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Evaluation of Foamed Warm-Mix Asphalt Incorporating Recycled Asphalt Pavement for Volumetric and Mechanical Properties

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Abstract: This study evaluated mixes obtained from a warm-mix asphalt (WMA) pilot project in Reno, Nevada, in the United States, in which the Ultrafoam® technology was used to produce the WMA. The evaluated mixtures included 15% recycled asphalt pavement (RAP). The study addressed the impact of curing time on volumetric properties of foamed WMA in addition to including a sample reheating study. Additionally, the field-produced WMA mixes were evaluated for moisture damage, permanent deformation and thermal cracking resistance. It was recommended that production testing for volumetric properties should be conducted within four hours of manufacturing foamed WMA at the plant. The mix should be cured in a sealed container at the expected lay-down/compaction temperature. Overall in the laboratory, the WMA mix showed no significant additional reduction in moisture damage resistance although the reverse was true for permanent deformation resistance. The WMA exhibited better thermal cracking resistance than the hot mix asphalt (HMA). A distress survey conducted after thirteen months of service showed no distresses in the WMA pavement despite its relatively lower rutting resistance observed in the laboratory.

***Key words**: Curing; Foamed Asphalt; Hot Mix Asphalt; Moisture Damage; Performance; QC/QA; Reheating; Warm Mix.*

Introduction

The most critical part of constructing the hot mix asphalt (HMA) layer is to obtain a uniform and durable layer that can withstand the combined actions of traffic loads and environmental conditions. These desirable properties have been achieved through effective design, uniform mixing and coating during the manufacturing process and effective compaction during lay-down operations. For HMA mixtures, mixing and compacting at elevated temperatures (typically 135-175°C) have been necessary to achieve these properties. This however, is at the expense of the constantly increasing asphalt binder prices and energy costs. Therefore, by reducing the energy required to produce and construct the HMA layer, significant cost savings can be realized. The past few years have seen the introduction of warm mix asphalt (WMA) technologies in efforts to achieve this. WMA is produced at temperatures 30-75°C lower than those required for HMA [1], and this is directly related to savings in the energy required for production.

Whatever the economical, practical, and environmental benefits of using WMA technologies, the produced WMA must be highly resistant to moisture damage, cracking, and permanent deformation in addition to being adaptable to use of recycled asphalt pavement (RAP) in the mixtures.

Among the WMA technologies available today, this study evaluated the Ultrafoam® technology. It is a water-based technology that uses a foaming nozzle to inject a percentage of water (usually about 1-2% by weight of binder) into the asphalt binder flow line.

Three mixes; one lab-produced HMA and two field-produced WMA mixes were evaluated. Both field-produced WMA mixes were obtained from a pilot project that was laid down along Chism Street in Reno, Nevada in the United States. In a study of impact of curing time on mixtures' volumetrics, one WMA mix was compacted right on delivery to the laboratory while the other was compacted later in a sample reheating study.

HMA samples are often reheated for a variety of acceptance and performance tests. However since the Ultrafoam® WMA technology produces foamed asphalt, which is an irreversible component, reheated samples should not be used for volumetric acceptance [2]. Nevertheless, reheated samples can be used to evaluate the mechanical properties of WMA mixtures provided the reheating effect on WMA is similar to that for HMA. Therefore, the evaluation of impact of curing time on volumetric properties was conducted to determine a convenient cap on curing time. The cap was based on how long foamed WMA may be cured prior to compaction at WMA temperatures and still meets the requirements for volumetric properties. This was also motivated by the understanding that foamed WMA loses its foaming effect with time. The results of this evaluation would therefore be helpful in performing quality control/quality assurance on similar mixtures.

All mixes were evaluated for resistance to moisture damage, permanent deformation and thermal cracking using dynamic modulus testing, repeated load triaxial (RLT) and thermal stress restrained specimens testing (TSRST), respectively. 2D planar image processing was also used in an attempt to distinguish between performances of the evaluated mixtures.

Objectives

The overall objectives of this study are summarized below:

- Evaluate the rheological properties of asphalt binder recovered from the WMA mix.

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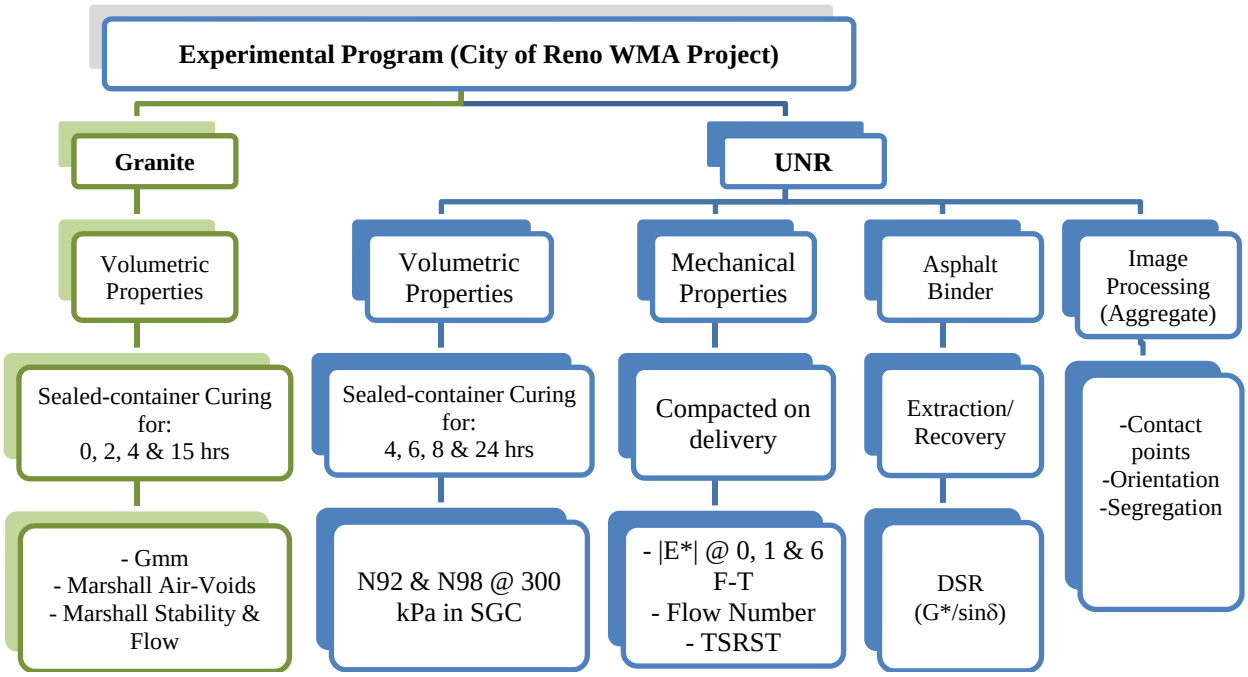


Fig. 1. Experimental Program.

- Evaluate the impact of curing time on volumetric properties of WMA mix.
- Evaluate the mechanical properties of WMA mix.

City of Reno WMA Pilot Project

A WMA test strip was placed along Chism Street in Reno, Nevada in June 2009. Field mixtures were sampled and subjected to an extensive laboratory evaluation study in a collaborative effort between University of Nevada, Reno (UNR) and Granite Construction, Inc. The WMA mix was produced at the Granite Construction plant in Lockwood, Nevada, using the Ultrafoam® process at an average water addition rate of about 1.25% by weight of binder. The mix included 15% RAP and 1.5% hydrated lime by dry weight of virgin aggregate. The lime was added dry on damp aggregate. Approximately 900 tons of WMA was produced and placed into a thickness of 150 mm comprising two lifts each 75 mm thick.

Experimental Program

Two sets of WMA mixes were sampled during production. The first was sampled out of windrows at the plant at the discharge time into tightly-sealed buckets and brought to the UNR Pavement/Materials laboratory. The approximate haul time between plant and UNR was 20-30 minutes (similar to that between plant and paving site). The second set of samples was transferred to the plant laboratory for evaluation by Granite Construction. Additionally, cold feed aggregates, RAP and asphalt binder were sampled during production and shipped to UNR. These materials were used to produce a laboratory HMA mix to serve as a control, since no HMA field mix was produced on this project.

The contractor performed plant and field trials at different temperatures to achieve good coating, mixing and compactability. Through this process about 130°C and 120°C were determined from experience as mixing and compaction temperatures, respectively. The temperature of the WMA as it came out of the plant was checked using an infrared heat gun and ranged between 129°C and 132°C. Similarly the average lay-down temperature was recorded as 121°C and consequently used in all WMA laboratory evaluations.

The WMA mix that was brought to the UNR laboratory was compacted right on delivery for mechanical properties and after 4, 6, 8 and 24 hours of curing in a sealed container at 121°C for volumetric properties. “Right on delivery” for mechanical properties in this case also meant compaction after 4 hours of curing because that is how long it took to bring the mix temperature back up to 121°C after significantly dropping through the haulage and splitting processes. Some of the WMA mix was stored in tightly-sealed buckets at room temperature for use in a sample reheating study. At the plant laboratory, the WMA mix was tested for Marshall mix design properties after 0, 2, 4 and 15 hours of curing in a sealed container at 121°C. In the sample reheating study, reheating consisted of first heating the plant-sampled WMA in the oven at 135°C for 4 hours in a sealed container before splitting the material into individual sample sizes and conditioning them for 1.5 hours at 121°C before compaction. The following nomenclature was used for the evaluated mixtures:

- WMA-No Reheat: WMA mix that was compacted, right on delivery, at 121°C.
- WMA-Reheat: WMA mix that was used in the sample reheating study.
- HMA: laboratory-produced HMA manufactured with PG64-22 asphalt binder. Mixing and compaction temperatures of 156°C and 145°C were used, respectively, as per the mix design.

Fig. 1 shows the experimental program for this effort. It included the following three major aspects.

- Rheological properties of extracted/recovered asphalt binders:

Table 1. Test Matrix for Mechanical Properties' Evaluation.

Property	Mixture Type					
	WMA – No Reheat		WMA – Reheat		HMA – Lab Produced	
	Unaged[a]	Aged[a]	Unaged[a]	Aged[a]	Unaged[a]	Aged[a]
Resistance to Moisture Damage - $\|E^*\|$ vs. Freeze-Thaw (F-T) cycles	3 Samples @ 0-1-6 Cycles	--	3 Samples @ 0-1-6 Cycles	--	3 Samples @ 0-1-6 Cycles	--
Resistance to Permanent Deformation - Unconditioned Flow Number	3 Samples	--	3 Samples	--	3 Samples	--
Resistance to Thermal Cracking - Unconditioned TSRST	--	3 Samples	--	3 Samples	--	3 Samples

[a] Aged: long-term aging of compacted samples in a forced draft lab oven at a temperature of 85°C for 5 days.

Table 2. Superpave Performance PG Grading of Asphalt Binders.

Material	Critical temperature (°C)					True PG Grade	SP PG Grade
	Original	RTFO	RTFO+PAV				
	G*/sinδ ≥ 1.0 kPa	G*/sinδ ≥ 2.2 kPa	G*sinδ ≤ 5000 kPa	S-value ≤ 300 MPa	m-value ≥ 0.3		
Virgin Binder	67.1	69.6	19.6	-27.7	-25.1	PG68.6-25.3	PG64-22
RAP binder	76.0	77.2	22.9	-27.5	-18.8	PG76.2-18.8	PG76-16

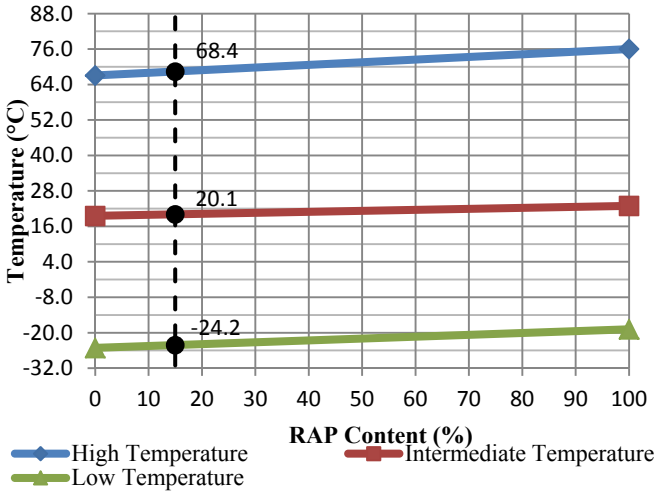


Fig. 2. Blending Chart Results.

asphalt binders were extracted in accordance with AASHTO T164 using trichloroethylene as the solvent and recovered following ASTM D5404, from all mixes and were tested in the Dynamic Shear Rheometer (DSR).

- Impact of curing time: the following properties were measured after curing the WMA-No Reheat mix in a sealed container at 121°C:
  - Maximum theoretical specific gravity (Gmm)
  - Marshall air-voids
  - Marshall stability and flow
  - Number of gyrations to 8 percent and 2 percent air-voids (N92 and N98, respectively). N92 was found to provide a simple indicator of mixture workability and compactability [3]. The higher the number of gyrations the higher is the compaction effort required to reach the target air-voids.
- Mechanical properties: Table 1 shows the test matrix for this effort.

Materials and Mix Design

The Marshall Mix Design method as outlined in the Asphalt Institute's Mix Design Methods Manual MS-2 [4] was used to design the mixes following City of Reno standard specifications. The aggregates used were obtained from the pit in Lockwood, Nevada. Gradations done on extracted aggregates from all three mixes revealed that all were well-controlled in both lab and field and were all similar. This could help validate the HMA mix as a true control albeit it was laboratory-produced.

An unmodified PG64-22 virgin asphalt binder was used with all mixes. The Superpave Performance Grading (PG) binder system was used to grade the virgin binder and RAP binder following AASHTO M320. The RAP binder was extracted (AASHTO T164), and recovered using the rotary evaporator (ASTM D5404). The recovered RAP binder was graded by testing it as original, short-term aged through the Rolling Thin Film Oven (RTFO), and long-term aged through the Pressure Aging Vessel (PAV). Table 2 summarizes the critical temperatures and PG grades of both binders. Critical temperatures are temperatures at which a binder just meets the appropriate specified Superpave criteria.

Using virgin and RAP binder grading results, the blending chart process was conducted as shown in Fig. 2. The data show that at 15% RAP the blended binder graded as PG64-22 which was the target grade. The need to assess effectiveness of using the blending chart even at low RAP contents motivated the choice of RAP content as low as 15%. In addition the contractors conducted trials with different RAP contents and showed that the target binder grade remained unaffected at 15% RAP. Table 3 summarizes the mix design data.

Laboratory Evaluation

Rheological Properties of Extracted and Recovered Asphalt Binders

Table 3. Mix Design Summary and Specifications.

Property	Values	Requirements
3/4" Stockpile – Bin Percentage	18	--
1/2" Stockpile – Bin Percentage	11	--
3/8" Stockpile – Bin Percentage	23	--
Rock Dust – Bin Percentage	21	--
RAP – Bin Percentage	15	15
Natural Sand – Bin Percentage	12	--
Hydrated Lime by Dry Weight of Virgin Aggregate	1.5	--
RAP Binder Content (%TWM)	5.7	--
Optimum Binder Content (OBC), (%TWM)	4.9[b]	--
Total Air Voids (%)	4.0	4.0
Voids in Mineral Aggregates (%)	13.9	≥ 13
Voids Filled with Asphalt (%)	71.6	65-75
Marshal Stability (kN)	14.5	> 8
Marshall Flow (0.25 mm)	13	8-20

[b] With OBC of 4.9% and RAP binder content of 5.7%, the blended binder consisted of 82.6% of PG64-22 and 17.4% of RAP binder.

Fig. 3 shows the G*/sinδ of the various asphalt binders as function of temperature. A significantly lower stiffness was observed for WMA-No Reheat mix binder when compared to the HMA mix binder. However, reheating the WMA resulted in a significant increase in binder stiffness. The stiffness of WMA-Reheat mix binder was slightly lower than that from the HMA mix. The HMA mix was laboratory-produced and the two hours aging at 145°C before compaction may not have replicated the aging at the plant.

Additionally, Fig. 3 shows the G*/sinδ of the RTFO-aged PG64-22 binder. The stiffnesses of binders from all three mixes were higher than the RTFO-aged binder stiffness. These mixes included 17.4 percent RAP binder while the latter was 100 percent virgin.

Fig. 3 also shows that the stiffness of binders from HMA and WMA-Reheat mixes was similar. This is consistent with the finding in the NCHRP 9-43 sample reheating study where reheating WMA increased its stiffness to close to that of the corresponding HMA. As a result of this and the similarity in gradations (Fig. 4), the HMA mix was considered an appropriate control mix for this study.

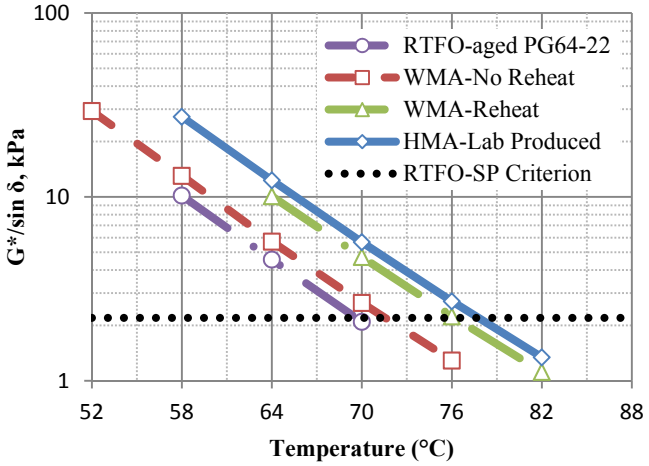


Fig 3. G*/sinδ of the Extracted/recovered Binders.

Impact of Curing Time on Volumetric Properties

Fig. 5 shows the total voids in the mix, flow and stability for the Marshall-compacted specimens. Sample groups 1 and 2, in the figure, were drawn at different times but are grouped together because their drawing times were relatively close. Fig. 5(a) shows an increase in air voids as function of curing time. This would suggest that the mix became less compactable with curing time. A significant increase in air voids was observed after 15 hours of curing. Additionally on average, all specimens met the job mix formula of 4±0.5% air voids except when compacted after 15 hours of curing. The results also suggest that the mix fell short of the job mix formula somewhere between 4 and 15 hours of curing time.

The flow and stability data show that their criteria were met at all curing periods. The specimens exhibited similar flow and stability after 0, 2, and 4 hours of curing. However after 15 hours a lower flow and higher stability were obtained. These results show that both properties also significantly changed somewhere between 4 and 15 hours of curing time.

In determining N92 and N98, specimens were gyratory-compacted at 121°C to 495 gyrations and sample height data recorded at each gyration. 300 kPa compaction pressure was used since at 600 kPa most mixtures show little change in

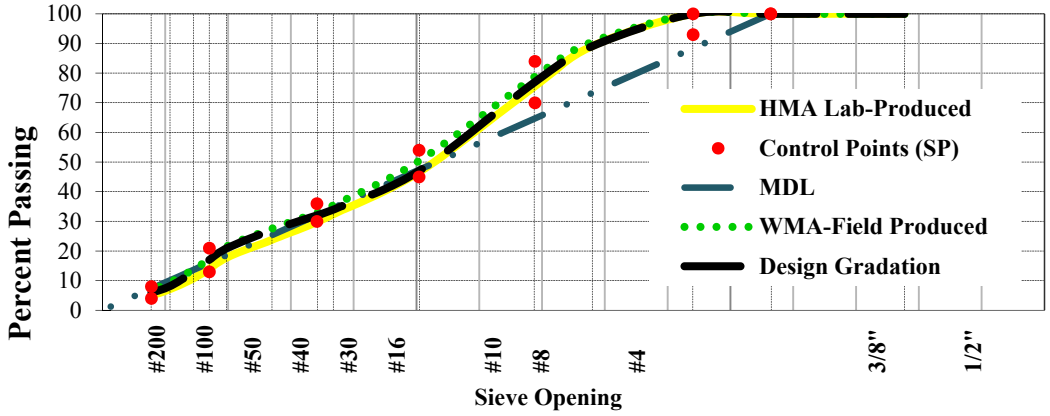


Fig. 4. Gradations of the Extracted/recovered Aggregate.

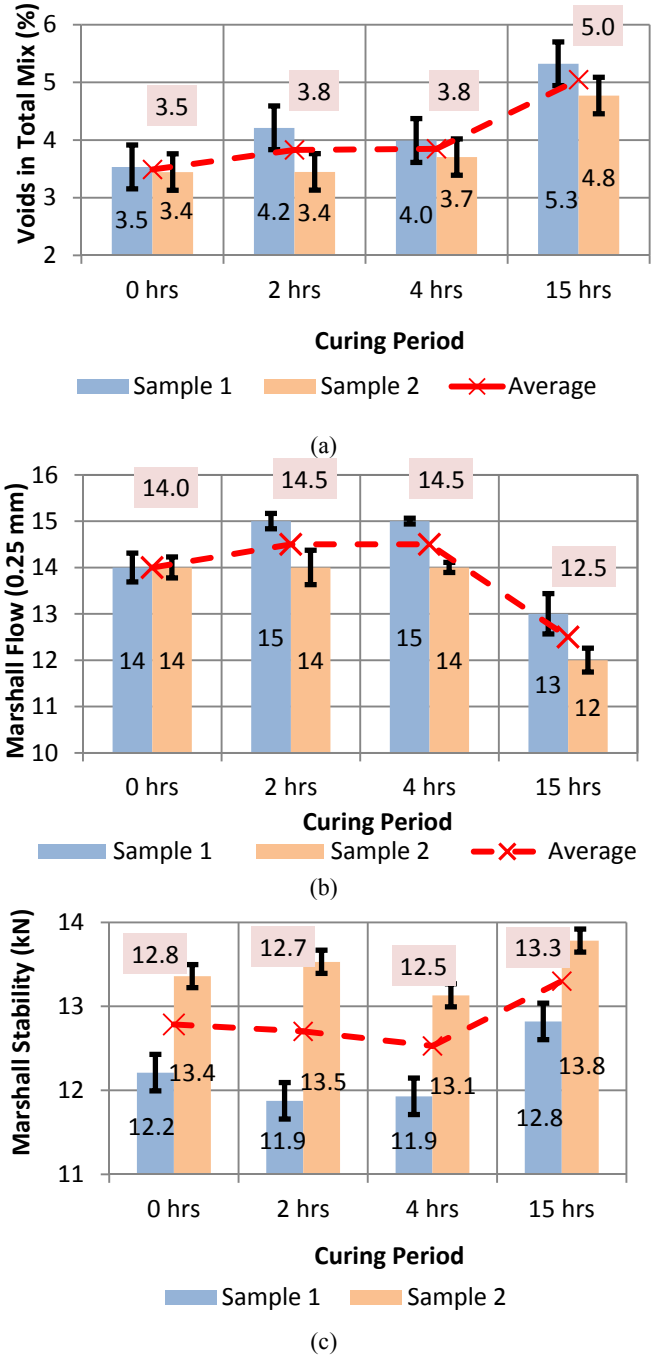


Fig. 5. Impact of Curing Period on Marshall-compacted Specimens: (a) Voids in Total Mix; (b) Marshall Flow; (c) Marshall Stability. (Numbers in Bars Represent the Individual Means for Sample Groups 1 and 2 Each Based on 3 Replicates and Whiskers Represent Mean ± 1 STD, Numbers Above Bars Represent Overall Means).

workability index [3]. Fig. 6 shows the results for N92 and N98. The data show an increase in number of gyrations as function of curing time, which would also suggest a decrease in compactability with curing time. This was more significant in N98. It can be observed that rates of increase of N92 and N98 both decreased significantly after 8 hours of curing. Consequently, the 8 hours of curing seems to indicate the point after which the mixture lost most of the foaming effect. Additionally, the 8 hours could be the curing

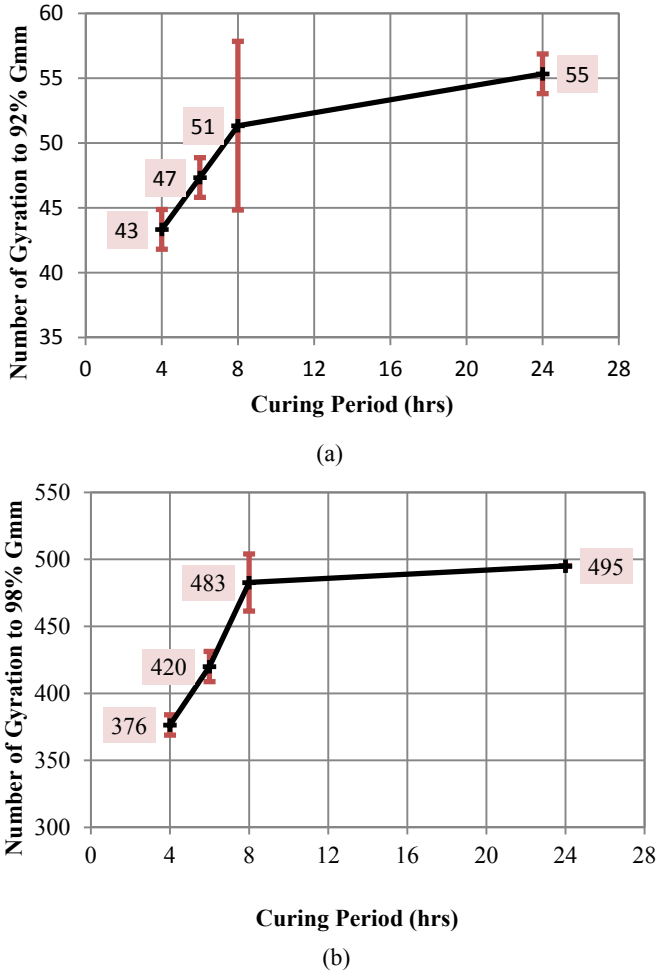


Fig. 6. Impact of Curing Time on Gyratory-compacted Specimens: (a) Number of gyrations to 8% air voids; (b) Number of gyrations to 2% air voids. (Numbers Represent Mean Values of 3 Replicates and Whiskers Represent Mean ± 1 STD)

time between 4 and 15 hours at which the mix fell short of the job mix formula based on what was observed in Fig. 5(a).

Resistance to Moisture Damage

The procedure that was used to evaluate moisture damage resistance is based on recommendations from NCHRP Report 589 [5] i.e. measurement of the dynamic complex modulus ($|E^*|$) under multiple freeze-thaw (F-T) cycling. The rationale behind this is in the fact that the gradual loss of strength, or degradation, of the mixture is a typical situation associated with moisture damage. The multiple F-T cycling used followed the procedure also outlined in AASHTO T-283 at multiple stages. The $|E^*|$ master curve was obtained at the unconditioned stage (0 F-T) and after 1 and 6 F-T cycles at 21°C as reference temperature. The use of $|E^*|$ for moisture damage evaluation uses ratios instead of absolute values of mixture stiffness. The conditioned stiffnesses are related to their corresponding unconditioned values.

Beside the $|E^*|$ master curve of the WMA-No Reheat being the lowest of them all, the master curves of WMA-Reheat and HMA mixes were observed to be almost inseparable at every F-T cycle.

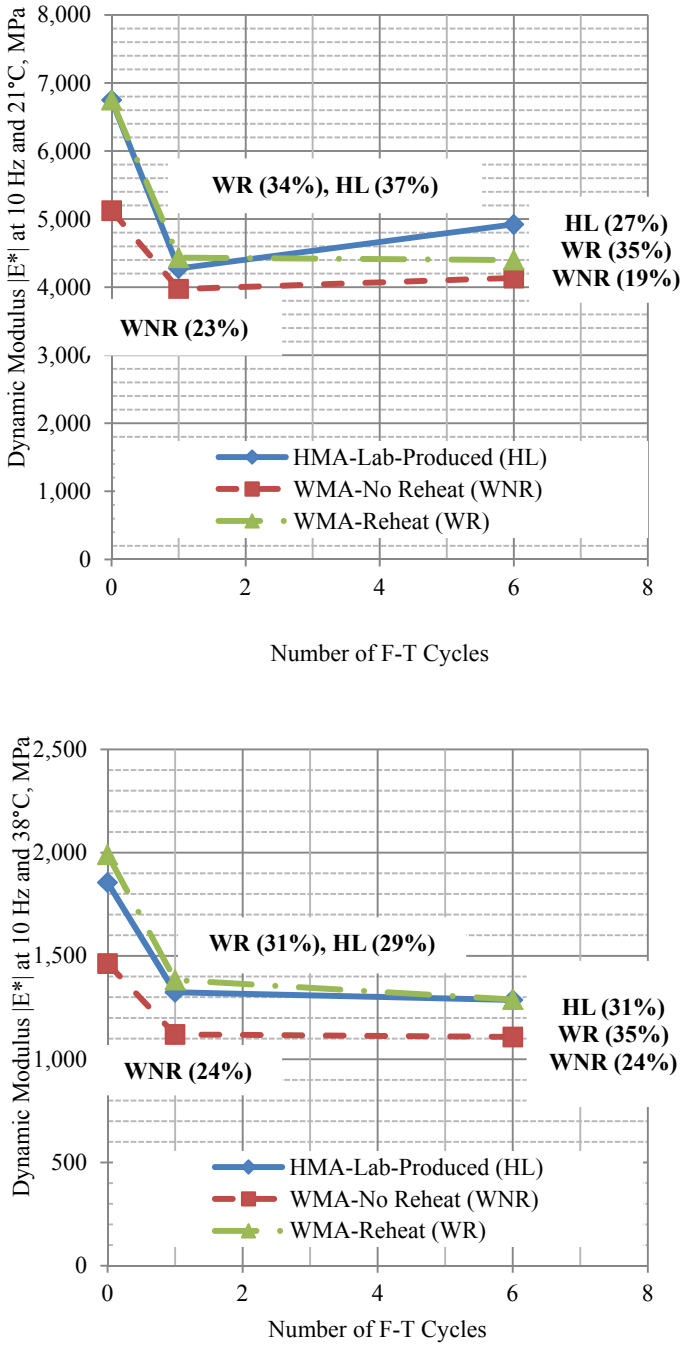


Fig. 7. Dynamic Modulus Versus F-T Cycles (Numbers in Parentheses Correspond to Percent Reduction in the Unconditioned |*E**| after 1 F-T and 6 F-T cycles).

The WMA reheating process increased the mixture's |*E**| to a value similar to that of HMA. This finding was consistent with results from the asphalt binder study where the WMA-Reheat mix binder stiffness was slightly lower than the HMA but significantly higher than the WMA-No Reheat binder stiffness.

Fig. 7 shows the |*E**| properties of the mixtures at a loading frequency of 10Hz as a function of multiple F-T cycling at both 21°C and 38°C. The data show a reduction in |*E**| as function of multiple F-T cycling. The |*E**| of WMA-No Reheat mix was the lowest at all F-T cycles, but showed a lower reduction when compared to the other two mixes, albeit the numbers were close in magnitude. For example, the |*E**| at 38°C of WMA-No Reheat, WMA-Reheat, and HMA mixes dropped 24, 31, and 29 percent, respectively, from their unconditioned value after 1 F-T cycle. The reduction in |*E**| for WMA-Reheat and HMA mixes was observed to be generally similar. Overall, the data revealed no additional reduction in the mixture's resistance to moisture damage when the foaming process was used to produce WMA.

Resistance to Permanent Deformation

Since WMA exhibits lower initial stiffness than conventional HMA due to its lower production temperatures, the evaluation of its resistance to rutting relative to that of HMA was necessary. This was done using the RLT test which consists of testing a 100 mm by 150 mm cylindrical sample under triaxial state of stresses. Under a constant confining pressure, a repeated haversine deviator stress is applied for an appropriate pulse time (loading) followed by a rest period (unloading). The sample's axial deformation is measured over its middle portion by two linear variable differential transformers placed 180° apart. The resulting cumulative permanent axial strain is plotted versus number of load cycles and can be defined by the primary, secondary, and tertiary stages which are described below.

- Primary stage – Permanent strain increases rapidly producing a high initial level of rutting with a decreasing rate of plastic deformations.
- Secondary stage – Permanent strain rate maintains a constant value.
- Tertiary stage – High level of permanent axial strain predominantly associated with plastic or shear deformations under no volume change. The point at which the tertiary flow starts is called the flow number (FN) and it is the number of load cycles corresponding to the minimum rate of change of permanent axial strain.

The FN test was among those selected for further evaluation under the NCHRP 9-19 project based on an extensive study of laboratory-measured FN and field-measured rutting at three field sites: Westrack, MnRoad, and the FHWA ALF test facility. In all three it was found that FN was highly correlated to field rut depth (within the asphalt layer) at any particular traffic level.

The RLT test parameters (pulse time, rest period, deviator and confining stresses) were determined for 150 mm layer thickness using predictive equations developed by Hajj et al. [6]. Non-braking conditions were assumed in all calculations since braking would be more critical at intersections and/or for urban streets where there is lots of stop-and-go. A pulse time of 0.06 seconds was determined for the street's operational speed of 24 km/h. The rest period was determined as 1.0 second based on a tandem axle separation of about 9.14 m (typical for 18-wheeler truck). All tests were conducted at 52°C using 538 kPa and 241 kPa as deviator and confining stresses, respectively. The test temperature was determined as the effective pavement temperature at 50 mm below pavement surface for the location using the LTPPBind software. The FN was calculated using the Francken model [7] whose results are

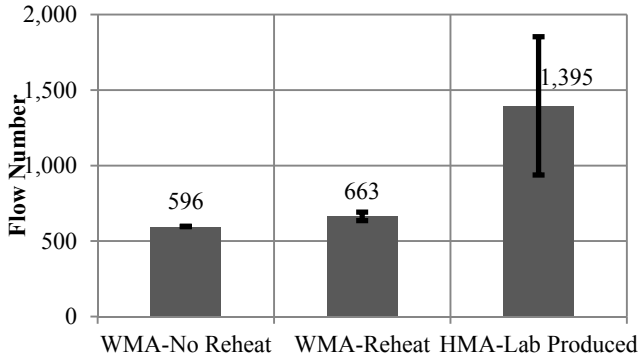


Fig. 8. Flow Number Results of Evaluated Mixtures by the Francken Method. (Numbers Represent Mean Values and Whiskers Represent Mean ± 1 STD).

shown in Fig. 8.

The observed large variability in the HMA results persisted despite testing as many as seven replicates, thus invalidating statistical analysis on the FN results. However the data was useful in providing overall trends. It showed that HMA exhibited a significantly higher FN than both WMA mixes. Reheated WMA samples showed slightly higher FN than WMA-No Reheat samples. This trend is consistent with the finding of Wielinski et al. [1] where the former mix showed a lower rut depth than the latter mix, hence similarly raising the question of which of the two mixes' data best represents the field-placed mix. Notably, since WMA-Reheat and HMA mixtures had similar stiffness, the permanent deformation characteristics would therefore be expected to be similar as well. However, the results in Fig. 8 suggest otherwise. Overall, the data show a reduction in the mixture's resistance to rutting when the foaming process was used to produce WMA. 2D planar image processing was then used in attempt to understand the difference in the findings between the dynamic modulus and FN test results.

2D Planar Image Processing

Despite the two mixtures; HMA and WMA-Reheat having similar stiffness, they had totally different permanent deformation characteristics as noted above. Since neither asphalt binder characteristics nor aggregate gradation could be used to explain this discrepancy, resort was made to other aggregate properties namely; aggregate contact points, orientation and segregation; which were obtained through planar image processing.

A 2D image analysis software, developed by RILEM, can be used to determine aggregate structure in compacted asphalt mixtures. From a scanned image of a specimen, the software uses such properties as; minimum size of aggregate, percent air-voids, asphalt binder content, combined aggregate bulk specific gravity, asphalt binder specific gravity and aggregate gradation; as input, to output such aggregate structure data as contact points, orientation, segregation and gradation. An attempt is made to match the true gradation with the calculated gradation. This is done through comparing the true volumetric percent of aggregate and true percent retained on each sieve, which are calculated from the input data, with their corresponding quantities calculated from image attributes. The true quantities are therefore volume-based while the calculated quantities are area-based.

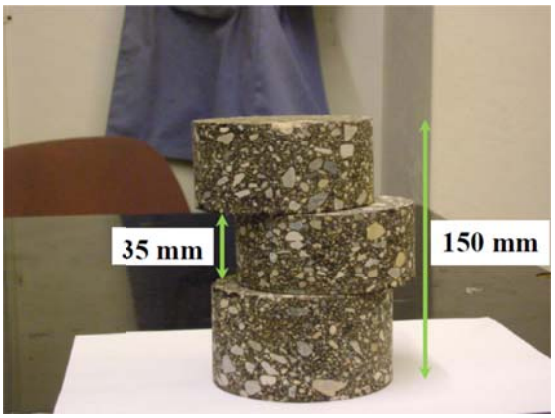
Unconditioned $|E^*|$ samples were re-used in this effort. A slice, about 35 mm thick, was cut out of the middle portion of the gauge length (about 70 mm) as illustrated in Fig. 9(a) exposing 4 surfaces that were each scanned using a flatbed scanner and analyzed, as replicates. A resolution of 600 dpi was used for all scans. Results of aggregate orientation and segregation, unlike contact points, were found to be similar for all three evaluated mixes.

Fig. 9(b) shows determination of aggregate contact points. Aggregates are considered to be in contact when the minimum distance between their surfaces is less than a user-defined surface distance threshold (SDT) value. An SDT value of 2 mm was used in this study.

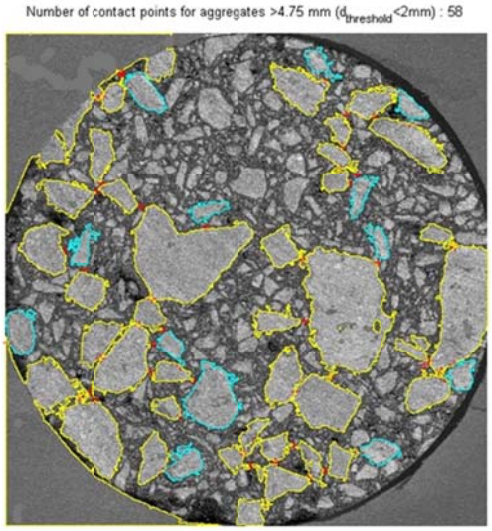
The results of aggregate contact points for the evaluated mixtures are shown in Fig. 9(c). The figure shows that the two WMA mixes were statistically the same at a 5% significance level. HMA was statistically significantly greater than both WMA mixes. The fact that the HMA production temperatures were relatively higher could explain this. This is because the higher workability generally associated with higher temperatures improves the probability of aggregate particles contacting one another. Additionally, the relatively higher asphalt absorption by aggregate particles when temperatures are higher may contribute to improvement of inter-particle contact. The discrepancy that the dynamic modulus test could not be used to differentiate between the WMA-Reheat and HMA mixes, whereas the FN test could, can therefore probably be explained by the results in Fig. 9(c). This is because the $|E^*|$ test being limited to the material's linear viscoelastic region thereby not significantly damaging the sample, the role played by aggregate contacts is minimal. It is important to note here that the inability of the $|E^*|$ test to significantly damage the specimen is from the load viewpoint rather than environmental. However in the FN test which simulates rutting as a load-related distress, specimens are loaded to deformation that leads to considerable change in specimen shape. Under such conditions, the contacts between aggregates play a major role in the material's overall resistance to applied loads. Henceforth the HMA mix showed the best rutting resistance among all the evaluated mixes.

Resistance to Thermal Cracking

Since WMA mixtures are produced and placed at lower temperatures than conventional HMA mixtures, they should undergo less binder oxidation. However, the effect of less oxidative aging on the thermal cracking resistances of WMA mixtures is still not well defined. Given that thermal cracking is identified as one of the major types of distresses in northern Nevada, this study evaluated the resistance of the WMA mixture to thermal cracking. The TSRST (AASHTO TP10-93) was used to determine the low-temperature cracking resistance of the mixtures. The test cools down a 50 by 50 by 250 mm beam specimen at a rate of 10°C/hour while restraining it from contracting. Tensile stresses are therefore generated in the process and the specimen would fracture as these stresses exceed its tensile strength. The fracture temperature represents the temperature at which the asphalt mixture will crack due to thermal stresses while the fracture stress represents the magnitude of stress caused by the thermal contraction of the mix. Additionally, the latter controls the



(a)



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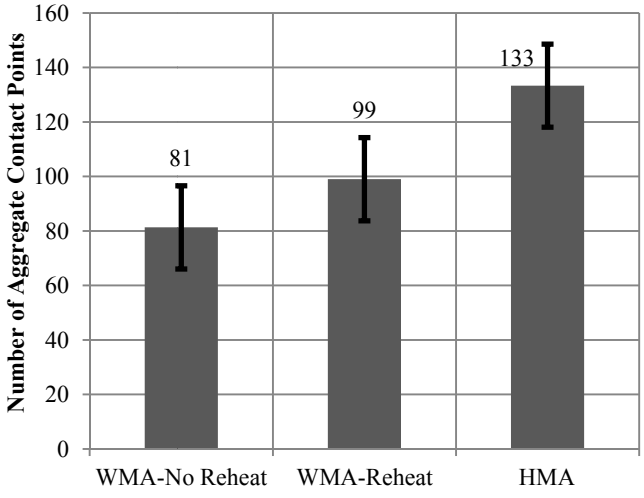

(c)

Fig. 9. Image Processing and Analysis: (a) Specimen Preparation; (b) Determination of Contact Points; (c) Results of Aggregate Contact Points. (Numbers Represent mean Values and Whiskers Represent Mean ± 1 STD)

spacing of thermal cracks once they occur. It is believed that a higher fracture stress would indicate longer spacing of transverse cracks in the field which would in turn minimize maintenance costs.

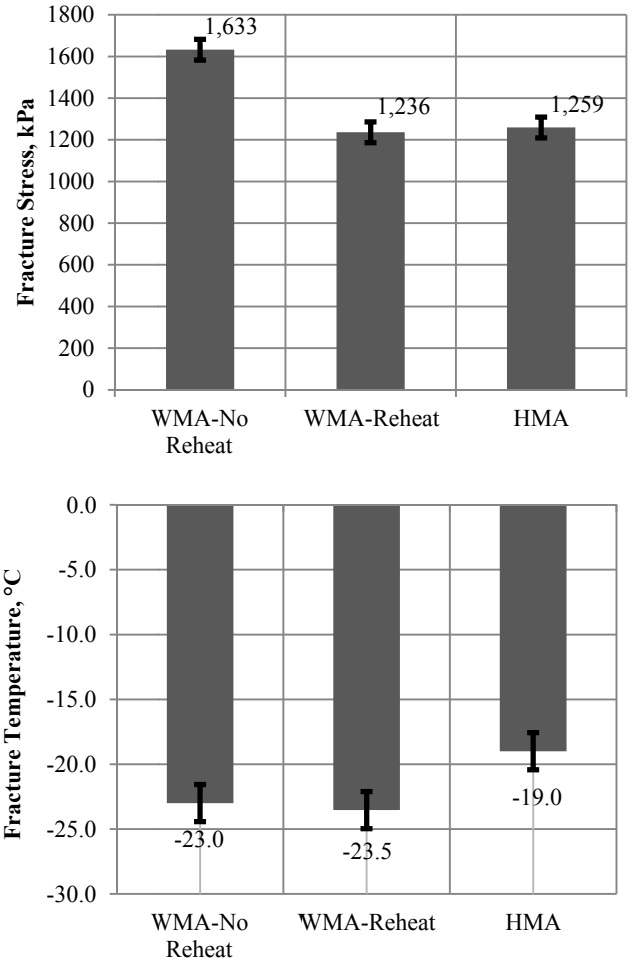

Fig. 10. Thermal Cracking Properties. (Numbers Represent Mean Values and Whiskers Represent Mean ± 1 STD).

The TSRST loose mixtures were short-term oven aged 4 hours at 135°C and 2 hours at compaction temperature for HMA and WMA, respectively. The WMA short-term aging procedure followed the recommendation in NCHRP 9-43 [2]. All compacted samples were long-term aged since low-temperature cracking is a long-term pavement distress.

Fig. 10 shows the TSRST results of the evaluated mixes. The fracture stresses of WMA-Reheat and HMA mixes, just like the fracture temperatures of both WMA mixes, were statistically the same. The fracture temperatures of both WMA mixes were statistically greater than that of HMA. However, WMA-No reheat mix showed significantly higher fracture stress which would indicate that, once thermal cracking occurs, pavements with this mix would experience fewer cracks per kilometer than the HMA mixture. The relatively lower stiffness of the WMA mix probably explains the better thermal cracking resistance.

Initial Field Performance

Regular field visual inspection has so far revealed no distresses in the WMA pavement with regard to moisture damage, rutting and cracking after 13 months of service, as shown in Fig. 11. Despite the extremely cold 2009-2010 winter season evidenced by temperature

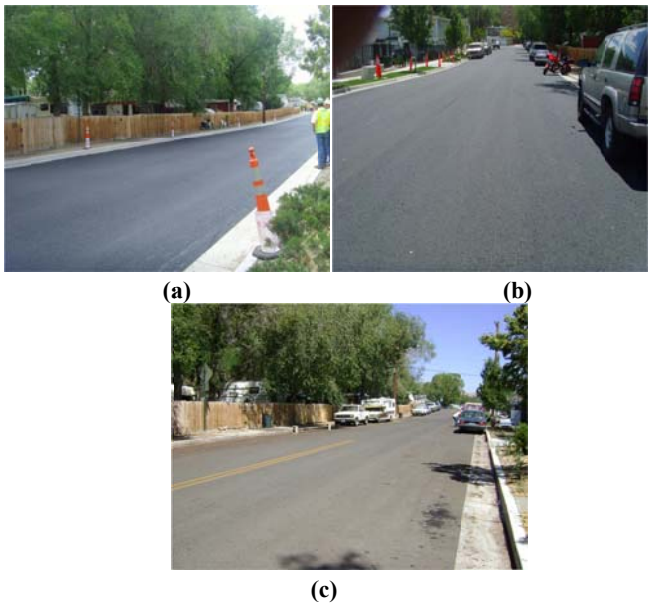

Fig. 11. Initial WMA Field Performances: (a) Freshly-finished Product on 06-11-2009; (b) After a Rainy Day on 06-14-2009; (c) Current State as of 07-27-2010.

drops to as low as -18°C and -19°C on 12-08-2009 and 12-09-2009, respectively, no thermal cracks have been observed in the pavement. This however could also be due to the relatively low mix stiffness of WMA. Field performance will continue to be monitored regularly.

Conclusions and Recommendations

This study conducted a laboratory evaluation of the impact of the Ultrafoam® WMA foaming technology on volumetric and mechanical properties of asphalt mixtures. Based on the data generated the following conclusions were made:

1. The data from the Marshall-compacted specimens showed that the air-voids' requirement was still met after 4 hours of curing, while that from the gyratory-compacted specimens suggested a probable loss of the foaming effect within 8 hours of curing.
2. The stiffness of asphalt binder recovered from the field WMA mix was significantly lower than that recovered from the HMA-lab produced mix.
3. The WMA mix exhibited:
   a. Similar resistance to moisture damage as the HMA.
   b. Lower resistance to permanent deformation than the HMA.
   c. Better thermal cracking resistance than the HMA.
4. Reheating WMA increased both binder and mixture stiffness. The reheated WMA mix exhibited:
   a. Similar resistance to moisture damage as the HMA.
   b. Lower resistance to permanent deformation than the HMA mix but higher than the WMA-No Reheat mix.
   c. Higher thermal cracking resistance than the HMA.
5. The distress survey conducted to date showed no distresses in the WMA pavement after 13 months of service.

In summary, based on the findings of this study, it was recommended that production testing for volumetric properties is to be conducted within 4 hours of manufacturing the foamed WMA at the plant. The mix should be maintained in a sealed container at the expected lay-down/compaction temperature before compaction.

Based on the distress survey results and the fact that Chism Street is a low-volume road (< 0.3 million ESALs), the relatively low WMA flow number obtained in the laboratory was probably sufficient on this project. This is also because rutting is mostly an early-life pavement distress.

Using the mix constituent materials sampled in this study and the recently acquired laboratory foaming device, UNR is in the process of determining a laboratory procedure to produce WMA foam mixes with similar properties as the field-produced WMA mixtures presented herein.

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