull-Out Force for AC-15P with SRG and Two Types of Limestone Aggregates for Different Climate Conditioning.

Figure 22 and Figure 23 show two interesting observations during the pull-out testing process. Figure 22 shows three specimens using siliceous aggregate that were subjected to soaking in water as part of the conditioning regime. Siliceous aggregate that is hydrophilic (i.e., water loving) has a propensity to strip asphalt away from the siliceous aggregate. This is often the cause of aggregate loss from seal coats when a newly placed seal gets a thunderstorm within the first couple of days after sealing.

Figure 22. SRG after Soaking.

Figure 23 shows a limestone aggregate embedded in AC-20 XP tested at a temperature close to 32°F. With limestone, the sedimentary nature of the rock allows quick development of the bond with asphalt, and when the asphalt is put in the freezer as part of the conditioning process the failure in this case is not an adhesive one but rather a cohesive one where the fracture plane runs through the asphalt cement. The fact that AC-20 5TR is one of the stiffest binders tested at high temperature, its stiffness should be quite high at low temperature as well, hence the cohesive fracture failure. Furthermore, no elongation of the asphalt was observed because of the high stiffness of the binder.

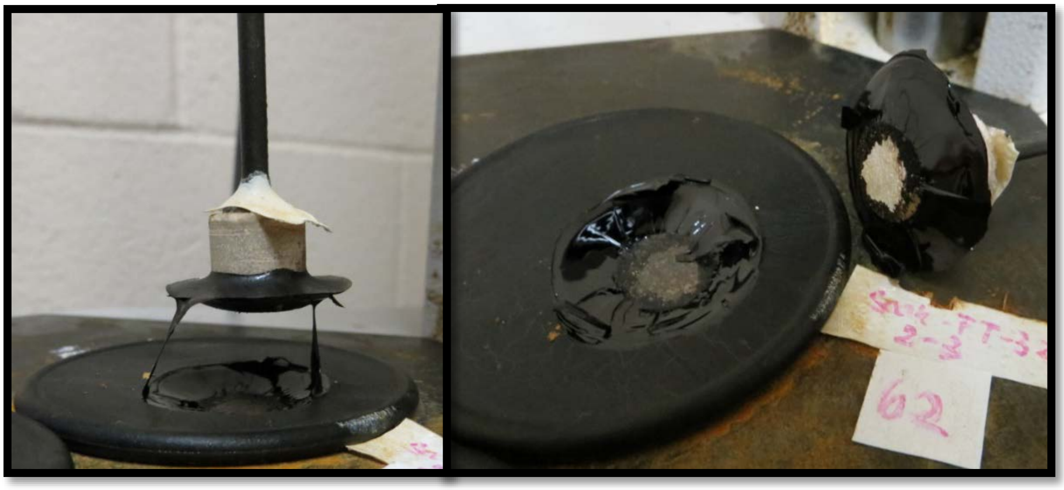


Figure 23. Pull-Out Failure of Limestone Aggregate in AC-20 XP Tested at 32°F.

SUMMARY

Three tests were conducted in this task of this research: the DSR Strain Sweep Test on asphalt binder, MSCR Test on asphalt binder, Pull-Out Test on Aggregate Embedded on Asphalt Binder. The strain sweep and MSCR tests are standard AASHTO tests, and the pull-out test was developed at Texas Tech University.

The strain sweep test measures the complex shear modulus of asphalt binder and the phase angle. It also allows the demarcation of the elastic, viscoelastic, and viscous regions for the binder in terms of percent shear strain. This test was used in this research to measure the complex shear modulus and phase angle and to calculate the linear viscoelastic limit of asphalt binder. Eight different hot asphalt binders were tested at both un-aged and RTFO-aged condition to compare the binders and to assess their aging potential.

The MSCR Test first developed at FHWA has been gaining popularity to assess the high temperature performance of asphalt binders. It was first introduced to characterize rutting in asphalt concrete, but efforts have been made by several researchers to use it for sprayed seal binders as well. The standard test was modified to accommodate a longer relaxation phase by increasing it from 9 seconds to 59 seconds. This modification was used to be able to conduct a parametric study of the flushing potential of seal coated roadways subjected to different truck traffic volumes. This modification to the MSCR test shows significant promise for more optimal selection of asphalts for TxDOT projects.

The pull-out test was not part of the original proposal, but was selected to replace the ASTM D7000 sweep test of seal coat specimens. Researchers have conducted many tests of the seal coat sweep test developed for emulsified asphalts and found the test to be not representative of the types of seals used by TxDOT. Furthermore, the repeatability of the test was very poor. Therefore, the Texas Tech research team undertook the task of developing a new test that can be conducted under more controlled conditions and can provide better repeatability. The aggregate pull-out test was the result of that effort. The repeatability of the test is quite good with good quality aggregates commonly used by TxDOT. Furthermore, results from the pull-out test help supplement the mechanistic model developed for flushing by measuring the shear strength of the asphalt aggregate bond.

CHAPTER 4: LABORATORY TESTING OF SEAL COAT AGGREGATES

The primary functions of a seal coat are sealing and protecting underlying pavement layers while providing an abrasive surface with adequate skid resistance. Many factors affect the performance of seal coats, including properties of the asphalt and aggregates, strength and condition of the existing pavement, construction techniques, and the amount and types of traffic. Useful service life of a seal coat generally ends due to cracking or loss of friction. Loss of friction can be the result of aggregate polishing, loss of macrotexture from aggregate reorientation, or asphalt flushing. Loss of macrotexture is sometimes due to the use of softer aggregates that polish, wear, and break down under traffic.

Districts were contacted and requested to provide aggregate samples from the seal coat program constructed during summer 2013. Many districts provided samples and quite a few use the same aggregate sources. Researchers selected 10 different types of aggregates thought to best represent the most typical aggregates and those representing a range of properties. Table 16 lists the aggregates and their types and sources.

ABRASION RESISTANCE TESTING

One of the test procedures used to evaluate the wear characteristics of seal coat aggregates was a modification of ASTM C 944. This test procedure was originally developed to determine the resistance of concrete to abrasion. It has been used successfully in the quality control of highway and bridge concrete subject to traffic. Figure 24 shows a drill press with a chuck capable of holding and rotating an abrading cutter at 750 rpms and exerting a force of 22 lb on the test specimen.

To evaluate the abrasion resistance of the seal coat aggregates, seal coat specimens were prepared by gluing the seal coat aggregates to a ceramic plate using a very strong epoxy. Figure 25 through Figure 28 show samples of some the seal coat specimens before and after abrasion resistance testing.

Table 16. Seal Coat Aggregate Samples Used for Laboratory Testing.

Sample ID	Producer Name	District Providing Sample	Sampled from:	Material	Description	County
Hunter LS (1)	Colorado Materials	San Antonio	Stockpile Roadway	PB Gr 4	US 90 EBML East of RM 562	Bexar
LRA Gr 4 Frio (3)	Vulcan Uvalde	San Antonio	Stockpile Roadway	PB Gr 4	BI 35-D	Frio
LRA Gr 3 Atascosa (4)	Vulcan Uvalde	San Antonio	Stockpile Roadway	PB Gr 3	IH 37 FR North of US 281-A	Atascosa
LRA Gr 3 Corpus (13)	Vulcan Uvalde	Corpus Christi	Stockpile Roadway	PB Gr 3	FM 1203 (origin), FM 3024, etc.	
Odessa (10)		Odessa	Stockpile Roadway	PB Gr 4	BL 20-D, etc.	Ward, etc.
Leach LS (16)	Zack Burkett	Wichita Falls	Stockpile Roadway	PE Gr 4	US 380	Young, etc.
Lightweight Gr 3	TXI	Tyler	Stockpile Roadway	PL Gr 3	US 80	Van Zandt
Gravel El Paso (26)	Heartland Asphalt Materials	El Paso	Stockpile Roadway	PD Gr	US 62/180 FM 054+0.465 ~1.501	Hudspeth
Gravel Pharr	Fordyce	Pharr	Quarry	Gr 3		
Limestone Perch Hill	Hanson	Producer supplied	Quarry	Gr 3		

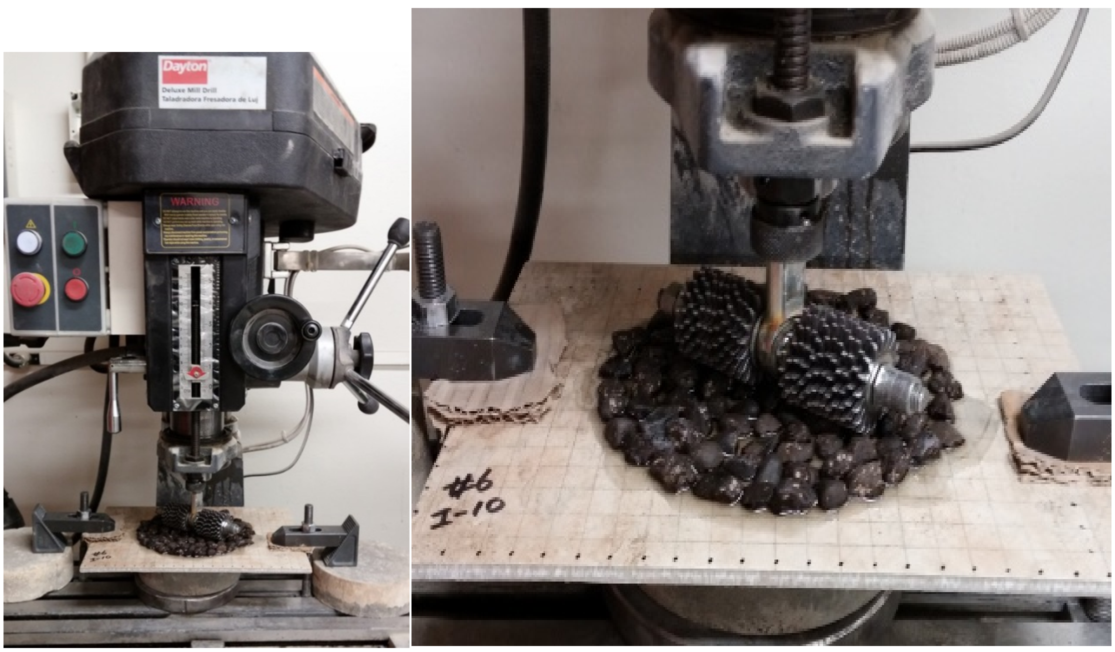


Figure 24. Modified Version of ASTM C 944, Abrasion Resistance Test.

(a) Before Abrasion Test

(b) After Abrasion Test

Figure 25. LRA Laboratory Fabricated Seal Coat Samples to Evaluate Aggregate Abrasion Resistance.

(a) Before Abrasion Test

(b) After Abrasion Test

Figure 26. Colorado Materials Limestone Laboratory Fabricated Seal Coat Samples to Evaluate Aggregate Abrasion Resistance.

(a) Before Abrasion Test

(b) After Abrasion Test

Figure 27. Perch Hill Limestone Laboratory Fabricated Seal Coat Samples to Evaluate Aggregate Abrasion Resistance.

(a) Before Abrasion Test

(b) After Abrasion Test

Figure 28. Fordyce Gravel Laboratory Fabricated Seal Coat Samples to Evaluate Aggregate Abrasion Resistance.

Figure 29 through Figure 31 presents results of the abrasion resistance testing. Figure 29 shows the results weight change of the seal coat specimen throughout the abrasion test. Samples were abraded at 750 rpms and samples were weighed throughout the testing at one minute intervals to determine the rate of aggregate loss. Figure 30 shows the final weight loss for each seal coat sample after 5 minutes of abrasion testing.

The three gravel specimens (Gravel- Pharr, Gravel Odessa, and Gravel El Paso) by far performed better than the other samples. The next group was the three limestone specimens (Perch Hill, Leach, and Hunter) all performed almost exactly the same. The LRA specimens followed with both Grade 3s performing quite poorly and yet the Grade 4 performed somewhat better than the Grade 3, which was unexpected. These results may be repeated to validate. Finally, the worst performer in terms of wear was the lightweight aggregate.

Figure 31 shows the sieve analyses of the fines, which were collected from the abraded specimens. No significant trends were observed here.

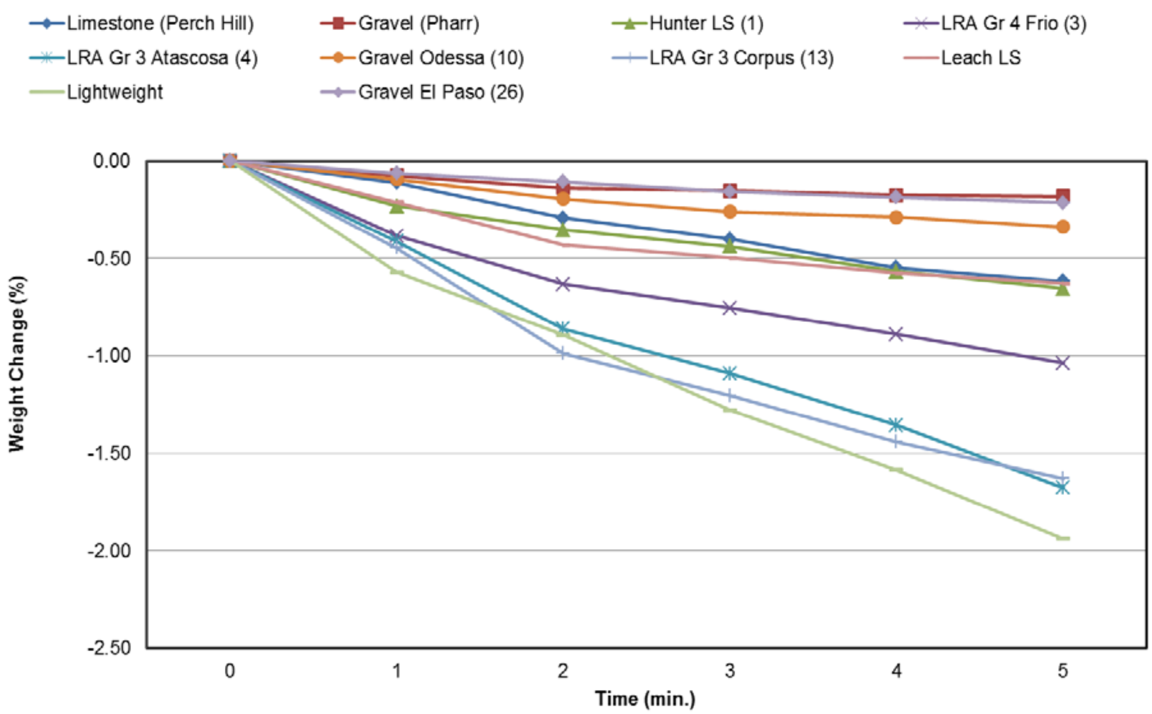


Figure 29. Abrasion Loss of Aggregate Seal Coat Samples.

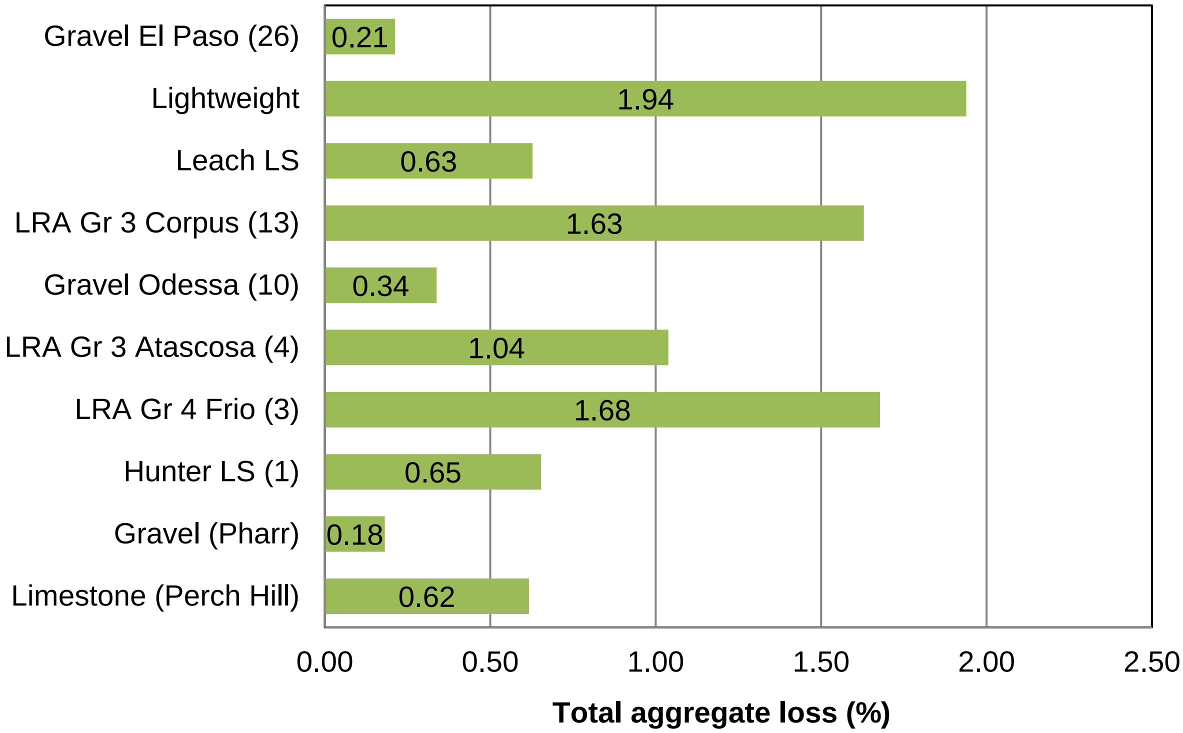


Figure 30. Total Weight Loss after 5 Minutes of Abrasion Testing at 750 RPM.

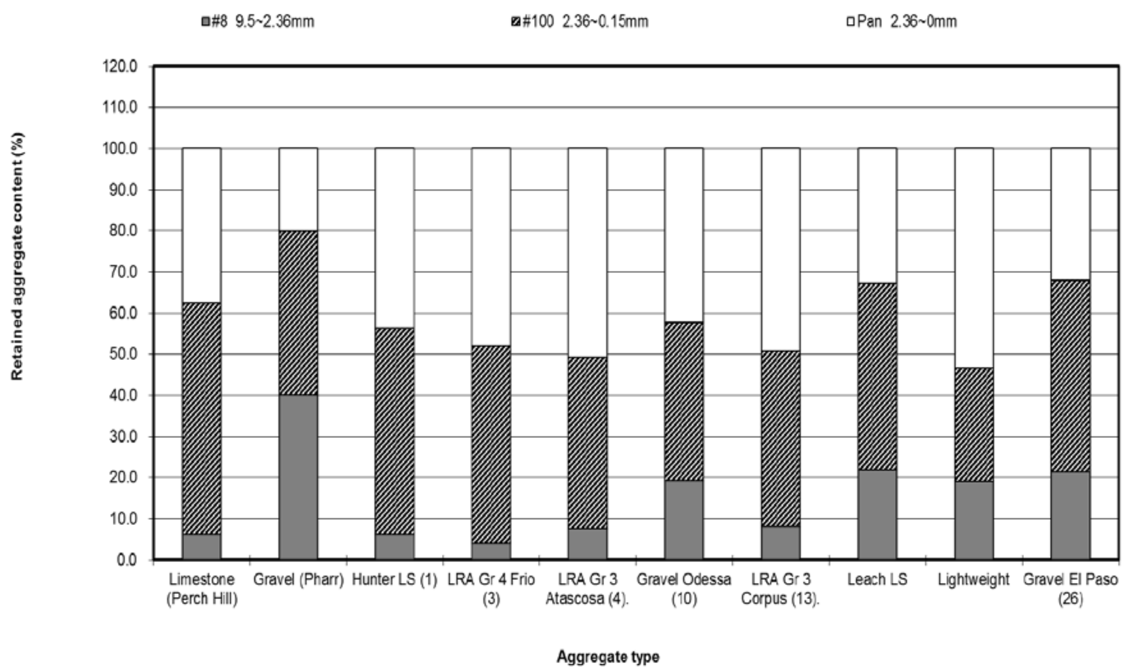


Figure 31. Sieve Analysis Results of Fines Lost in Aggregate Abrasion Test.

MICRO-DEVAL TEST RESULTS

The Micro-Deval Test (Tex 461-A) is a test procedure to measure an aggregate's resistance to abrasion and weathering. After soaking in water for a minimum of one hour, a coarse aggregate sample is placed in the Micro-Deval Apparatus (a steel cylinder) with 5000 g of stainless steel balls bearings and then rotated for 105 minutes at 100 rpms. After abrasion, the aggregates are washed and the weight loss is considered to be that passing the No. 16 sieve. Figure 32 shows the Micro-Deval results from the seal coat aggregate samples. The gravel aggregates performed the best and most of the limestones, LRAs and lightweight materials performed similarly ranging between 15 and 25 percent loss. The Hunter limestone was an exception with a very high loss of 45 percent.

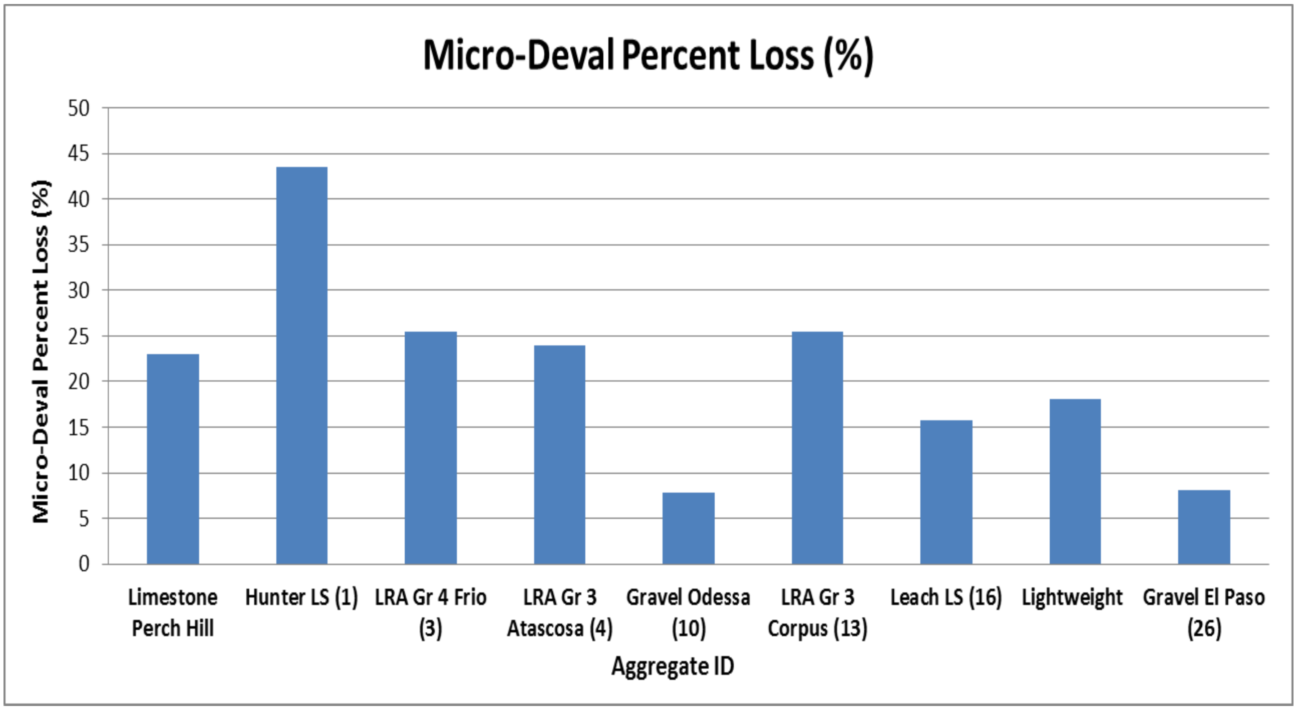


Figure 32. Micro-Deval Test Results for Seal Coat Aggregates.

AGGREGATE IMAGING SYSTEM

AIMS determines shape characteristics of aggregate through image processing and analysis techniques. AIMS equipment consists of a computer automated unit that includes an aggregate measurement tray with marked grid points at specified distances along x and y axes. Coarse aggregate sample is placed on the specified grid points, while fine aggregate sample is spread uniformly on the entire tray. The system is also equipped with top lighting, back lighting, and a camera unit. The AIMS software analyzes the aggregate images and produces measurements of their shape, angularity, and surface texture. Aggregate texture is quantified using wavelet analysis method (Texture index); aggregate angularity is described by measuring the irregularity of a particle surface using the gradient and radius methods (Angularity index); and shape is described by 2D form and 3D form (Sphericity). The sphericity is a measure of how close in length the three dimensions of an aggregate particle are. A sphericity of 1.0 denotes that a particle is a perfect sphere or cube while sphericity decreases as a particle becomes more flat and/or elongated.

AIMS testing was conducted on the seal coat aggregate samples both before and after Micro-Deval abrasion (Figure 33), and these results are presented in Figure 34 through Figure 36.

All of the seal coat samples exhibited moderate angularity prior to Micro-Deval Testing (Figure 34); however, only the gravel samples maintained a moderate angularity after abrasion while the remaining samples exhibited low angularity after abrasion.

Figure 35 presents texture before and after Micro-Deval abrasion. Most of the seal coat aggregate samples were precoated with asphalt, so texture before Micro-Deval will certainly be affected by that. Because of the asphalt precoating, only the texture results after Micro-Deval abrasion will be discussed. All three of the limestone seal coat samples exhibited lowest texture while all three of the LRA samples had the best texture of all the seal coat aggregate samples, including the gravel. Perhaps the voids known to exist within the LRA containing naturally occurring asphalt contribute to the good texture.

All of the seal coat aggregate samples exhibited good sphericity both before and after Micro-Deval abrasion (Figure 36). Again, a value of 1 would indicate a perfectly cubical aggregate and all were generally above about 0.65. This is a good indication that the aggregates in our seal coat program have a desirable shape to provide good field performance.

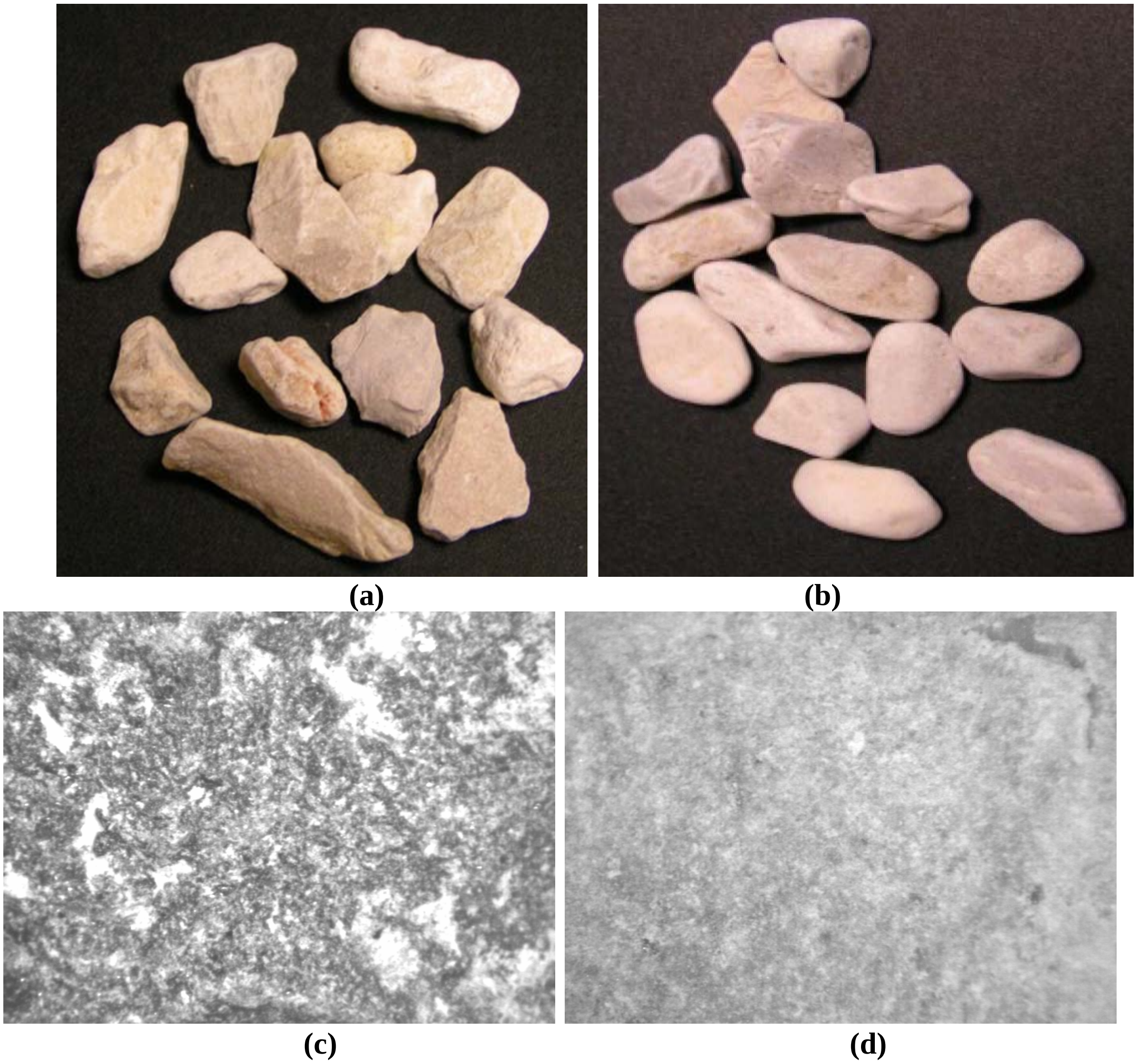


Figure 33. Aggregate Images: a) Aggregate Particles before Micro Deval, b) Aggregate Particles after Micro Deval, c) Aggregate Surface Texture before Micro Deval, d) Aggregate Surface Texture after Micro Deval.

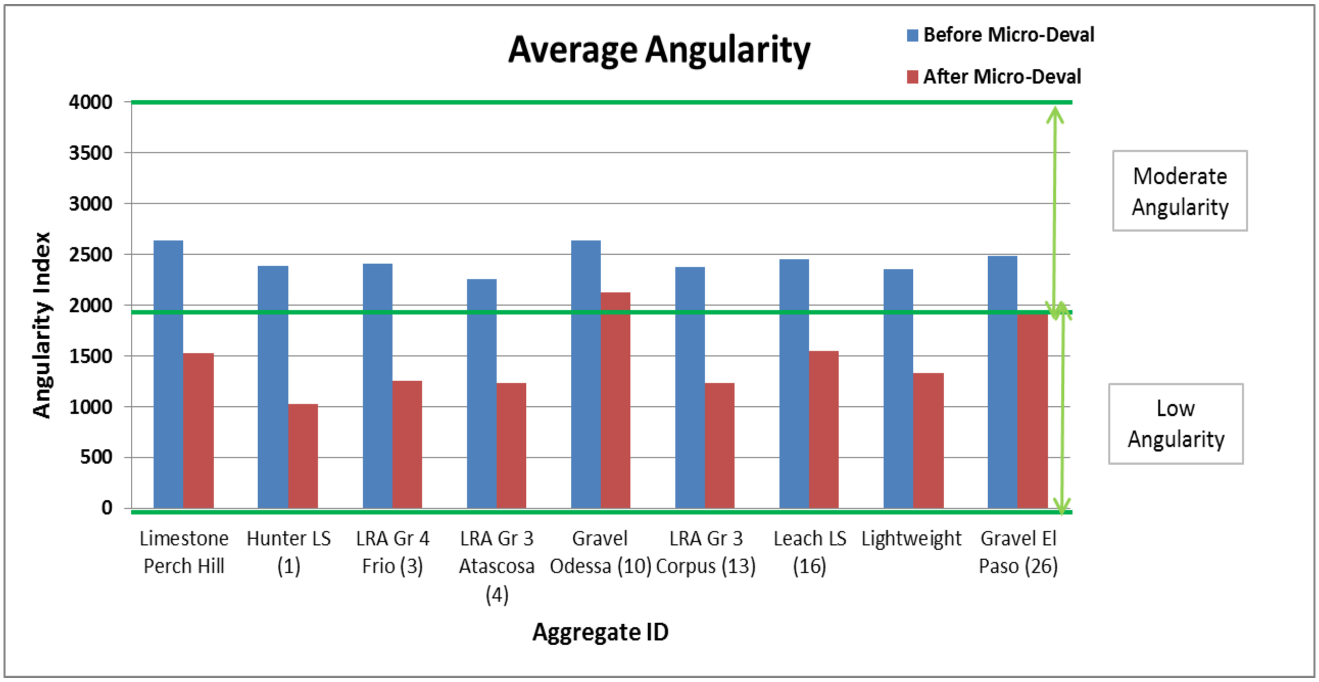


Figure 34. Average Angularity before and after Micro-Deval.

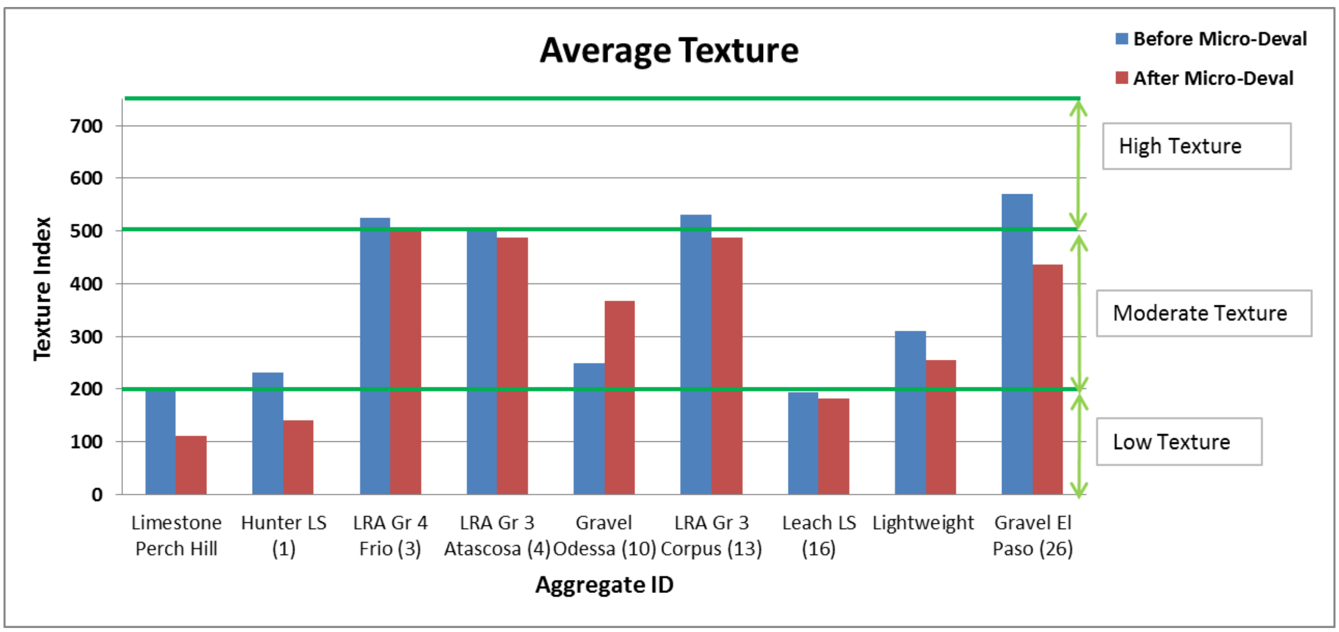


Figure 35. Average Texture before and after Micro-Deval.

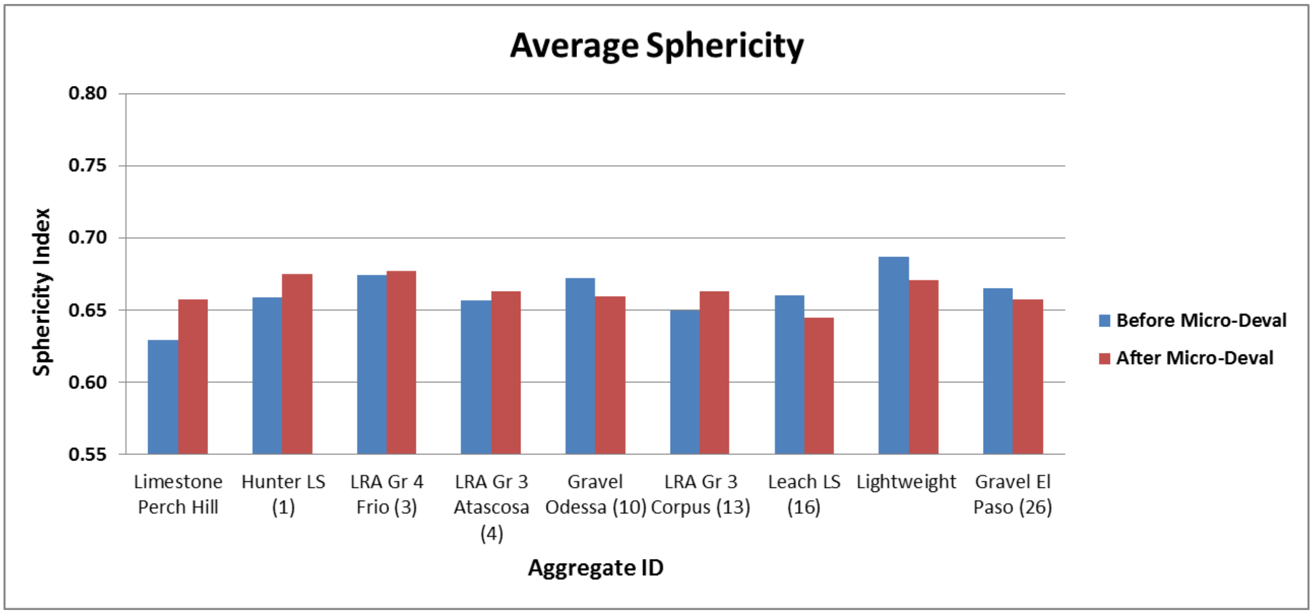


Figure 36. Average Sphericity before and after Micro-Deval.

MEASURE WEAR CHARACTERISTICS USING THREE-WHEEL POLISHER

Laboratory scale seal coat samples were prepared on 24-in × 24 tiles fabricated in TTI's laboratory. The samples were trafficked in TTI's three-wheel polisher as shown in Figure 37. The device runs three load-bearing tires over a slab in a constant turning motion. Water is applied to the surface to simulate wet conditions and to wash away abraded particles. Change in texture depth and friction will be measured after every 10,000 cycles up to 100,000. This will provide an indication of how seal coat aggregates polish and lose their friction, and it will also provide a realistic measure of wear that the aggregate particles undergo as a result of traffic. This information could be used to better classify seal coat aggregates for different traffic levels.

Texture depth is measured by the Circular Texture Meter on the slab specimen shown in Figure 38a. The portable device uses a laser scanner to measure the texture depth along a circular track. The measurements are used to calculate the mean profile depth (MPD), according to ASTM E1845 (Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth).

Figure 38 through Figure 49 show the results.

Figure 37. Three-Wheel Polisher and Circular Track Meter.

Figure 38. Test Specimen Fabrication Using Fordyce Gravel.

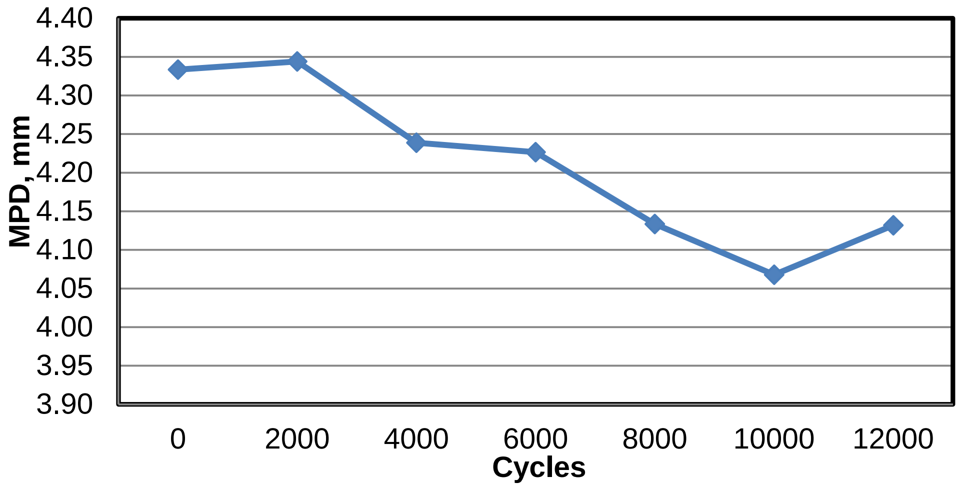


Figure 39. Loss of MPD vs. Number of Cycles in Polisher for Fordyce Gravel.

Figure 40. Test Specimen Fabrication Using LRA.

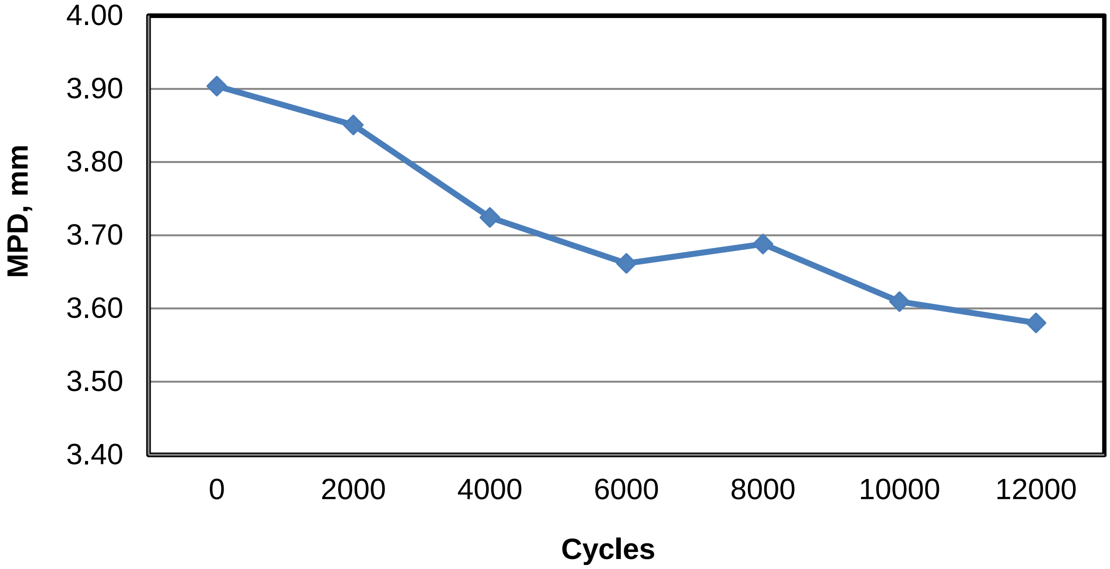


Figure 41. Loss of MPD vs. Number of Cycles in Polisher for LRA.

Figure 42. Test Specimen Fabrication Using Perch Hill Limestone.

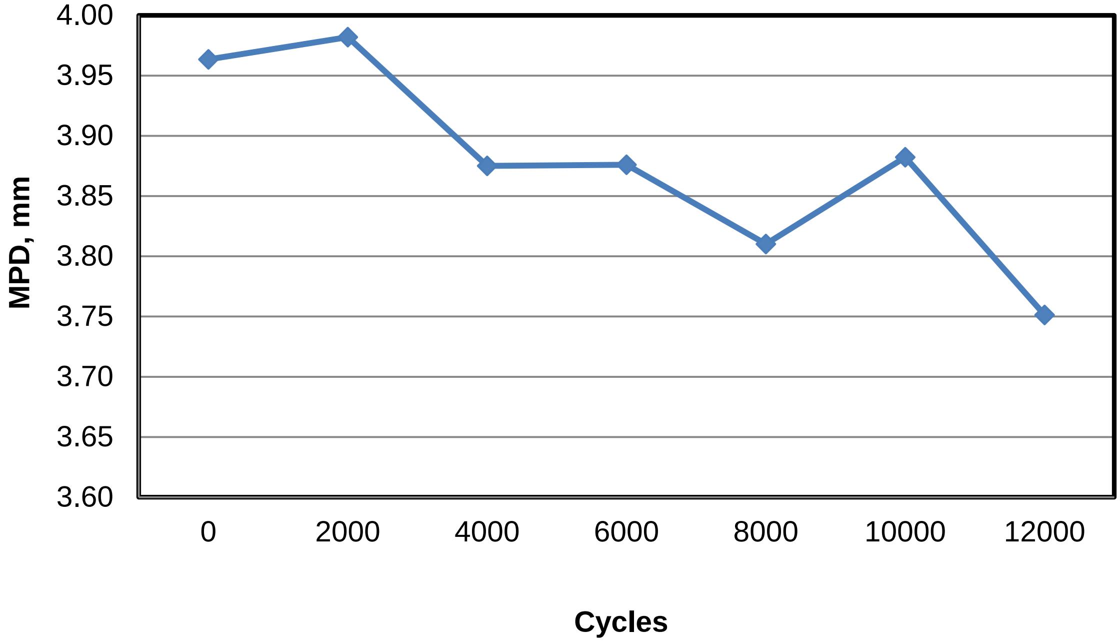


Figure 43. Loss of MPD vs. Number of Cycles in Polisher for Perch Hill Limestone.

Figure 44. Test Specimen Fabrication Using Ward Co. Gravel.

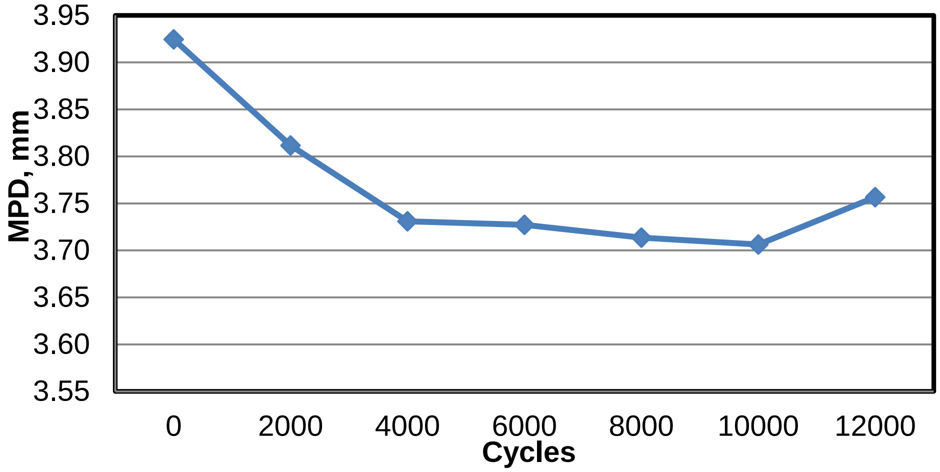


Figure 45. Loss of MPD vs. Number of Cycles in Polisher for Ward Co. Gravel.

Figure 46. Test Specimen Fabrication Using Leach Pit Limestone.

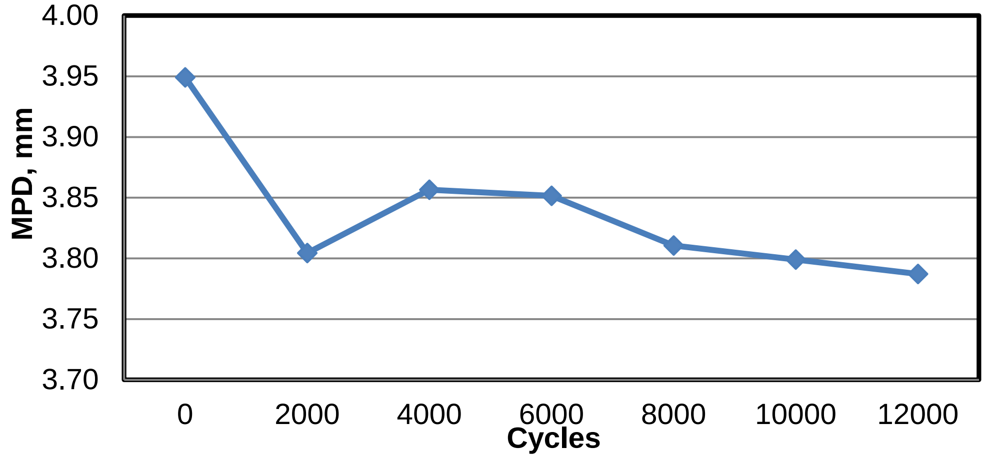


Figure 47. Loss of MPD vs. Number of Cycles in Polisher for Leach Pit Limestone.

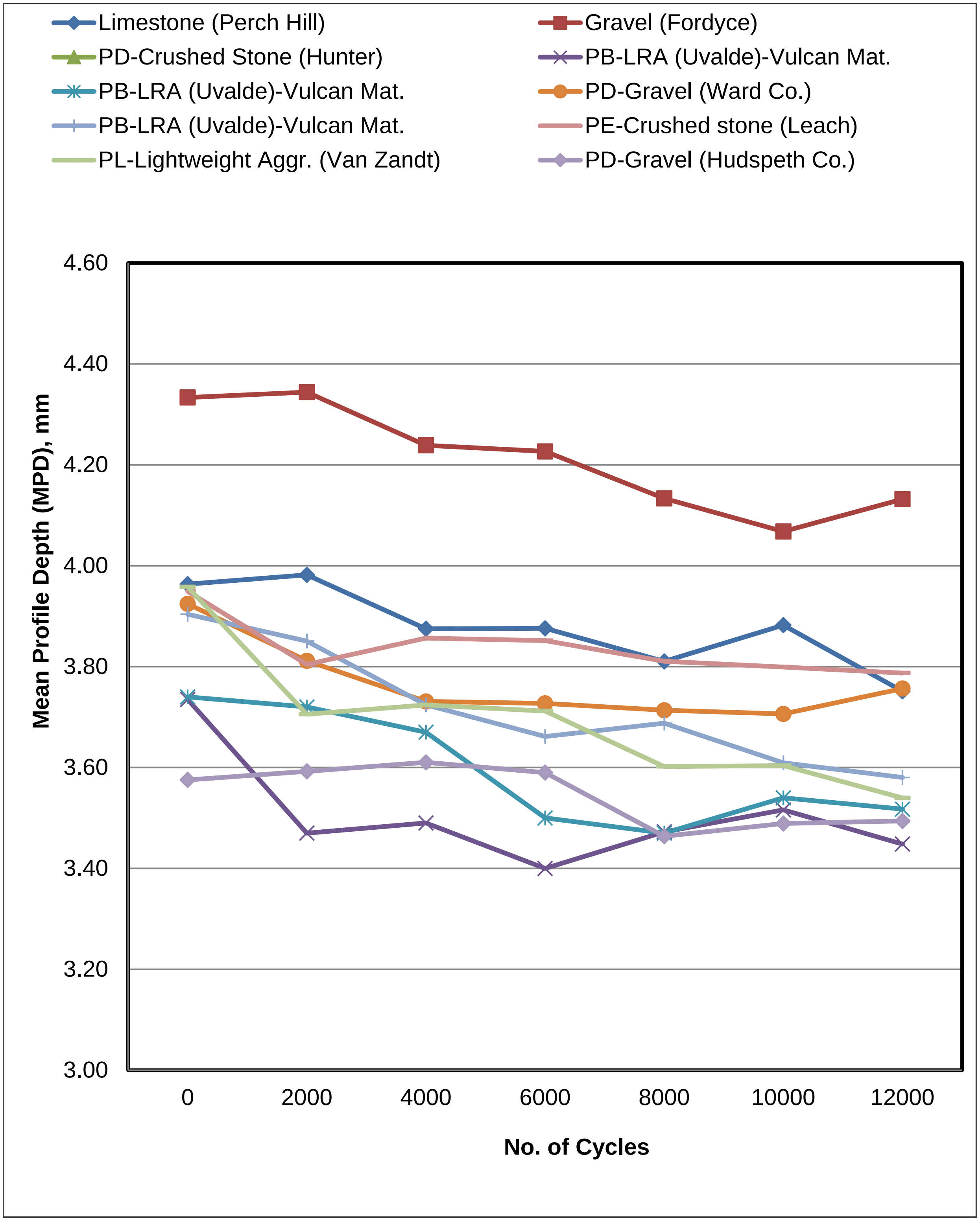


Figure 48. Summary of Loss of MPD vs. Number of Cycles for All Aggregates Tested.

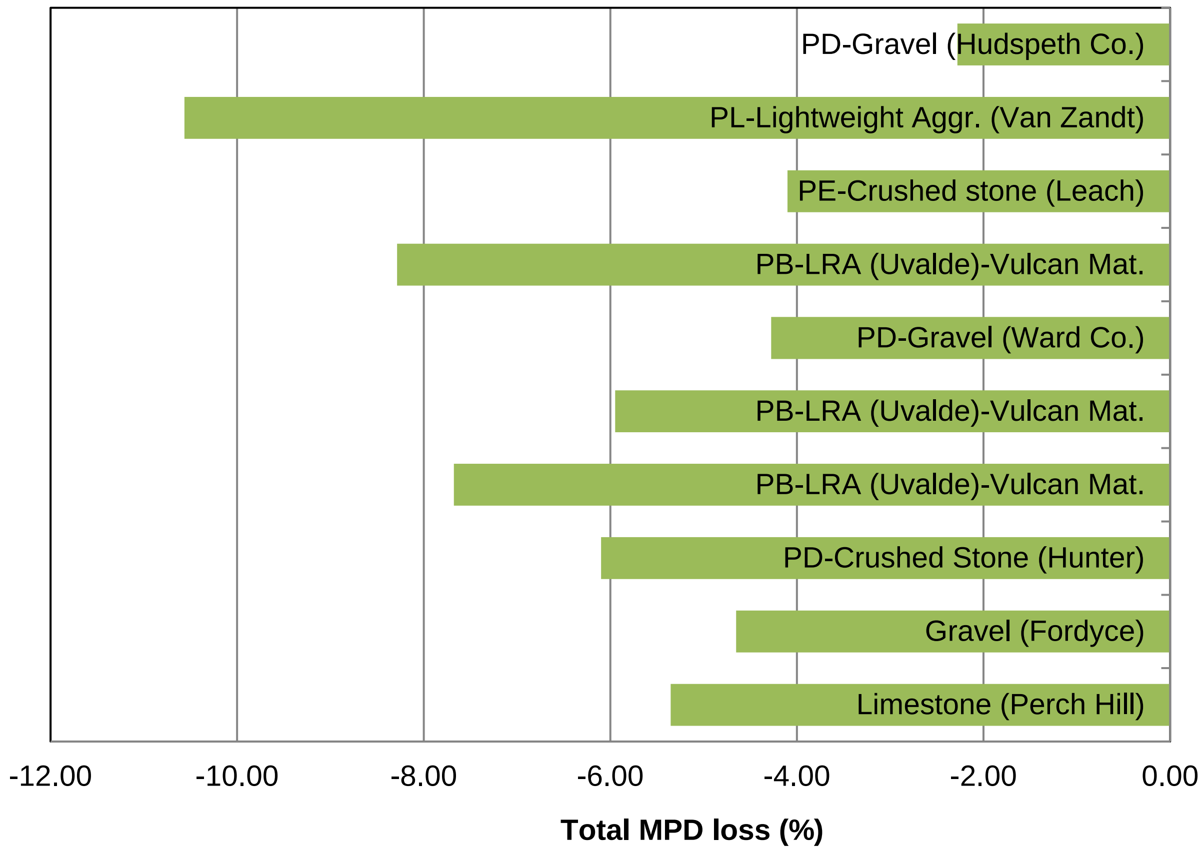


Figure 49. Total Loss in MPD for All Aggregates Tested.

SUMMARY

The gravel aggregates, which are also SAC A aggregates, performed the best in terms of wear resistance as measured with the methods described here. The remaining aggregates, which consisted of limestones, LRA, and lightweight, exhibited a range in wear characteristics. The Hunter limestone exhibited very poor performance in the Micro-Deval test and yet performed like the other limestones in the abrasion resistance test. The abrasion resistance test seems to distinguish between different SAC B materials and generally indicates the LRA aggregates to be poor performers in terms of wear resistance. This also seems to be consistent with field reports. Lightweight aggregate, which is a very popular seal coat aggregate with unique properties, also performed poorly in the abrasion resistance test.

Additional testing combined with ongoing field evaluations be used to validate these findings and make final recommendations as to specification changes if warranted.

CHAPTER 5: FIELD EVALUATION OF TEST SECTIONS

TEST SECTION SELECTION

Consistent with the previous TxDOT Project 0-1710, a test section was defined as a representative subsection of a field section with an area of approximately 5000 to 7000 ft^2 for which performance monitoring was conducted. Characteristics of a test section are as follows:

- Each test section was 500 ft long and 10 to 14 ft wide (equivalent highway lane width).
- Two to four test sections were established, depending on the length of the surface treatment project. Overall performance of the field section was taken as the average of the performance of the individual test sections.
- Multiple test sections were used for each field section to avoid the possibility of overrating or underrating performance due to the absence or presence of localized distresses or geometric features such as turns or changes in surface elevation.
- Data were collected from the outside lane only.
- Intersections, junctions at access roads, grades, and curves were avoided to minimize the effects of extremely slow and turning traffic, which could exaggerate distress, and for safety reasons.

Distresses

Each test section was monitored for aggregate loss (raveling), bleeding, and cracking.

Aggregate Loss (Raveling)

Aggregate loss is the loss of stone that ravels from the surface of the seal coat.

The aggregate loss, in terms of square feet of affected surface area at each severity level, was recorded on a field performance monitoring survey sheet as shown in the example in Figure 50. Low, moderate, and high severity levels were identified as shown in Table 17.

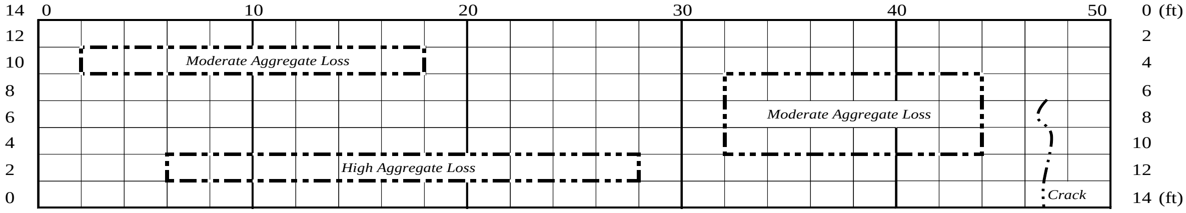
Table 17. Severity Levels for Aggregate Loss.

#	Level	Description
1	Low	The aggregate has begun to ravel off but has not significantly progressed. Evidence of loss of some fine aggregate.
2	Moderate	Surface texture becoming rough and pitted; loose particles generally exist; loss of fine and some coarse aggregates.
3	High	Surface texture very rough and pitted; loss of coarse aggregates.

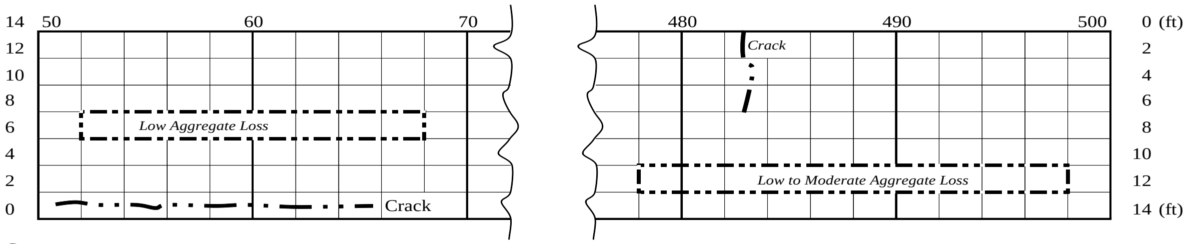
COMPLETED FIELD PERFORMANCE MONITORING SURVEY

VISUAL DISTRESS SURVEY SHEET

Hwy Section:	*HS P3*			Inspection No.	*3*
Date:	*9/5/2002*	Time:	*1.00PM*	Weather:	*Sunny*
Test Sction No.	1	Start:	*196 K6*	End:	*196 K6 + 500 miles*



Comment: *Aggregate embedment = approximately 65% in wheel path, and about 30 to 40 % between wheel path*



Comment: *Evidence of aggregate loss. Some transverse cracks from underlying structure. Generally - inadequate performance (aggregate loss)*

Surveyed by: *Tom Freeman*

Example of Distress Observations:
Consider for example, the following field survey observations on a particular highway section:

Aggregate Loss

Area coverage on 4 test sections:	***20%, 5%, 10%, and 3%***
Mean area coverage on 4 test sections:	***9.5%***
SCI score for distress area coverage (DAC):	***72%***
Severity levels for 4 test sections:	***Low to moderate, low to moderate, low, & low***
Percent severity on each test section is thus:	***10%10%, 5%, & 5%***
Mean percent severity:	***7.5%***
SCI score for degree of severity of aggregate loss (DSD):	***80%***

Cracking: ***Transverse cracking observed on some parts of the highway section***

Bleeding

Area coverage on 4 test sections:	***15%, 5%, 10%, & 10%***
Mean area coverage on 4 test sections:	***10%***
SCI score for distress area coverage (DAC):	***70%***
Severity levels for 4 test sections:	***High, low, moderate to high, & moderate to high***
Percent severity on each test section is thus:	***95%, 5%, 50%, & 50%***
Mean percent severity:	***50%***
SCI score for degree of severity of bleeding (DSD):	***300%***

Aggregate Embedment:	***60-90 % in wheel path***
	30-50 % between wheel path

Figure 50. Example Field Performance Monitoring Survey Sheet.

Bleeding

Bleeding occurs as a shiny, black, or glasslike reflective surface caused by liquid binder migrating to the pavement surface, often in the wheelpaths. It can also be defined as a film of excess bituminous binder occurring on the pavement surface. The result can be a dangerous, slippery pavement due to decreased frictional characteristics between the tire and pavement surface. Often, bleeding occurs at high pavement temperatures due to high binder application rates, low binder viscosity, use of very small aggregates and excessive embedment, inadequate and/or loss of aggregates, excessive compaction during construction, and high traffic.

Like aggregate loss, bleeding was defined and recorded in square feet of affected surface area at each of three severity levels (low, moderate, and high). Table 18 describes the severity levels.

Table 18. Severity Levels for Bleeding.

#	Level	Description
1	Low	An area of pavement surface discolored (black) relative to the remainder of the pavement.
2	Moderate	Distinctive black appearance and loss of surface texture due to free excess binder.
3	High	Wet-black shiny appearance on the pavement surface due to excess binder; excess binder may obscure aggregates; tire marks may be evident in warm weather.

Cracking – Transverse and Longitudinal

Transverse (perpendicular to the pavement centerline) and longitudinal (parallel to the pavement centerline) cracks are not the primary focus in this study, but where observed, these distresses were recorded and reported in the analysis.

Performance Evaluation and Rating Criteria

This study used the surface condition index (SCI) criterion used in TxDOT Project 0-1710 for performance evaluation and rating of the sections. The actual rating is based on calculated SCI scores, which range from 0.0 percent (very poor performance) to 100 percent (perfect performance). For each distress, the SCI score was calculated as an equal weighted function of the distress area coverage (DAC) and the degree of severity of distress (DSD), expressed as a percentage. This is illustrated in the equation below.

$$SCI_{Distress} = 0.5(P_{DAC} + P_{DSD})$$

where:

$SCI_{Distress}$ = SCI score as a percentage for a given distress.

P_{DAC} = distress area coverage as a percentage.

P_{DSD} = degree of severity of a distress in percentage.

The SCI scores for P_{DAC} and P_{DSD} were determined as shown in Figure 51 and Figure 52; a completed distress evaluation sheet is shown in Figure 53.

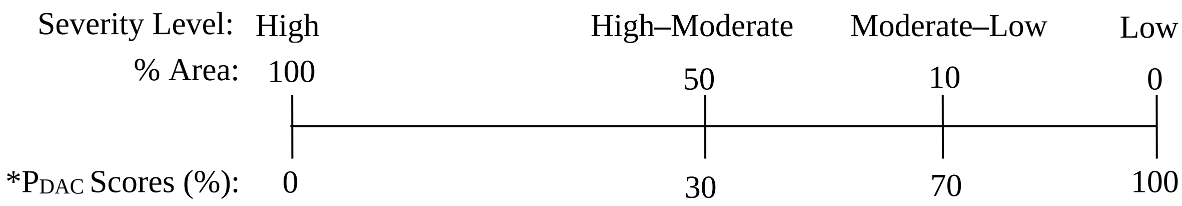


Figure 51. SCI Distress Evaluation and Scores – DAC.

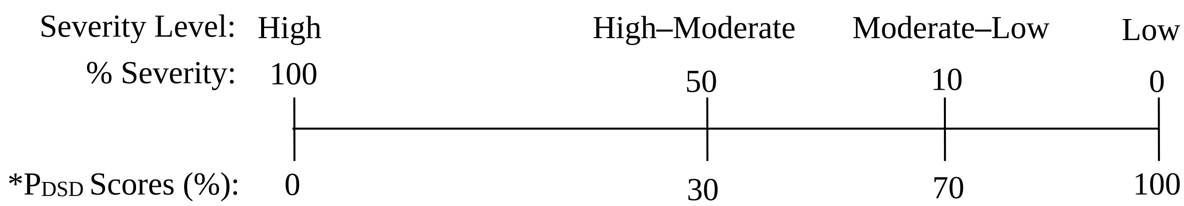
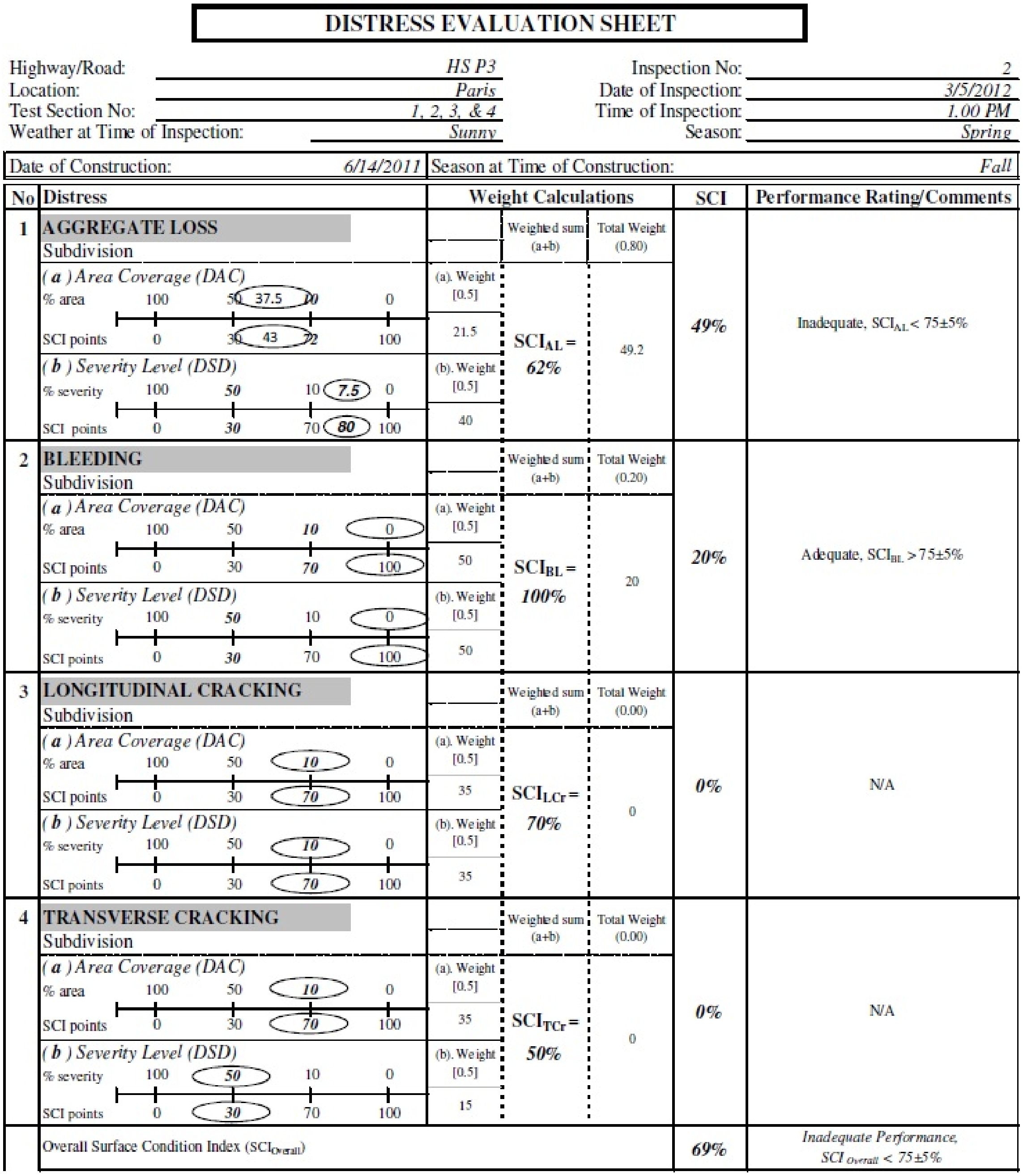


Figure 52. SCI Distress Evaluation and Scores – DSD.


DISTRESS EVALUATION SHEET

Highway/Road: HS P3 — Inspection No: 2
Location: Paris — Date of Inspection: 3/5/2012
Test Section No: 1, 2, 3, & 4 — Time of Inspection: 1.00 PM
Weather at Time of Inspection: Sunny — Season: Spring

Date of Construction: 6/14/2011 — Season at Time of Construction: Fall

No	Distress	Weight Calculations			SCI	Performance Rating/Comments
1	AGGREGATE LOSS (Subdivision: (a) Area Coverage (DAC) % area 100, 50, 37.5, 20, 0; SCI points 0, 30, 43, 72, 100; (b) Severity Level (DSD) % severity 100, 50, 10, 7.5, 0; SCI points 0, 30, 70, 80, 100)	(a). Weight [0.5]: 21.5; (b). Weight [0.5]: 40	Weighted sum (a+b): SCISCI_{AL} = 62%	Total Weight (0.80): 49.2	49%	Inadequate, SCI_{AL} < 75±5%
2	BLEEDING (Subdivision: (a) Area Coverage (DAC) % area 100, 50, 10, 0; SCI points 0, 30, 70, 100; (b) Severity Level (DSD) % severity 100, 50, 10, 0; SCI points 0, 30, 70, 100)	(a). Weight [0.5]: 50; (b). Weight [0.5]: 50	Weighted sum (a+b): SCI_{BL} = 100%	Total Weight (0.20): 20	20%	Adequate, SCI_{BL} > 75±5%
3	LONGITUDINAL CRACKING (Subdivision: (a) Area Coverage (DAC) % area 100, 50, 10, 0; SCI points 0, 30, 70, 100; (b) Severity Level (DSD) % severity 100, 50, 10, 0; SCI points 0, 30, 70, 100)	(a). Weight [0.5]: 35; (b). Weight [0.5]: 35	Weighted sum (a+b): SCI_{LCr} = 70%	Total Weight (0.00): 0	0%	N/A
4	TRANSVERSE CRACKING (Subdivision: (a) Area Coverage (DAC) % area 100, 50, 10, 0; SCI points 0, 30, 70, 100; (b) Severity Level (DSD) % severity 100, 50, 10, 0; SCI points 0, 30, 70, 100)	(a). Weight [0.5]: 35; (b). Weight [0.5]: 15	Weighted sum (a+b): SCI_{TCr} = 50%	Total Weight (0.00): 0	0%	N/A
	Overall Surface Condition Index ($SCI_{Overall}$)				69%	Inadequate Performance, $SCI_{Overall}$ < 75±5%

Figure 53. Example Distress Evaluation Sheet (Walubita and Epps Martin 2005).

Overall Field Section SCI Scores

For each field section, each distress was evaluated, analyzed, and reported separately, and then combined to get an overall field section SCI score and performance rating. This is illustrated:

$$SCI_{Overall} = [\alpha_{AL} \times SCI_{AL}] + [\alpha_{BL} \times SCI_{BL}] + \cdots + [\alpha_{Distress} \times SCI_{Distress}]$$

and

$$\alpha_{AL} + \alpha_{BL} + \cdots + \alpha_{Distress} = 1.00$$

where:

$SCI_{Overall}$ = overall field section SCI score as a percentage.

SCI_{AL} = SCI score for aggregate loss as a percentage.

SCI_{BL} = SCI score for bleeding as a percentage.

$SCI_{Distress}$ = SCI score for other distresses as a percentage.

α_{AL} = distress weighting factor for aggregate loss.

α_{BL} = distress weighting factor for bleeding.

$\alpha_{Distress}$ = distress weighting factors for other distresses.

FIELD EVALUATION RESULTS

The test section pavement evaluation results are presented in the following as the SCI in terms of aggregate loss (SCI_{AL}) and bleeding (SCI_{BL}). Seal coat surfacings represented here were evaluated between one and three years after the surface was placed. Some of these test sections were evaluated from previous project 0-1710 and 0-6616 (Vijaykumar, et al 2013). Table 19, Figure 54, and Figure 55 show the results of all low volume traffic sections (less than 1000 annual average daily traffic (AADT). Table 20, Figure 56, and Figure 57 show the results of all the moderate traffic volume sections (Between 1000 and 5000 AADT). Table 21, Figure 58, and Figure 59 show the high-traffic volume results.

Figure 60 and Figure 61 show all traffic levels combined and ranked from low to high SCI. Figure 62 and Figure 63 show all traffic levels combined and ranked by binder type.

Table 19. Low Traffic Volume (Less than 1000 AADT) Test Sections.

County	Highway	ID	Asphalt Binder	SCI_{AL}	SCI_{BL}
Camp	FM 2455	1	AC 20-5TR	64	90
Camp	FM 2254	2	AC 20-5TR	98	51
Stephens	FM 3148	3	CRS-2	57	65
Brown	FM 0590	4	CRS-2	47	100
Stephens	FM 701	5	CRS-2	77	47
Stephens	FM 1287	6	CRS-2	91	45
Collingsworth	FM 1035	7	AC-10	66	100
Knox	FM 2279	8	AC-10	58	60
Wheeler	FM 2299	9	AC-10	60	98
Sabine	FM 1	10	CRS-2P	64	99
Grayson	FM 901	11	CRS-2P	69	88
Red River	FM 3281	12	CRS-2P	88	99
Medina	FM 2676	13	AC 15P	83	78
Menard	US 190	14	AC 10-2TR	100	42
Kimble	US 377	15	AC-10	90	100

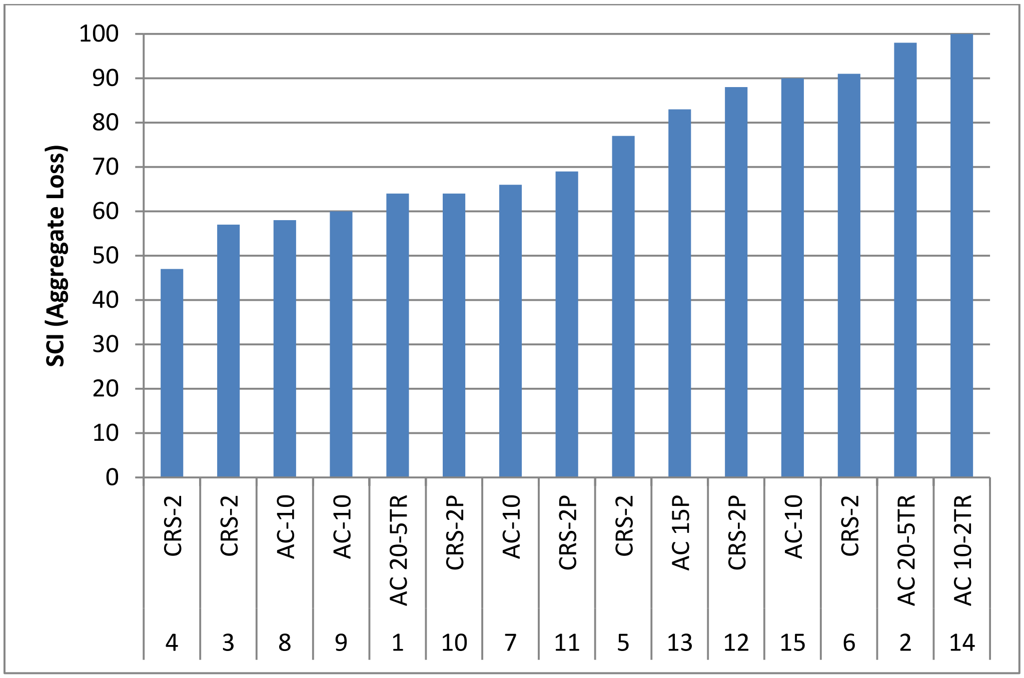


Figure 54. SCI (Aggregate Loss) for Low Traffic Volume Roads.

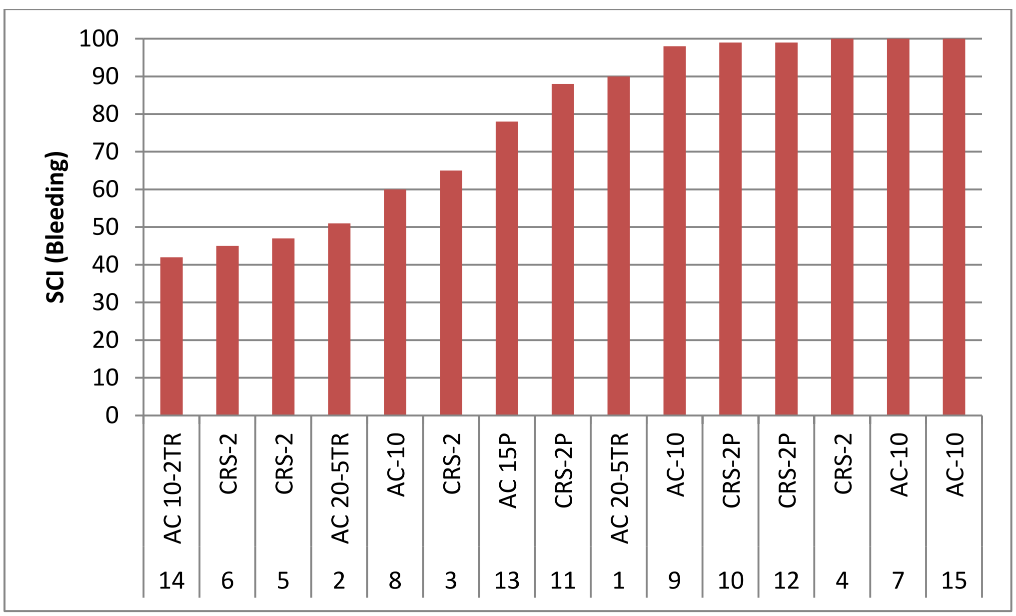


Figure 55. SCI (Bleeding) for Low Traffic Volume Roads.

Table 20. Moderate Traffic Volume (between 1000–5000 AADT) Test Sections.

District	County	Highway	ID	Asphalt Binder	SCI_{AL}	SCI_{BL}
Atlanta	Titus	SH 11	16	AC 20-5TR	69	81
	Harrison	FM 968	17	AC 20-5TR	88	69
Brownwood	Brown	US 377	18	CRS-2P	65	87
	Comanche	SH 16	19	AC 20-5TR	71	97
	McCullough	US 377	20	CRS-2H	45	100
	Comanche	SH 36	21	CRS-2H	98	45
Lufkin	Shelby	SH 87	22	AC 20-5TR	65	97
	Nacogdoches	SH 21	23	AC 20-5TR	100	62
Paris	Grayson	SH 91	24	AC 20-5TR	88	99
	Hunt	BU 69D	25	AC 20-5TR	60	99
San Antonio	Wilson	LP 181	26	AC-15P	66	68
	Guadalupe	FM 725	27	AC-15P	65	64
San Angelo	Kimble	US 377	28	AC-10	100	46
Odessa	Midland	FM 662	29	AC 20-5TR	100	44

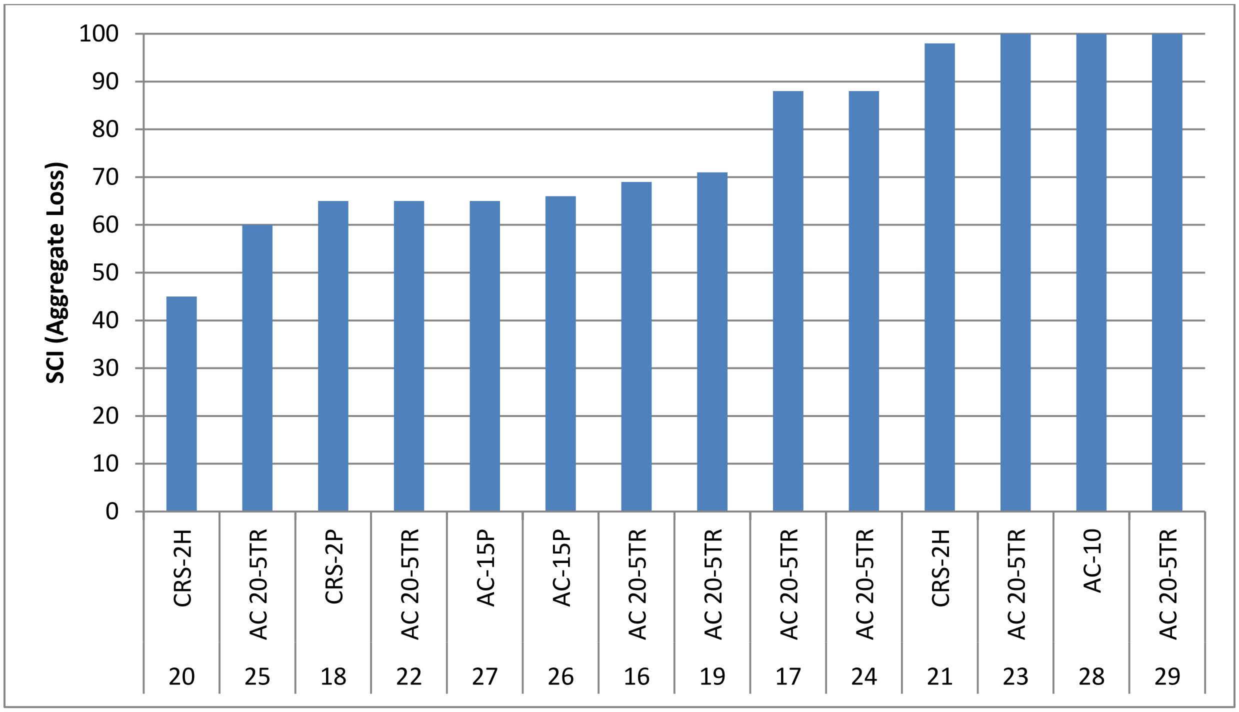


Figure 56. SCI (Aggregate Loss) for Moderate Traffic Volume Roads.

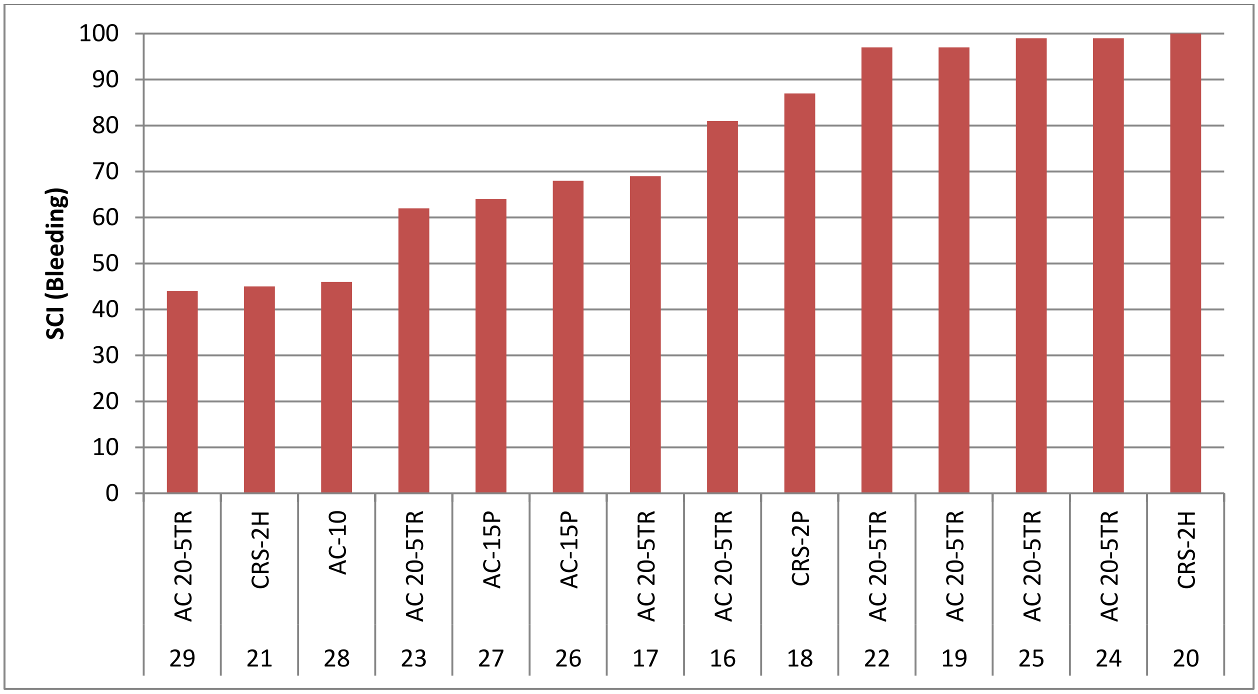


Figure 57. SCI (Bleeding) for Moderate Traffic Volume Roads.

Table 21. High Traffic Volume (Greater than 5000 AADT) Test Sections.

District	County	Highway	ID	Asphalt Binder	SCI_{AL}	SCI_{BL}
Atlanta	Panola	SH 11	30	AC 20-5TR	93	38
	Upshur	FM 968	31	AC 20-5TR	71	93
Brownwood	Comanche	SH 16	32	AC 20-5TR	71	74
	Brown	US 67	33	AC 20-5TR	72	75
Lufkin	Trinity	SH 19	34	AC 20-5TR	86	82
Paris	Grayson	FM 1417	35	AC 20-5TR	96	75
	Grayson	SS 503	36	AC 20-5TR	61	100
San Antonio	Guadalupe	FM 78	37	AC-15P	72	49
	Uvalde	US 90	38	AC-15P	80	89
Austin	Lee	US 77	39	HFRS-2P	100	37
San Angelo	Tom Green	US 67	40	AC 20-5TR	81	94
Abilene	Taylor	FM 3438	41	AC 20-5TR	100	38

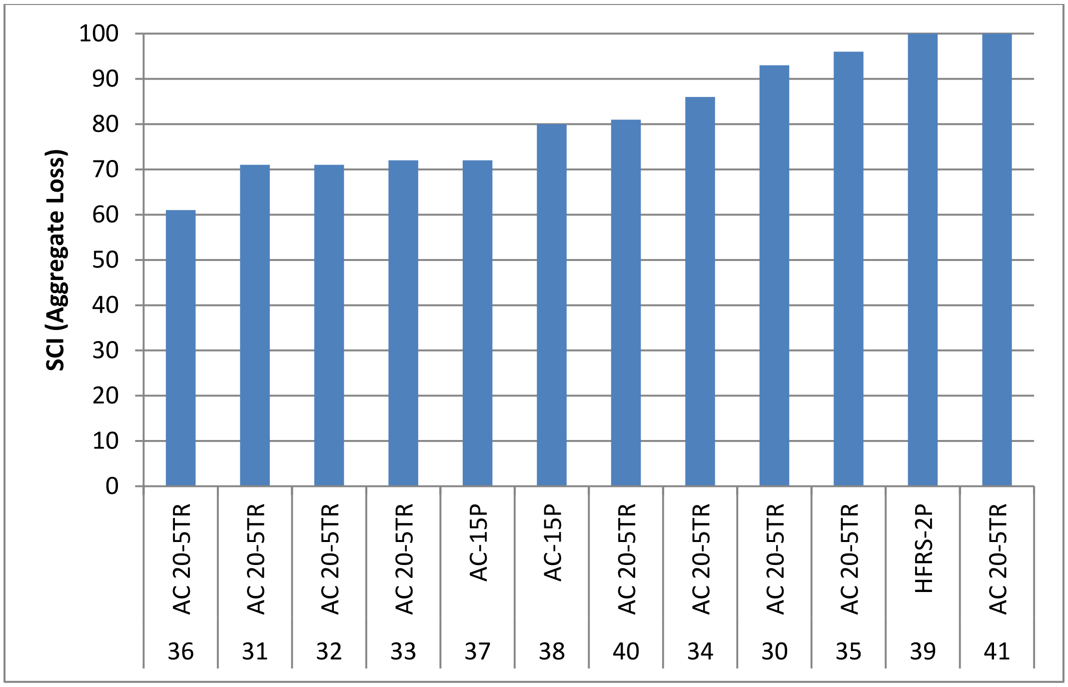


Figure 58. SCI (Aggregate Loss) for High Traffic Volume Roads.

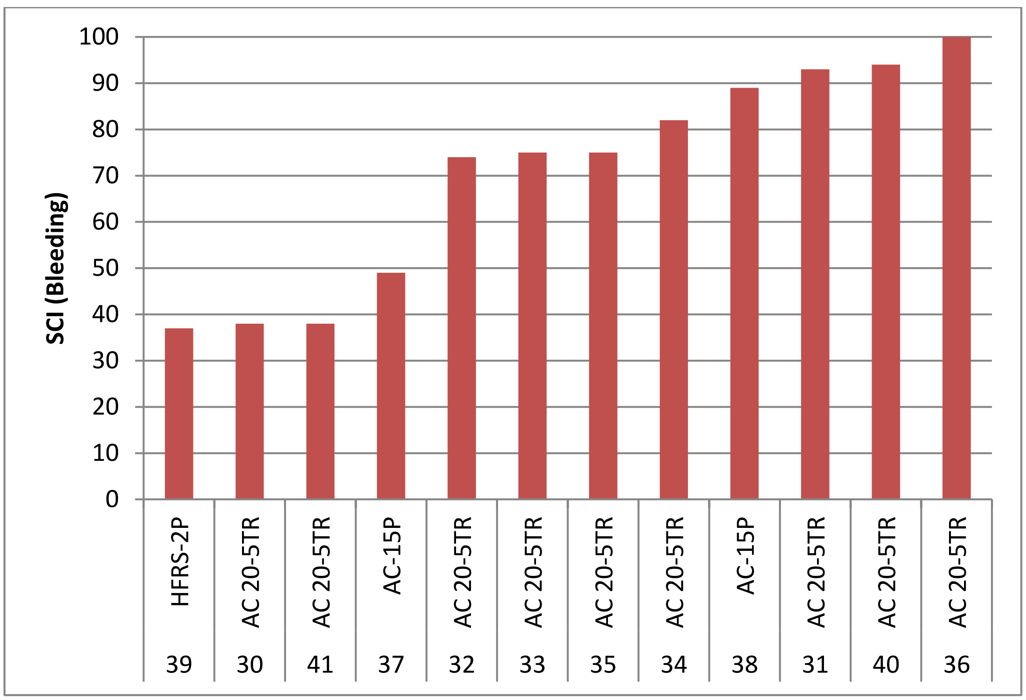


Figure 59. SCI (Bleeding) for High Traffic Volume Roads.

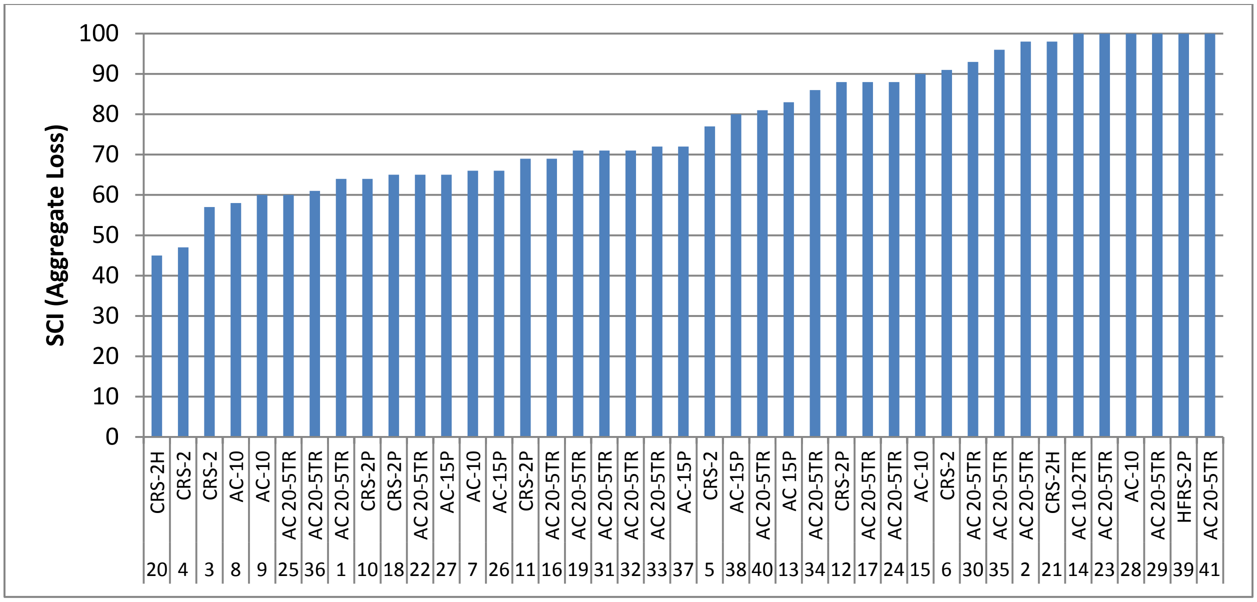


Figure 60. SCI (Aggregate Loss) for All Traffic Levels Ranked Low to High.

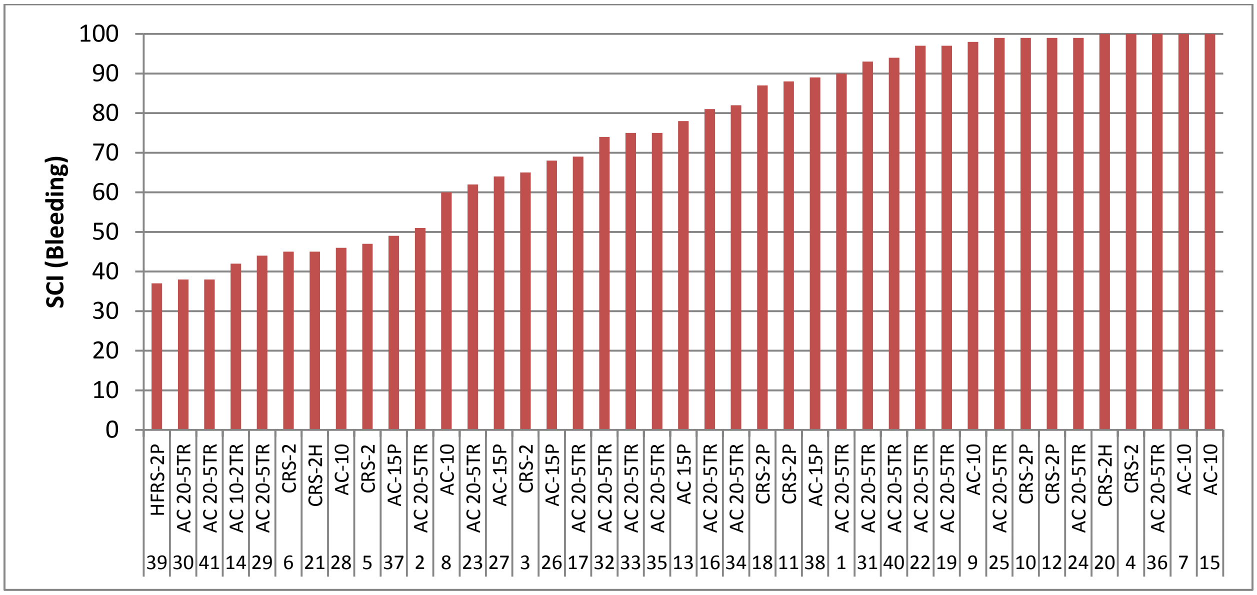


Figure 61. SCI (Bleeding) for All Traffic Levels Ranked Low to High.

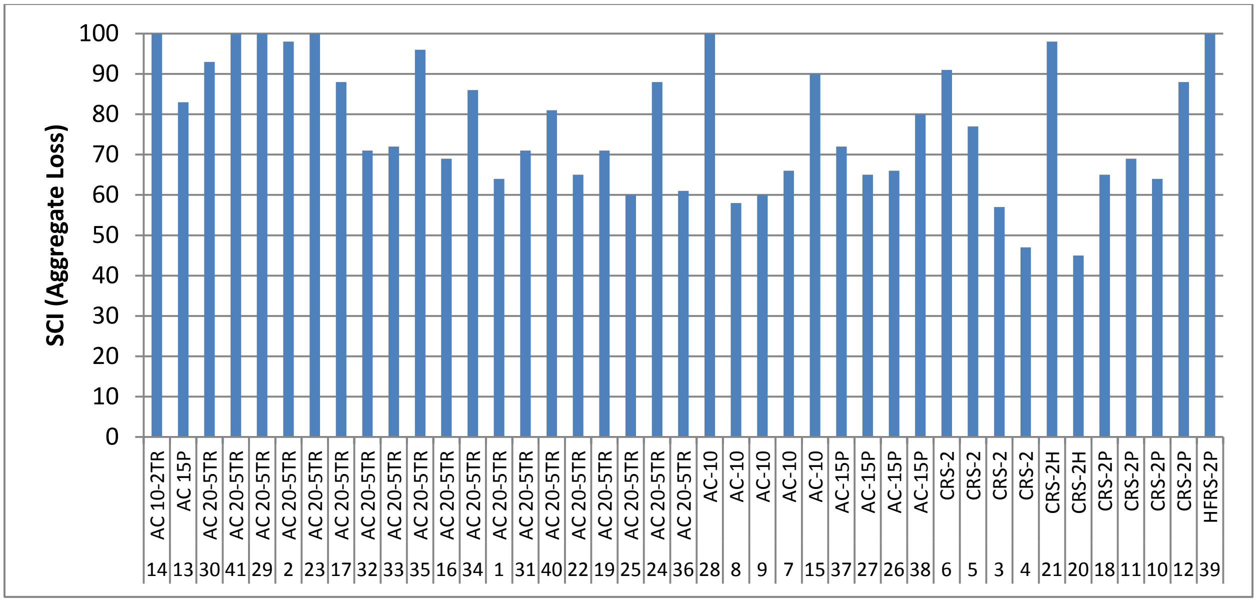


Figure 62. SCI (Aggregate Loss) for All Traffic Levels Ranked by Binder Type.

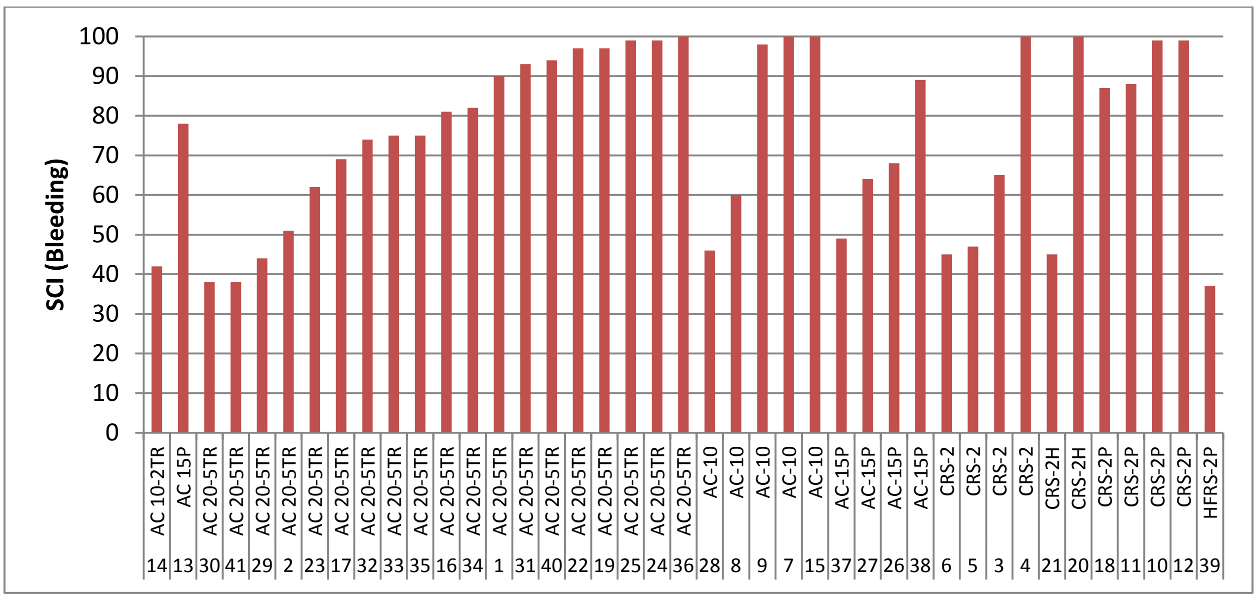


Figure 63. SCI (Bleeding) for All Traffic Levels Ranked by Binder Type.

Most of the unmodified binders (CRS-2, AC-10) were used on low volume roadways as shown in Figure 54 and Figure 55. In terms of aggregate loss (Figure 54), eight of the 15 roadways had a SCI_{AL} less than 70. Five of these eight used unmodified binders, either CRS-2 or AC-10. In terms of bleeding, half of the unmodified binders had SCI_{BL} over 70 and half were below 70. A total of eight of the test sections had unmodified binder. Five performed poorly in terms of aggregate loss (sections 4, 3, 8, 9, 7). An additional two test sections (6 and 5) performed poorly in terms of bleeding while Sections 8 and 3 performed poorly in both aggregate loss and bleeding. Seven of the eight unmodified binder test sections performed poorly either from bleeding, aggregate loss, or both.

Fourteen test sections were on moderately trafficked roadways (Figure 56 and Figure 57). Binders used here included AC-20-5TR, AC-15P, CRS-2P, CRS-2H, and AC-10. In terms of aggregate loss, half of the roadways had SCI_{AL} below 70 and all but one of these was constructed with polymer modified premium binders (AC-20-5TR, AC-15P, CRS-2P). In terms of SCI_{BL}, half of the sections performed poorly (below 70). Two of these were constructed with unmodified binders. Of the 14 total test sections, three were constructed with unmodified binders and all three performed poorly in terms of either bleeding or aggregate loss.

Twelve test sections were constructed on high traffic roadways (Figure 58 and Figure 59). Only one of these sections had an aggregate loss SCI_{AL} less than 70 and it was constructed with AC-20-5TR. Four sections had a bleeding SCI_{BL} less than 70 and these sections were constructed with HFRS-2P, two with AC-20-5TR and AC-15P. No unmodified binders were used on these high volume facilities.

Figure 62 shows the overall SCI for all the pavement test sections. This is a combined score determined by averaging the values of SCI_{AL} and SCI_{BL}. The predominantly used binder by TxDOT is the AC-20-5TR, so most of the test sections are constructed using this binder. The median SCI values for all of the binder types are follows:

Polymer Modified Binders (AC-10-2TR, AC-20-5TR, CRS-2P, HFRS-2P) *Median SCI = 78.5*
Unmodified Binders (AC-10, CRS-2, CRS-2H) *Median SCI = 72.5*

While the polymer modified binders overall performed at a higher level, the test section with the highest score happened to be an unmodified binder (AC-10). As is well known, there are many factors that can influence the performance of seal coats and material selection is only one. If constructed properly and if the roadway is a good candidate, unmodified binders may perform well. For higher volume facilities, it still seems that polymer modified binders are likely to give better success.

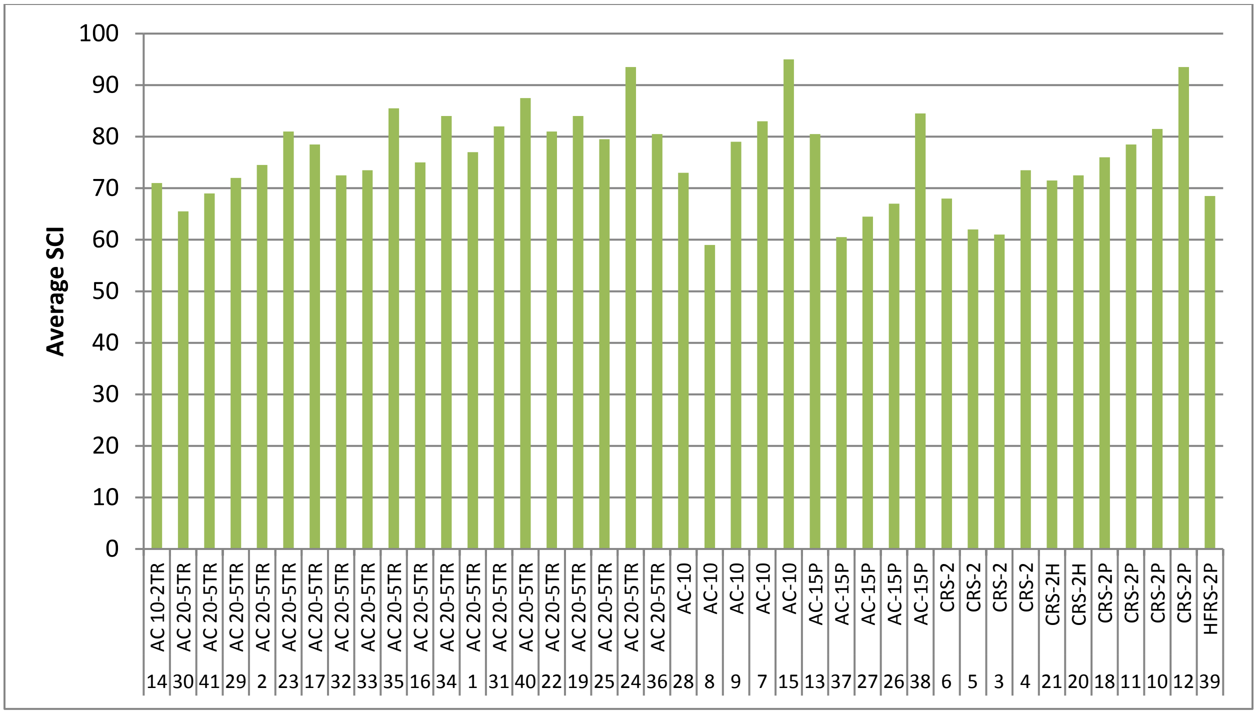


Figure 64. Average SCI for All Traffic Levels Ranked by Binder Type.

The SCMST has been used as a guideline to select binders based on a tiered approach in terms of traffic levels. However, the service conditions of roadways with seal coat surfaces have changed over the years. With higher speed limits even in minor collector roadways where seal coats are commonly used, one can see heavy trucks using them. Even though the truck traffic volumes are not as high as on other major collectors and arterials, these minor collectors such as farm-to-market roads do take a beating from even low volumes of heavy traffic. This is further accentuated by the changes in climate patterns resulting in drought conditions for extended periods such as that occurred during summer 2011. This flushing performance even on low volume roadways is evident from Figure 65 where the SCI for flushing is plotted against estimated cumulative truck traffic during its service period until the date of survey. Figure 65 shows that unacceptable levels of flushing, as evidenced by SCI values below 60, was present on highways that had a wide range of truck volumes from very low to very high. In low truck volume roadways, the softer asphalt binders recommended in the SCMST are not able to withstand even low numbers of heavy traffic.

The non-recoverable creep compliance values calculated from the MSCR test for commonly used seal coat binders such as AC-10, AC-10 2TR, AC-15P, AC-20 5TR, AC-20 XP, and A-R showed significantly different performances from binders tested at 64°C. Softer asphalt cement binders such as AC-10 and softer but modified binders such as AC-10 2TR showed significant non-recoverable strain build-up during the 10 cycles of MSCR test for both un-aged and RTFO-aged binder. The stiffer binders such as A-R, AC-20 XP, AC-20 5TR, and AC-15P showed much improved performance in flushing behavior as indicated from lower non-recoverable creep compliance values. This shows that using low-cost softer binders in low ADT highways is not likely to reduce flushing of the seal coat and will lead to wet-weather traffic safety problems.

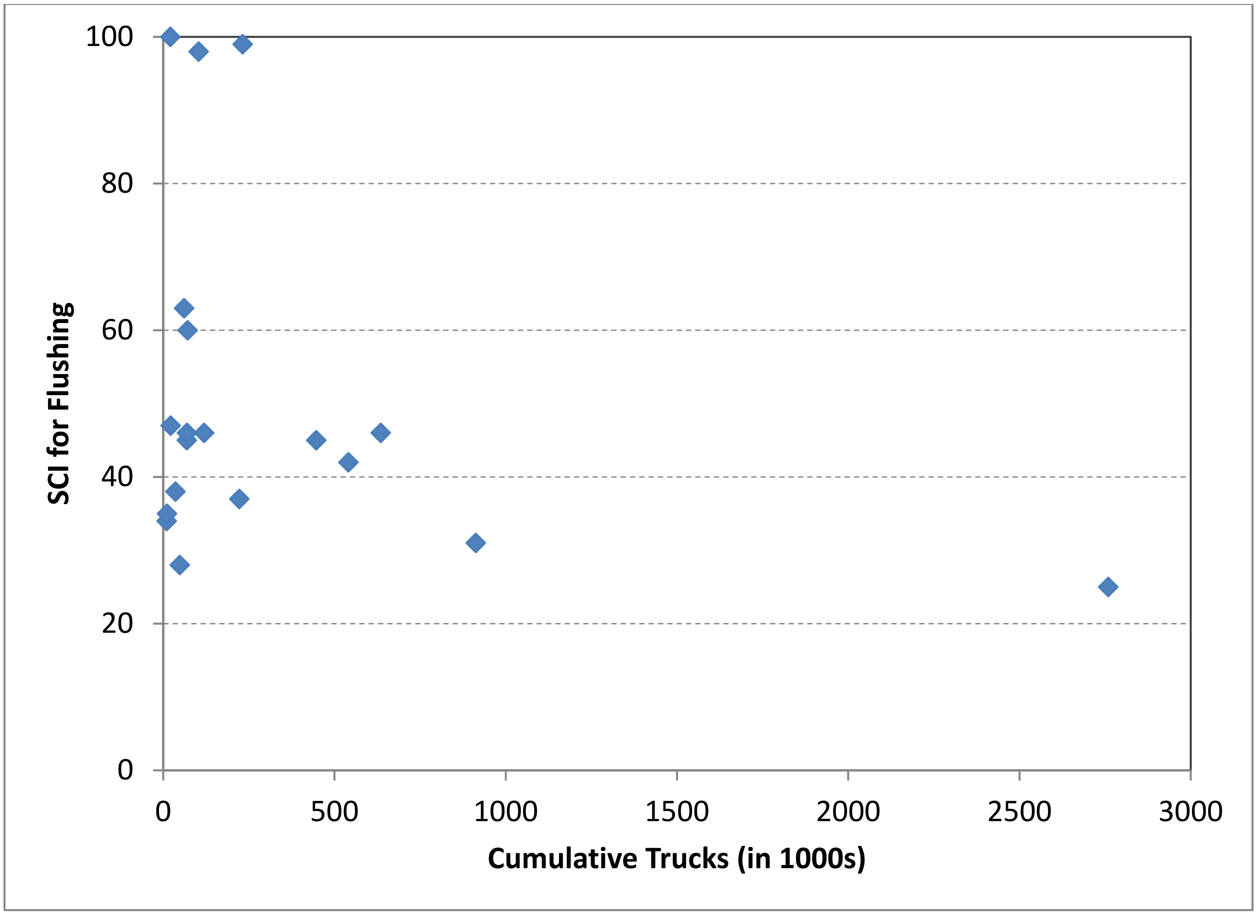


Figure 65. SCI for Seal Coat Surfaces vs. Estimated Cumulative Heavy Trucks.

CHAPTER 6: CONCLUSIONS

Researchers conducted a laboratory test program to evaluate binders and aggregates commonly used for seal coat construction. For aggregates, Micro-Deval and AIMS testing were conducted on the aggregate samples. In addition, two new procedures were employed. One of the test procedures used to evaluate the wear characteristics of seal coat aggregates was a modification of ASTM C 944. This test procedure was originally developed to determine the resistance of concrete to abrasion. It has been used successfully in the quality control of highway and bridge concrete subject to traffic. Another procedure consisted of fabricating seal coat samples in the laboratory and trafficking them in a three-wheel polisher, which runs three-load-bearing tires over the specimen in a constant turning motion. Change in texture is measured using a laser scanner at several times throughout the process. The gravel aggregates, which are also SAC A aggregates, performed the best in terms of wear resistance as measured with the methods described here. The remaining aggregates, which consisted of limestones, LRA, and lightweight, exhibited a range in wear characteristics. One of the limestone sources exhibited very poor performance in the Micro-Deval test and yet performed like the other limestones in the abrasion resistance test. The abrasion resistance test does distinguish between different SAC B materials and generally indicates the LRA aggregates to be poor performers in terms of wear resistance. This also seems to be consistent with field reports. Lightweight aggregate, which is a very popular seal coat aggregate with unique properties, also performed poorly in the abrasion resistance test.

Asphalt binders were sampled from field projects and test sections. Three tests were conducted in this research: the DSR Strain Sweep Test on asphalt binder, MSCR test on asphalt binder, and Pull-Out Test on Aggregate Embedded on Asphalt Binder. The strain sweep and MSCR tests are standard AASHTO tests and the pull-out test was developed at Texas Tech University. The non-recoverable creep compliance values calculated from the MSCR test for commonly used seal coat binders such as AC-10, AC-10 2TR, AC-15P, AC-20 5TR, AC-20 XP, and A-R showed significantly different performances from binders tested at 64°C. Softer asphalt cement binders such as AC-10 and softer but modified binders such as AC-10 2TR showed significant non-recoverable strain build-up during the 10 cycles of MSCR test for both un-aged and RTFO-aged binder. The stiffer binders such as A-R, AC-20 XP, AC-20 5TR, and AC-15P showed much improved performance in flushing behavior as indicated from lower non-recoverable creep compliance values. This shows that using low-cost softer binders in low ADT highways is not likely to reduce flushing of the seal coat. The pull-out test was developed at the Texas Tech laboratories and shows potential for future research. The test was developed to measure shear strength at the interface of various binder-aggregate combinations. While the data on this test are limited, the repeatability of the test is quite good with good quality aggregates commonly used by TxDOT.

Field test sections consisting of many of the commonly used binders were evaluated for performance in terms of bleeding and aggregate loss. Most of the unmodified binders (CRS-2, AC-10) were used on low volume roadways. In terms of aggregate loss, 8 of the 15 roadways had a SCI_{AL} less than 70. Five of these eight used unmodified binders, either CRS-2 or AC-10. In terms of bleeding, half of the unmodified binders had SCI_{BL} over 70 and half were below 70. A total of eight of the test sections had unmodified binder. Five performed poorly in terms of aggregate loss. Seven of the eight unmodified binder test sections performed poorly either from bleeding, aggregate loss, or both.

Fourteen test sections were on moderately trafficked roadways, binders used here included AC-20-5TR, AC-15P, CRS-2P, CRS-2H, and AC-10. In terms of aggregate loss, half of the roadways had SCI_{AL} below 70 and all but one of these was constructed with polymer modified premium binders (AC-20-5TR, AC-15P, CRS-2P). In terms of SCI_{BL}, half of the sections performed poorly (below 70). Two of these were constructed with unmodified binders. Of the 14 total test sections, three were constructed with unmodified binders and all three performed poorly in terms of either bleeding or aggregate loss.

Twelve test sections were constructed on high traffic roadway. Only one of these sections had an aggregate loss SCI_{AL} less than 70 and it was constructed with AC-20-5TR. Four sections had a bleeding SCI_{BL} less than 70, and these sections were constructed with HFRS-2P, two with AC-20-5TR and AC-15P. No unmodified binders were used on these high volume facilities.

A blended SCI score were compared for all of the test sections. This is a combined score determined by averaging the values of SCI_{AL} and SCI_{BL}. The predominantly used binder by TxDOT is the AC-20-5TR and thus most of the test sections are constructed using this binder. The median SCI values for all of the binder types are follows:

Polymer Modified Binders (AC-10-2TR, AC-20-5TR, CRS-2P, HFRS-2P)	*Median SCI = 78.5*
Unmodified Binders (AC-10, CRS-2, CRS-2H)	*Median SCI = 72.5*

While the polymer modified binders overall performed at a higher level, the test section with the highest score happened to be an unmodified binder (AC-10). There are many factors that can influence the performance of seal coats, and material selection is only one. If constructed properly and if the roadway is a good candidate, unmodified binders may perform well. For higher volume facilities, it still seems that polymer modified binders are likely to give better success.

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