USE OF HOT MIXED WARM COMPACTED ASPHALT IN CONSTRUCTION

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ABSTRACT

Warm mix additives have the potential to be advantageous in a variety of asphalt construction applications. Applications that would not have been considered a few years ago are beginning to be considered. Long haul distances provide numerous construction advantages. This paper presents the results of a study of hot mixed-warm compacted asphalt incorporating warm mix additives for use in emergency construction following a hurricane. A two component investigation was performed. Component one developed a series of short term aging protocols for use in preparation of test specimens for component two. Component two evaluated compactability and rut resistance of the mixtures. Results indicated that the two warm mix additives studied improved compactability of hot mixed-warm compacted asphalt, and that rut resistance was acceptable for emergency conditions. Discussion related to the fate of the material after all emergency trafficking is complete was also provided.

INTRODUCTION

Following the occurrence of a natural disaster, pavement structures can be damaged such that response and recovery actions can be hindered. Pavement damage after a natural disaster (e.g. hurricane) can take many forms from minor damage to total loss of the pavement structure. Howard et al. (*1*) described four categories of pavement damage that may be encountered post-natural disaster: intact pavements, damaged-passable pavements, damaged-dangerous pavements and impassable pavements. Figure 1 illustrates examples of damage-passable pavements after a hurricane.

FIGURE 1 Examples of Damage-Passable Pavement Damage Post-Natural Disaster.

It is vitally important that pavements be available for rescue personnel and supplies to be transported to the affected area. Howard et al (*1*) have developed protocols in order to quickly and reasonably evaluate, prioritize, and repair pavement networks post natural disaster for initial response operations. The primary intent of these protocols was to provide repair strategies with minimum performance lives, with the focus being on response and recovery. Note that a residual value could exist after recovery depending on damage to the rapid repair during recovery operations.

Of the many repair techniques described by (*1*), hot mixed-warm compacted asphalt is discussed in this paper. A significant advantage over other techniques is that it can be produced inland away from the disaster area (where electricity may not be available for a week or more) and hauled to the damaged areas. Table 1 shows warm mix additives (WMA's) have been successfully used in permanent construction in a variety of conditions supporting their versatility, especially their ability to facilitate compaction. Long haul distances with WMA are shown in Table 1, and in one instance (Pacific Coast Highway 1) hot mixed-warm compacted asphalt was successfully used in construction. Other sources (*2*, *3*) have discussed WMA, and in particular extended haul distances. Note that haul distance and/or haul time do not necessarily describe the environment fully and should only be used as subjective indicators of the project environment. The difference in the asphalt mixing temperature (T_{mix}) and the compaction temperature (T_{comp}) are more quantifiable parameters.

TABLE 1 Construction Projects Incorporating WMA 1 and Dense Gradation

Project	PG Binder	NMAS (mm)	Site Conditions	T_{mix} (C)	T_{comp} (C)	Haul Time (hr)	Haul Dist (km)	V_a (%)
I-70, MO[a]	64-22	12.5	Overcast: 9 C	---	125	---	97	5.8
I-78, NJ	76-22	12.5	Night: cool: rain	116-143	102-127	1	58	5.1
I-70, CO	58-28	12.5	Air < 0 C	121	116	0.5	26	5.3
US 84, TX[b]	64-22	9.5	Sunny: 13 C	133	116-127	---	48-64	6.0
I-37, TX	76-22	12.5	Sunny: 21-32 C	127-130	116-118	Metro area	48	< 8.0
BU 287, TX	64-22	19.0	Sunny	116	88-110	1	80	5.5
BU 287, TX	76-22	12.5	Sunny	113-132	93-116	1	80	3 - 6
Hwy 1, CA[c]	64-16	12.5	Chilly: foggy	149-152	105-116	3-4	137	< 8.0
HVS, CA[d]	64-16	12.5	Sunny: balmy	121	80	---	---	7.1
NCAT, AL	64-22	19.0	Sunny	116-121	82-116	short	short	<5.0
NCAT, AL	64-22	12.5	Sunny	116-121	82-116	short	short	<5.0

a: Fewer roller passes required to achieve density.

b: Contractor began using WMA 1 when problems arose with foamed asphalt.

c: Very long haul on Pacific Coast Highway 1 with all laydown operations proceeding smoothly.

d: Heavy Vehicle Simulator (HVS) of Caltrans. Rutting performance same as control with T_{mix} of 155 C.

OBJECTIVE

The objective of this research was to evaluate the ability to produce asphalt using WMA at typical hot mix temperatures (i.e. T_{mix} on the order of 165 C), transport these materials over a large distance (e.g. 250 km), compact these materials at warm temperatures (e.g. 105 to 116 C), and achieve reasonable performance. Therefore, the research focused upon; 1) the ability of available mixtures to be laboratory compacted at anticipated field conditions and 2) short term performance.

RESEARCH APPROACH

The research approach carried out to accomplish the objective of this project entailed two primary components performed in series. Within the first component, laboratory methods were evaluated that would simulate the cooling of mixture during extended haul distances/times. The second component entailed compacting numerous specimens in the laboratory that were aged using data from the first component with a linear asphalt compactor (*LAC*) and a Superpave gyratory compactor (*SGC*). The compacted specimens were evaluated in terms of air void content and rutting susceptibility.

Within the first component, laboratory testing was conducted to evaluate methods that would simulate the loss of temperature that occurs during transport of mixture to the project site. Two target time periods (240 and 360 min) were utilized to develop laboratory short term aging protocols (*STAPs*). These time frames were selected because asphalt plants would be located that could supply any location along the Gulf Coast within these constraints. The time frames also allow time on site for transport between needed areas for patching, traffic delays, and similar.

The *STAPs* were then used to age mixtures that were subsequently compacted using the *LAC* and *SGC* during component two. These specimens were used to compare rutting resistance of the mixtures as a function of in place air voids using the Asphalt Pavement Analyzer (APA). The relative compactability of mixtures with and without WMA was also studied using the *LAC*.

COMPONENT 1: SHORT TERM AGING PROTOCOL DEVELOPMENT

A literature review and thermodynamic assessment of hauling asphalt was performed during the research, with full details provided in (*1*) and a summary provided herein. Thermal imaging data (*4*), long haul distances in Australia with temperature measurements (*4*), and temperature measurements during warm mix asphalt field trials in Virginia (*5*) were the most notable literature. The mix in Australia was transported 240 km and upon arrival the mix boundaries were 80 to 96 C, while the mix center was 152 C. Test data reported from (*5*) was used to calculate a cooling rate constant (*k*) for materials used in the study ($1{,}100*10^{-6}$ min^{-1}) in the core portion of the truck. Extrapolation of the data showed how a relatively large mass of asphalt can retain heat in its core for a long period of time. Temperatures predicted with the extrapolation are believed to be higher than would occur at the paver once the entire truck load was mixed in the transfer vehicle; an expected behavior.

Four methods were investigated to evaluate the rate of HMA cooling within a laboratory setting. All entailed the evaluation of 33.1 kg of field mixed HMA placed into a 19-liter metal pail. All cooling occurred within a 0.708 m^3 capacity forced draft oven. The first method entailed taking HMA from an oven set at 171 C and transferring to a second oven set at a specified temperature. A second method entailed heating the HMA to 171 C and then reducing the temperature of this oven to a specified temperature. The third method entailed heating the HMA to 171C and then incrementally reducing the temperature within this oven. Finally, HMA mix was heated to 171 C and then the oven was shut off with the door remaining closed.

Eleven experiments were performed during the cooling rate investigation that incorporated two probe thermocouples measuring the temperature of the core of the asphalt in the pail and bead thermocouples measuring temperature of the air 30 cm above the mixture. A *National Instruments NI Compaq Daq 9172* chassis and *NI 9211* module were used in conjunction with a program written in *LabView*™ to acquire temperature data every ten seconds. This data was used to develop short term aging protocols (*STAPs*) used to simulate hot mixed-warm compacted asphalt placed in the field.

Data from methods one and two were averaged and plotted in Figure 2 alongside overall standard deviations for the data; temperatures are those measured for the center of the mixture. Mix temperatures predicted from methods three and four were not directly utilized. The measured laboratory mix temperatures at 240 and 360 min were lower than estimated temperatures calculated using cooling rates from (*5*); these temperatures were previously judged higher than probable field conditions in many applications (Table 1 data supports this statement).

Cooling rate constants were calculated to be 4.3 to 5.8 times higher than the value calculated from the Virginia study of $1{,}100*10^{-6}$ min^{-1}. The faster cooling rate is credible considering the much smaller mass. The difference in cooling rate could be viewed as a scale factor of sorts. The tendency of a large mixture mass (> 20,000 kg) in the field to retain more heat than the comparatively small mixture mass (~30 kg) utilized during laboratory testing would be very difficult to precisely repeat in terms of time to a temperature. Rather than take this approach, the authors used data in Table 1 (Pacific Coast Highway project in particular) to select reasonable mixture compaction temperatures that would occur after a long haul time while reducing the temperature as the haul time increased. A family of time-temperature curves could be produced depending on ambient air temperature, total mix mass, travel speed, and the like. The approach taken provides a very reasonable aging protocol that uses cooling rate principles coupled with field measured temperatures during compaction on warm mixed asphalt projects.

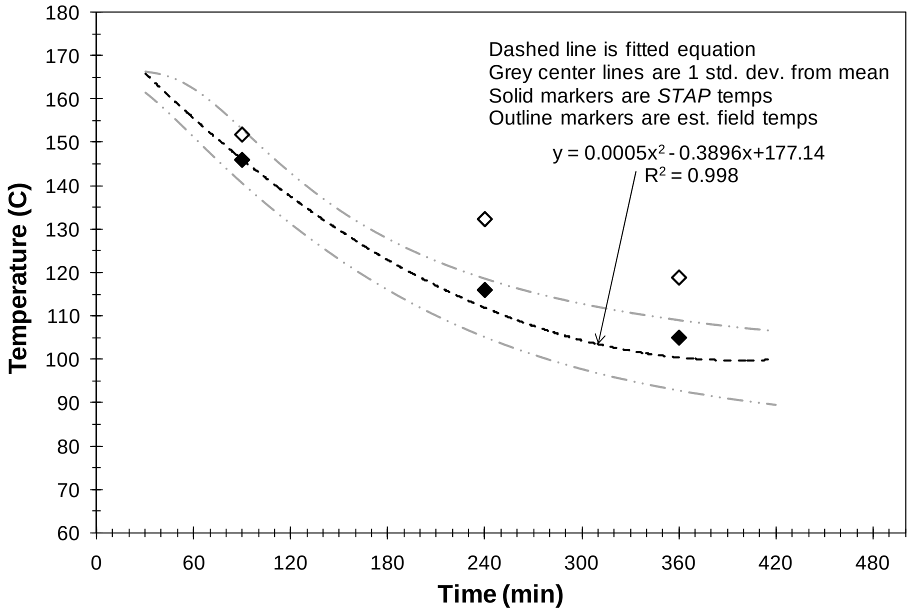


FIGURE 2 Development of Short Term Aging Protocols (*STAPs*).

Six *STAPs* were developed, each consisting of a specific combination of target mixture temperature and oven aging time (Table 2). The goal was reasonable simulation of probable field conditions for long haul times that could be practically implemented in a laboratory. Three oven curing times were chosen: 90 min, 240 min, and 360 min. For the 90 min protocol a compaction temperature of 146 C was chosen as it is standard practice; it is labeled *STAP 1*. Compaction temperatures for 240 and 360 min aging times were determined with the approach described in this section.

TABLE 2 Short Term Aging Protocols *(STAPs)*

STAP	**Aging Time[1]**	**Target Temperatures**		
		T_{mix}	T_{STAP}[2]	T_{comp}
(---)	**(min)**	**(C)**	**(C)**	**(C)**
LAC protocols				
1	90	165	152	146
2	240	165	122	116
3	360	165	111	105
SGC protocols				
4	90	165	146	146
5	240	165	116	116
6	240[3]	165	105	105

1) Time elapsed from conclusion of mixing and placement of mix in oven until removing mix from oven just prior to compaction. Time period targets were ± 5 min. MDOT standard aging time is 90 min.

2) One oven temperature was maintained during STAP for entire aging time; 152, 113, and 102 C for STAP 1 to 3, respectively. Temperature targets were ± 3 C.

3) No difference in 240 and 360 minute aging for SGC sized specimens.

COMPONENT 2: TESTING OF HOT MIXED-WARM COMPACTED ASPHALT

Twenty four factor-level combinations were considered: three *STAPs*, four compactability scenarios, and two aggregates. A minimum of two replicates were used at each factor-level combination. The four compactability scenarios were: 1) PG 67-22 control mixture; 2) PG 67-22 sequentially mixed with aggregate; 3) PG 67-22 with WMA 1; and 4) PG 67-22 with WMA 2. Control mixtures were mixed according to laboratory standard practice. Sequentially mixed samples did not utilize additives but instead were mixed in two stages similar to (*6*). Coarse and fine aggregate were batched separately, the coarse aggregate and all binder placed in the mixer for 40 sec of mixing, and the fine aggregate added and given an additional 40 sec of missing. WMA 1 and WMA 2 were added in conventional manner.

Materials Tested

Two MDOT approved asphalt mixtures were selected that contained 15% RAP and used PG 67-22 as the base binder. *Mixture 1* was a medium design traffic 19 mm NMAS that consisted of 74% limestone aggregate with 0.6% water absorption and 4.1% virgin asphalt. *Mixture 2* was a high design traffic 12.5 mm NMAS that consisted of 63% crushed gravel aggregate with 1.8% water absorption and 5.7% virgin asphalt. Two warm mix additives were tested: WMA 1 (Evotherm 3G™) at 0.5% of total binder mass; and WMA 2 (Sasobit®) at 1.0% of total binder mass based on previous testing (*7*). Table 3 provides test results of binder prior to use within a mixture. As seen the values of G* /sin δ were lowest for binder containing WMA 1 and highest for binder containing WMA 2.

TABLE 3 Un-aged Binder *DSR* and Brookfield Viscosity Properties

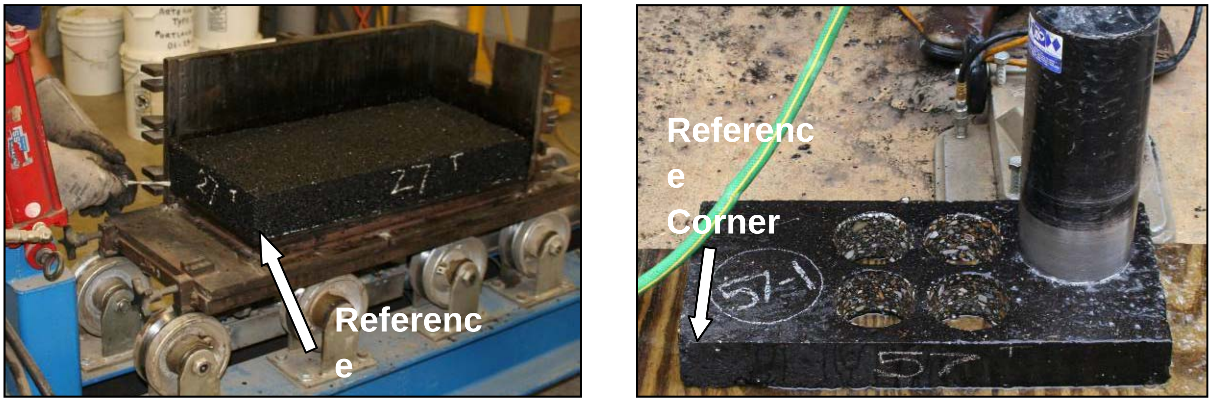
Mix	Binder	*G** (kPa)	*δ* (^{o})	*G** / sin *δ* (kPa)	Viscosity (cP) AASHTO T 316 105 C	116 C	146 C
All	Neat PG 67-22	1.29	84.9	1.29	4391	2366	379
1	PG 67-22 w/ WMA 2	1.73	83.5	1.75	4262	2100	354
1	PG 67-22 w/ WMA 1	1.06	85.7	1.06	4115	2084	446
2	PG 67-22 w/ WMA 2	1.56	83.9	1.57	---	---	---
2	PG 67-22 w/ WMA 1	1.14	85.2	1.15	---	---	---

Note: AASTO T 315-DSR test temperature was 67 C and angular frequency was 10 rad/s.
Note: High G^* and low δ are desirable for rut resistance.

Linear Asphalt Compactor (*LAC*) Specimens

Seventy-nine slabs 75-85 mm thick were compacted with the *LAC* described in (*8*) to compare air voids under a standard compactive effort. The *LAC* produces rectangular slabs 29.2 cm by 62.2 cm and 3.8 cm to 10.2 cm thick by moving the compaction mold under a roller and allowing vertically arranged plates to create a kneading compactive effort (Figure 3). A target of +10% air voids was selected for slab compacted control specimens; preliminary slabs were compacted to establish the protocol for *Mixture 1* and *Mixture 2*. After compaction, the slabs were marked with a reference corner and removed from the mold. After cooling, test specimens were sawn from the slabs in a standard fashion. Note that the only data discussed in this report are the two *APA* test specimens removed from each slab.

(a) Leveling of Mix in LAC *(b) Plates Over Mix During Compaction*



(c) Compacted Slab *(d) Coring Slabs to Create Test Specimens*

FIGURE 3 Slab Compaction Process Using the *LAC*.

Superpave Gyratory Compactor (*SGC*) Specimens

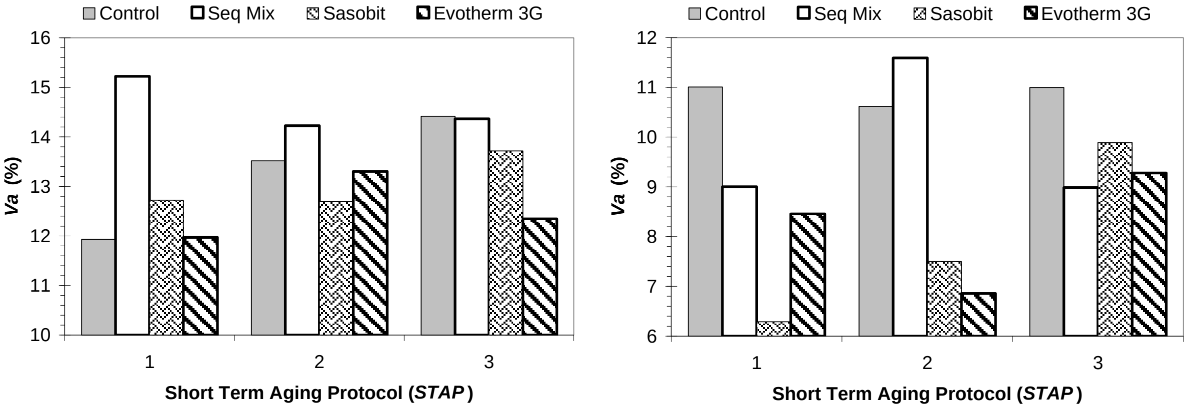
SGC specimens were prepared at 10% air voids; 48 specimens were compacted. Specimens were compacted in the *SGC*, cooled from compaction temperature to test temperature, and then immediately subjected to *APA* rut testing. The purpose was to assess rutting potential of mix opened to traffic very soon after compaction without being allowed to cool completely. The mix mass needed to obtain 10% air voids was determined via preliminary testing.

Test Methods

Bulk specific gravity (G_{mb}) was measured using AASHTO T 331-08 (CoreLok®) for all specimens (*LAC* and *SGC*). This method was selected due to initial samples tested according to AASHTO T 166-07 exhibiting high water absorption. Work performed by (*9*) indicated that the vacuum sealing method yielded the most consistent and accurate results for high air void mixes. Testing by the authors has indicated T 331 measured voids are higher than T 166 measured voids, so the void levels reported herein would be lower provided T 166 were used. Rut testing was performed to 8,000 cycles with an *APA*. All *APA* testing was performed at 64 C, the wheel load was 445 N and hose pressure was 690 kPa. Sawn specimens from compacted slabs that were more than 80 mm thick were trimmed to the specified 75 ± 5 mm thickness for *APA* testing.

Air Voids Test Results

Average V_a values from all slab testing are shown in Figure 4. Relative to the control specimens, sequential mixing was shown to be very erratic and performed worse than the control specimens in many instances. At standard hot mix compaction temperatures (i.e. *STAP* 1), *Mixture 1* control specimens performed the best while *Mixture 2* control specimens performed the worst. Both warm mix additives outperformed the control specimens for *STAP* 2 and 3, which are the conditions of interest to this research. From a compactability standpoint, both WMA 1 and WMA 2 provided superior performance to control specimens.



(a) Mixture 1 *(b) Mixture 2*

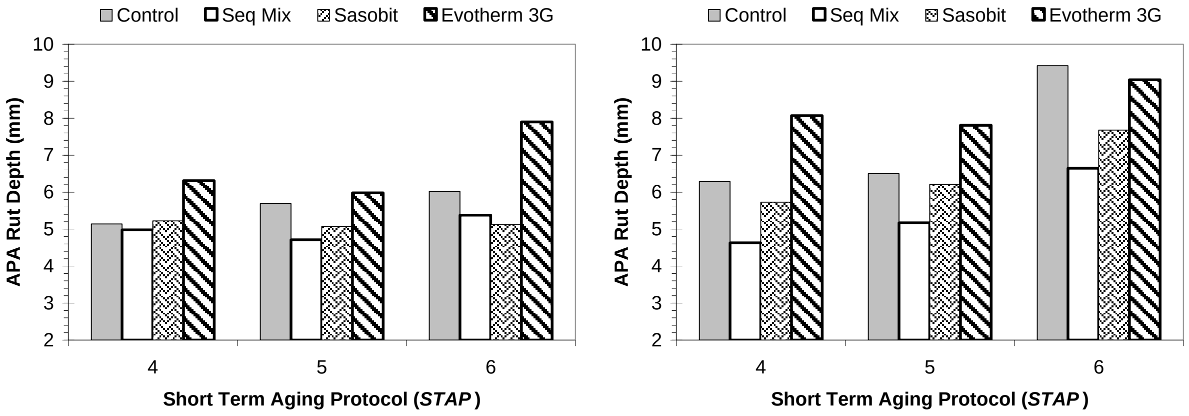
FIGURE 4 Average Slab V_a Test Results.

Analysis of *APA* Rut Test Data

Brown et al. (*10*) suggested an 8 mm rut depth as the pass/fail criteria in the *APA* for high traffic permanent construction materials tested at the high temperature grade of the binder with a 445 N wheel load and 690 kPa hose pressure. Other criteria were found in literature that are provided in (*1*); some of these criteria are higher than 8 mm. The criteria would typically be applied to a specimen compacted to 6.5 to 7.5% air voids.

Pass/fail criteria for an emergency construction material are not readily available. Since the goal of these materials is performance over a brief anticipated service life, a less rigid failure criteria is suggested relative to high trafficked permanent pavement. A failure criteria of 10 to 12 mm is suggested as a reasonable value for emergency construction when tested in the *APA* under the aforementioned conditions. This is not to say that a 13 mm rut depth wouldn't work reasonably well in a temporary application after a disaster, rather it is to say that anything less than 10 to 12 mm would work reasonably well after a disaster.

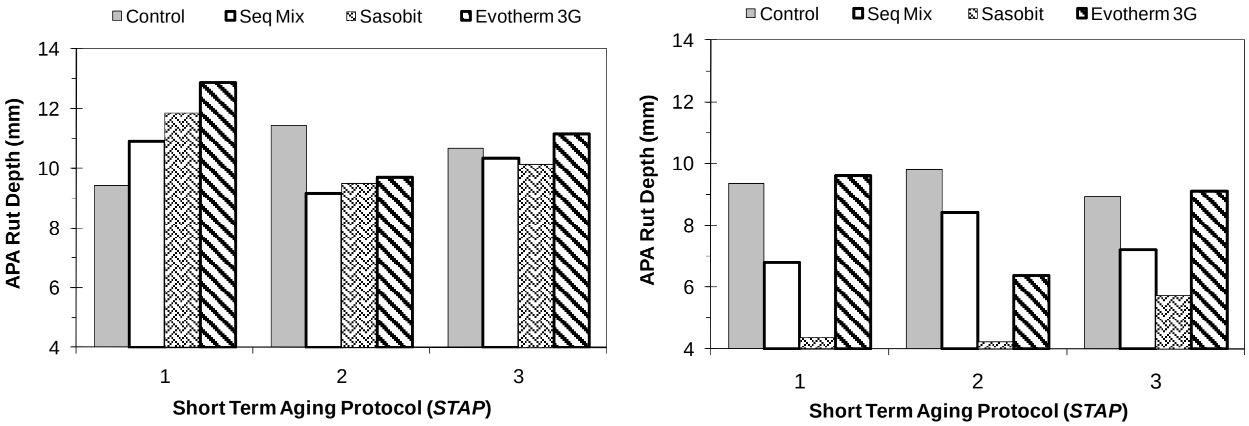
Figure 5 provides rut depth test results of all *SGC* compacted specimens. This data represents a condition where all mixtures are compacted to the same density. At 10% air voids, no difficulties are observed for emergency construction based on specimens compacted in the *SGC*. WMA 1 rutted at to slightly above the permanent construction pass/fail criteria of 8 mm for *Mixture 2*. Otherwise, WMA met permanent construction criteria, which are more than adequate for emergency construction.



(a) Mixture 1 at V_a of 10% *(b) Mixture 2 at Va of 10%*

FIGURE 5 *SGC* Compacted *APA* Test Results at 8,000 Cycles.

Figure 6 plots average *APA* rut depths from specimens compacted in the *LAC*. This data represents a condition where the same compactive effort was applied to all specimens of each mixture and the density was allowed to vary. Rut depths were mostly below the 10 to 12 mm emergency construction threshold. The only exception was non control specimens of *Mixture 1* conditioned using *STAP* 1. Warm mix technology and *STAP 1* provide no construction advantage pertaining to this paper and are therefore of little concern.



(a) Mixture 1 *(b) Mixture 2*

FIGURE 6 Average Slab *APA* Rut Test Results at 8,000 Cycles.

For *Mixture 1*, the hot mixed control (i.e. *STAP 1*) was in general the best performer with respect to rutting resistance. Sequential mixing, WMA 1, and WMA 2 were comparable at *STAP 2* conditions to the hot mixed control, and marginally higher at *STAP 3* conditions. WMA 1 rutted noticeably more than WMA 2 under *STAP 3* conditions. The *Mixture 2* hot mixed control rutted approximately the same amount as the *Mixture 1* hot mix control. WMA 1 performed better than the hot mixed control, while WMA 2 performed considerably better than the hot mix control. WMA 1 and WMA 2 performed well, which indicates they can be used in a hot mixed-warm compacted emergency response construction plan.

Correlations of air voids to rut depth were also performed and details are provided in (*1*). To be conservative, a 10 mm rut depth criteria was used. The majority of the data indicated that compaction in the field to air void levels of 11 to 14% for emergency construction would provide acceptable short term performance in terms of rutting.

USE OF WMA IN EMERGENCY CONSTRUCTION APPLICATIONS

Field procedures for using the approaches developed would be straight forward to experienced asphalt paving groups. A trial run of material should immediately be sent to the site (a moderate number of truck loads of material) to investigate if the material will work in conjunction with site specific conditions, equipment, and personnel. The haul time and on ground temperature should be carefully noted during the trial run. Once compacted, cores should be sawn for measurement of bulk density (as soon as the core can be dried) and subsequent calculation of air voids. Nuclear density gages could also be used if available. Test strips are another viable option that could be proof tested with loaded asphalt mixture trucks.

Emergency construction should use an asphalt content designed for permanent use rather than a modified mixture that would be easier to compact (i.e. more asphalt). The use of a permanent mix design provides the responsible agency with more options post disaster recovery. The test data provided in this paper indicates standard mixes can perform adequately for emergency conditions. If the pavement has been heavily damaged during disaster response, the asphalt could be milled and used in a high RAP mix design, or full depth reclamation could be performed.

Trafficking the mixture with heavy vehicles during hot weather just after placement should densify the mixture a noticeable amount as the binder has only been short term aged. This densification would not impede response and recovery traffic so long as the majority of the total rut depth was due only to densification. For example, if a 10 cm layer of a hot mixed-warm compacted mixture was placed at 12% air voids, and the emergency traffic reduced the air voids to 7%, the rut depth due to densification would be a manageable value of 0.5 cm. Rutting rate analysis of the data presented earlier in this paper indicated specimens rutted on the order of six times faster in the first 2,000 passes than in the last 6,000 passes irrespective of the initial air voids. The data supports densification during response, followed by evaluation that could leave the emergency material in place and used in conjunction with an overlay.

Typical construction practices are to have an initial voids level low enough to prevent excessive air and water infiltration yet high enough after a few years of service to avoid rutting due to plastic flow. When considering leaving the material in place for longer term use, it should be considered that mixtures with more than 8% air voids have higher permeability (*11*) and more binder stiffening (*12*). Data provided by (*13*) used 7% air voids as a baseline and reported that every 1% air void increase resulted in approximately 10% loss in pavement life.

Table 4 provides density requirements for several state Departments of Transportation (DOTs) in the southeast US. The average void level warranting removal and replacement was 10%. The condition of the emergency material and air voids at the conclusion of emergency trafficking should be considered alongside what is typically allowed for permanent construction when determining the fate of the hot mixed-warm compacted material.

TABLE 4 Summary of In-place Density Specifications in the Southeastern United States

Surface Course Specification	Specification State and V_a (%) Requirements								
	MS	**AL**	**GA**	**FL**	**SC**	**NC**	**AR**	**LA**	**TX**
Target Air Voids	7.0	6.0	<7.8	<7.0	6.0	<8.0	6.0	<8.0	7.0
Full Pay minimum	7.0	9.7	7.8	8.1	7.8	8.0	8.0	PWL	8.5
Full Pay maximum	4.0	2.2	3.8	2.0	4.0	---	4.0	---	4.7
Removal required	9.0	11.2	13.5	9.5	9.4	10.8	9.1	PWL	10.0

Notes: All states shown specify bulk gravity of roadway cores be measured by AASHTO T 166 or an equivalent state test method utilizing submerged specimens. For states that specify a range of target in-place density, the median of the range is reported. Louisiana utilizes a Percent within Limits (PWL) criteria.

Prowell and Brown (*14*) obtained initial field densities measured according to AASHTO T 166 from pavements in sixteen states throughout the US and found that 20% of the forty pavements studied had in place air voids in excess of 10% and values were recorded as high as 14.5%. In place air voids less than 8% were observed 45% of the time. The density reduction of the pavements with time was also studied and approximately 60% of the densification occurred within three months of construction. The as constructed properties of pavements within the authority of the responsible agency should also be considered when determining the fate of the hot mixed-warm compacted material. Removal of material that was not significantly damaged during emergency operations that has comparable compaction characteristics to other pavement within the network of interest does not seem logical.

SUMMARY AND CONCLUSIONS

Review of warm mix construction project data and literature coupled with laboratory testing and cooling rate calculations allowed development of laboratory aging protocols for hot mixed-warm compacted asphalt. Compaction of slabs in the *LAC* using these protocols showed WMA 1 and WMA 2 improved compactability in these conditions. Rutting performance was acceptable for emergency construction in all cases, and in the majority of cases the rutting performance would have been acceptable for permanent construction as well. The hot mixed warm compacted material should perform for the needed period of disaster recovery if compacted to 11 to 14% air voids.

At the conclusion of emergency recovery, the agency should examine the material and determine if it should be removed, or put into permanent service after placing an overlay. Test data indicated a considerable amount of rutting would likely occur during emergency trafficking, which, barring other distresses could make the material a candidate for permanent use. Regardless of the permanency of the material, hot mixed-warm compacted asphalt provides a very useful method to recover from disasters and any residual value would be a bonus.

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