Effect of Microwave Heating on Adhesion and Moisture Damage of Asphalt Mixtures

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Microwave energy has been demonstrated to be capable of heating pavements rapidly, uniformly, and to depths of up to 5 in. without overheating the surface. Microwave treatment of asphalt mixtures is believed to have the potential of improving asphalt adhesion to aggregate. Presented in this paper is the work that was carried out to investigate this aspect of microwave heating in two ways. First, possible mechanisms by which adhesion improvement may occur when mixtures are exposed to microwave energy are discussed. Second, results of resilient modulus and split tension tests conducted on mixtures that were prepared in the laboratory using a convection oven and a kitchen-type microwave oven are reported. The study involved preparing three groups of mixtures: plain, virgin with an antistripping additive, and artificially aged materials. Test results indicate that microwave energy treatment of asphalt mixtures improves their adhesion and their resistance to water damage.

Using microwave energy to heat and dry pavement materials was thought of more than 20 years ago (*1*). In the last 5 years, however, commercial applications have become of interest to private parties and government agencies in the United States. The FHWA and some state departments of transportation (*2*), the U.S. Air Force (*3*), and the U.S. Department of Energy (*4*) are some of the agencies that have sponsored early work on microwave heating applications for asphalt and portland cement concrete pavements. Prototype equipment has been built and several field trials have been carried out in the United States and Europe to demonstrate the feasibility of microwave heating of pavement beds. A system that uses microwave energy to heat reclaimed materials for recycling is already in operation in Texas and California (*5*). Development of more efficient and adaptable equipment for the production of various pavement materials and for road construction and maintenance is in progress.

Microwave energy was initially envisioned for rapid, uniform heating of asphalt pavement roads and materials. The benefit of deep heating by microwave without a significant difference in the temperatures of the surface and the bottom of the pavement was also recognized (*6–8*). However, other benefits of microwave heating have also been claimed. A lower aging rate for asphalt cement as a result of faster heating compared with conventional methods has been reported (*9, 10*). Possible improvement in the adhesion of asphalt to aggregate and a consequent increase in water damage resistance have also been reported (*11, 12*).

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Although not the subject of this paper, the successful implementation of commercial microwave equipment is emerging. The economic advantages of microwaves to heat paving materials in place or using an over-the-road technique appear to be positive for special applications that are limited only by imagination. Savings of 30 to 40 percent over currently used hot-mix recycling methods appear to be possible. Special applications might include pothole repair, longitudinal joint heating and repair, warm asphalt emulsion mixtures, and the like. The purpose of this paper and previous work by the authors (*11, 12*) is to explore possible problems with microwave heating as well as explore its many potential benefits.

Details and results of research to evaluate the effect of microwave heating on the adhesion of asphalt cement to aggregate and on the resistance of asphalt mixtures to water damage such as stripping are presented. The preliminary results of this effort were briefly reported earlier (*11*) and are part of a larger study (*12*).

MICROWAVE HEATING CONCEPTS

When microwaves pass through a material, the material is subjected to an alternating electromagnetic field that changes millions of times per second. If the material is electrically neutral (has no electric charge) microwaves will pass through it as if it were not there. Carbon tetrachloride, benzene, paraffin wax, and carbon dioxide are examples of microwave-transparent materials. However, when a material is not electrically neutral, its dipolar molecules, which carry a pair of closely spaced charges equal in magnitude but opposite in sign, tend to act like microscopic magnets in the presence of microwaves and attempt to line up (polarize) with the field. Maximum polarization occurs when all dipoles align with the applied field. Polarization is not restricted to dipolar molecules; any relative displacement of positive and negative charges within the material is considered a form of polarization. Other forms of polarization include electronic; atomic; and, in the case of two adjoining materials, interfacial polarization (*13*). Total polarization is the sum of all of these. Molecules usually fail to keep up with the rapid changes in the direction of the field because some forces, such as viscosity or solidity of the surrounding medium, restrict their movement and because of the effect of simultaneous movements of molecules. In trying to overcome these forces, microwave energy is converted to heat.

Materials differ in their response to microwave energy. Some, such as water and aggregate, heat quite well, but others, such as Teflon and asphalt, exhibit poor response. The penetration of microwaves will be infinite in perfectly transparent substances, zero in reflective materials such as metals, and a finite value in other absorptive materials. The efficiency of a material in absorbing microwave energy, which affects the rise of temperature and penetration of microwaves into the material, may be described by its dielectric properties. The variables that are of interest are the dielectric constant of the material (e'), the dielectric loss factor (e''), and the dissipation factor or loss tangent of the material (tan d). The dielectric constant (e') influences the amount of energy that can be stored in the material in the form of an electric field. The dielectric loss factor (e'') indicates how much of that energy a material can dissipate in the form of heat. The loss tangent is equal to e''/e'. The dielectric constant and loss tangent values have been tabulated for many materials at different frequencies and temperatures (*13, 14*).

The dielectric properties of asphalt cement and aggregates at microwave frequencies are quite low because of the viscosity of the asphalt cement and the lattice forces in the aggregate that hinder the orientation of polar molecules (*15*). Although aggregates possess low dielectric properties, it was found that they are the components that generate heat when asphalt mixtures are subjected to microwaves. Most aggregates respond well to microwaves; only a 14 percent variation in microwaves absorption of these materials has been reported (*6*). Success in heating aggregate is attributed to its low specific heat of 0.2 (*6*); its metallic mineral content (*11, 12*); and, most important, absorbed moisture (*2, 11, 12*). The dielectric properties of some types of aggregates, soils, rocks, and minerals are available (*13, 16, 17*). Dielectric properties of asphalt cement and some types of aggregate are given in Table 1.

MECHANISMS OF IMPROVING ADHESION BY MICROWAVE ENERGY

When pavement material is exposed to microwave energy, aggregate will generate heat and transfer it to the asphalt cement. As long as microwaves are applied, heat generation will continue. The addition of asphalt cement, although it will absorb some of the heat, will not stop the temperature of the mix from rising. The environment (i.e., the air temperature) around the self-heating material is cooler than the material itself. In recycled mixtures, the asphalt cement film on aggregate might be melted, redeposited, and even impregnate permeable voids in the particles as a result of continuous heating as shown in Figure 1a. Thus chances for improved adhesion of asphalt cement to aggregate and resistance to water-stripping action might be increased.

The polarization effect of microwaves could also contribute to improvement in the adhesion of asphalt cement. Polarization would be responsible for orienting dipolar molecules within one material, and interfacial polarization would be responsible for bringing opposite charges on adjoining surfaces to accumulate along the interface as shown in Figure 1b and c. Randomness in orientation of polar molecules in asphalt cement also might be reduced for higher cohesion and shear resistance, if enough energy were available to overcome the viscosity of the asphalt cement.

Polar antistripping agents that are used to promote adhesion of asphalt to aggregate could benefit from the polarization effect of microwaves. Positively charged (cationic) antistripping agents migrate to and are adsorbed by the aggregate surface, lowering its affinity for water and increasing its affinity for oil. This preferential modification of aggregate surface charge favors asphalt cement over water, resulting in stronger adhesion and water-stripping resistance. The degree of success of these agents depends on the concentration of the surfactant used, the efficiency of migration, and the force or strength of the adsorbing bond. The addition of these materials to asphalt cement in hot mixing is believed to be inefficient (*18*). Migration of the agent to the aggregate interface is hindered by the increase in asphalt viscosity on cooling. In typical hot mixtures, unless they are stored for a long time (12 hr), only approximately 30 to 40 percent of the original concentration of antistripping agent performs in the intended manner (*18*). Microwave energy could be used to speed the migration of agents by forced polarization action as shown in Figure 1d. The least microwaves can do is to reduce the randomness in the

TABLE 1 DIELECTRIC PROPERTIES OF ASPHALT PAVEMENT MATERIALS

Material	Temp. °C	freq. MHz	e'	tan d 10^{-4}	Ref.
Water	25	300	77.5	160	[13]
	25	3000	76.7	1570	[13]
Asphalt cement	26	3000	2.5	11	[13]
AC 60/70 Esso	20	2450	2.43	--	[16]
AC 40/50 Shell	20	2450	2.52	--	[16]
AC 180/220	20	2450	2.45	--	[16]
Aggregate -Diorite	20	2450	5.6-7	178 - 357	[16]
Asphalt concrete					
with diorite	20	2450	5.8	344	[16]
with limestone	20	2450	6.7	149	[16]
with quartzite	20	2450	4.0	62	[16]

orientation of charged molecules at the interface of the aggregate surface between agent and aggregate on one side and agent and asphalt cement on the other. The viscosity of the asphalt at which polarization is optimum is a key factor in taking advantage of this phenomenon. Interfacial polarization may not be as strong at microwave frequencies as it is at radio frequencies. However, the total polarization could have a favorable result. On the other hand, if poorly compatible aggregate and binder are treated with microwave energy, mismatching and a double layer may occur, resulting in a weaker bond or complete debonding.

In summary, fast heating by microwaves in conjunction with its polarization effect should reduce asphalt cement aging and improve the bonding of asphalt to aggregate, as well as resistance to water action. Furthermore, the increase in the polarity of the binder would increase its ability to polarize under the applied field, yielding stronger bonding.

EXPERIMENTAL PROCEDURES

The relative effect of microwave heating on asphalt adhesion to aggregate and resulting resistance to the weakening action of water was evaluated by Lottman's procedure for predicting moisture damage to asphalt mixtures (*19*) in conjunction with the diametral resilient modulus test as described by Schmidt (*20*) as well as the diametral split tensile strength.

Three groups of mixtures were tested: (a) virgin plain mixtures, (b) virgin mixtures with an added polar antistripping agent, and (c) recycled mixtures.

To represent existing and anticipated pavement microwave heating systems, several heating methods were used in preparing specimens from the three groups of mixtures. Conventional heating, microwave heating alone, and the latter in combination with conventional heating were the three basic heating methods. In this laboratory study, a kitchen-type microwave oven was used. These devices operate at 2450 MHz, whereas pavement heating equipment uses magnetrons operating at 915 MHz.

Materials

- Aggregate: Crushed glacial gravel, dense graded, conforming to Washington State Department of Transportation (WSDOT) Class B specification,

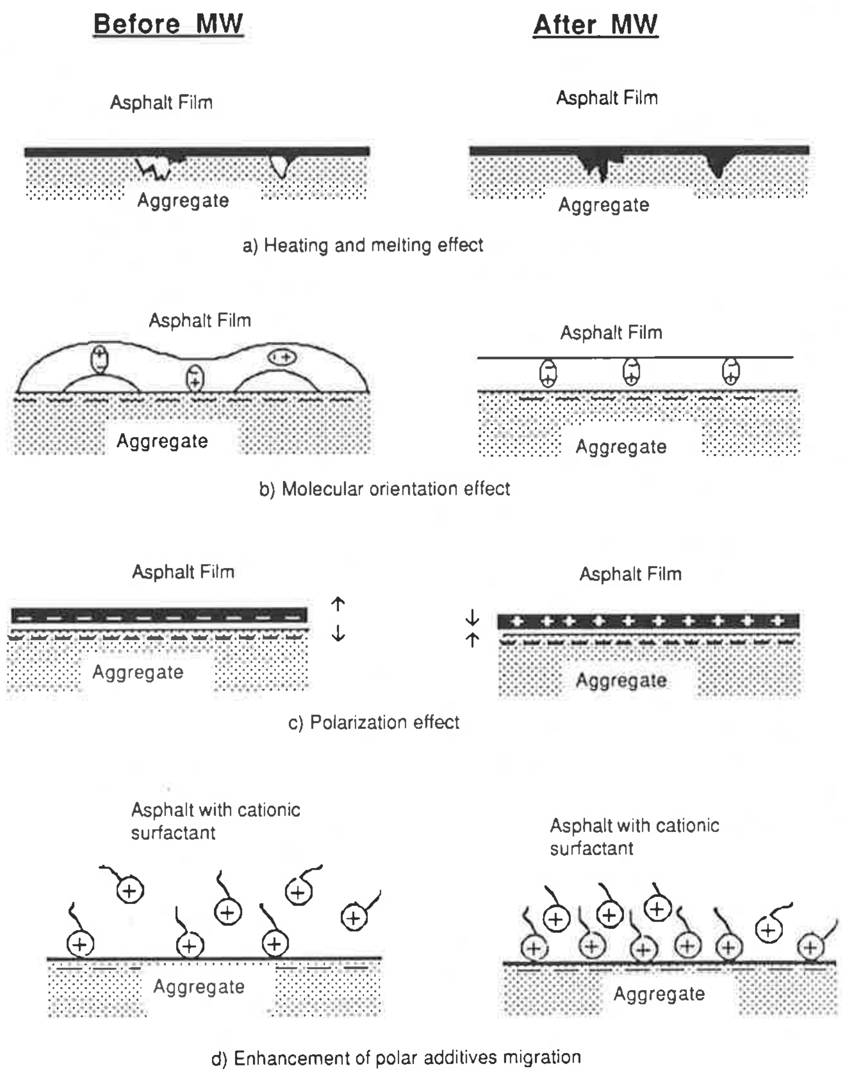


FIGURE 1 Mechanisms of asphalt adhesion improvement with microwave energy treatment.

- Asphalt cement: AR-4000W from Chevron,
- Recycling agent: RA-275 from Pester, and
- Antistripping agent: tallow tetramine from Exxon (Tomah).

Mixtures

- Virgin plain mixtures: These mixtures were prepared with 5.5 percent asphalt cement. Each sample was made by adding 70 g of asphalt to 1200 g of aggregate.
- Virgin mixtures with tallow tetramine: These mixtures were similar to plain mixtures except that tallow tetramine was added to hot asphalt in the amount of 0.5 percent of asphalt weight.
- Recycled mixtures: These mixtures were prepared from materials that were initially similar to plain mixtures. However, asphalt cement content was reduced to 4 percent of total weight. Artificial aging was accomplished by heating loose samples of mixture in a forced-draft oven at 240°F for 24 hr. The recycling agent was added to aged mixtures in the amount of 2 percent of total weight.

Preparation of Specimens

Specimens were fabricated according to the Marshall procedure (ASTM D-1159). Specimens were compacted by applying 50 blows on each side. The heating methods were as follows:

1. Conventional heating: A convection oven was used to heat asphalt cement, aggregate, and recycled asphalt pavement (RAP) to the mixing temperature of 300°F. RAP materials were heating for 2 hr in the convection oven before the addition of the recycling agent. Mixtures prepared by this method of heating were used to produce control specimens for the three groups of mixtures, and the method was intended to simulate conventional mixing in the plant.
2. Microwave heating: A kitchen-type microwave oven was used to heat plain aggregate for virgin plain mixtures and for mixtures with tallow tetramine in addition to RAP from 75°F to about 300°F in 10 min. The asphalt cement and recycling agent had to be heated in the conventional oven because they did not heat by microwaves. Moisture content of aggregate ranged from 0.3 to 0.5 percent. Aggregate was heated on a ceramic plate on top of a turntable in the microwave oven for 7 min. This was followed immediately by 3 min of heating in the microwave oven without the turntable, in order to get the center of the sample as hot as its edges. Preliminary trials showed that the use of the turntable resulted in heating the edges more than the center of the sample. This method was intended to simulate a plant in which only the aggregate is heated by microwaves.
3. Conventional oven plus "zapping" in microwave oven: After hot mixing of virgin plain mixtures and RAP with a recycling agent, the entire mix was treated for 2 min in the microwave oven. In the case of virgin mixtures with the tallow tetramine, three zapping periods were applied: 0.5, 2, and 5 min. This method can be used to simulate postmixing treatment with microwaves at a conventional hot-mix plant.
4. Conventional plus microwave oven supplemental recycle: This method of heating was restricted to recycled mixtures. RAP was heated in the convection oven for 2 hr at 250°F, followed by 4 min in the microwave oven to bring the mixture temperature to 300°F before the recycling agent was added. This technique was used to simulate one of the commercial microwave plants (*5*) that preheats RAP with hot gases, then finishes heating with microwaves.

In the recycled mixtures group, control mixtures, made with virgin and aged materials with no recycling agent heated in the convection oven, were also prepared. All recycled mixtures were subjected to a curing period of 20 min at 280°F in the convection oven after mixing with the recycling agent and before compacting. Materials that were zapped in the microwave oven for 2 min were cured for only 18 min.

Testing

Because the resilient modulus (M_R) test is nondestructive, each sample was used to determine dry M_R; M_R after water conditioning; and, finally, failure by split tensile strength (S_t) test. The extent of stripping was evaluated by visual inspection of failed specimens.

The diametral resilient modulus test was conducted at 74°F before and after Lottman conditioning. Applied load was 100 lb at a frequency of 20 cycles per minute and loading duration of 0.1 sec. Each specimen was tested twice by rotating it 90 degrees and taking the average of 5 readings after 50 conditioning pulses. Before dry testing, specimens were stored in a temperature control chamber overnight. In the case of tests after moisture conditioning, specimens were placed in a water bath at 74°F for at least 2 hr. The split tension tests were also performed at 74°F with a loading rate of 2 in./min. These tests were made only on dry specimens, and no data were available on retained tensile strength after moisture conditioning because comparison specimens were not made.

TEST RESULTS AND EVALUATION

Summaries of test results for all mixtures are given in Tables 2–4. The resilient moduli (M_R) before and after one cycle of freeze thaw conditioning are shown in Figures 2–4. The percentages of retained M_R-values after conditioning are shown in Figures 5–7. The results of the diametral split tensile strength test (S_t) after conditioning are shown in Figures 8–10.

Virgin Mixtures

Results show that zapped mixtures had a higher M_R before and after conditioning and higher S_t than conventionally prepared mixtures. Zapped mixtures were the only material that was entirely treated with microwaves. The heat generated from within aggregate particles coated with asphalt cement might have enhanced the coating and adhesion of asphalt, to which the increase in M_R and S_t might be attributed. It is also possible that heat from zapping caused the asphalt to flow and satisfy aligned charges on the aggregate particles' surface and even to flow into permeable voids. The failure surfaces after the split tension test showed no signs of stripping and compared closely with those of conventional mixtures.

Mixtures prepared from microwave-heated aggregate show the second highest averaged dry M_R. However, the actual data

TABLE 2 SUMMARY OF TEST RESULTS FOR VIRGIN MIXTURES

Specimen no.	Density p/cf	Voids %	M_R Dry 1,000 psi	Avg. 1,000 psi	M_R Cond. 1,000 psi	Avg 1,000 psi	% M_R Retained	Avg. % M_R Retained	S_t psi	Avg. S_t psi
CC1	148.2	3.71	239.26		207.98		86.9		73.4	
CC2	148.2	3.70	227.67		185.55		81.5		99.03	
CC3	148.2	3.74	227.91	231.61	197.32	196.95	86.5	85	106.4	92.9
MW1	147.5	3.98	248.92		169.19		67.9		70.5	
MW2	148.1	3.67	234.95		169.08		71.9		82.88	
MW3	149.0	2.99	278.16	254.01	206.96	181.74	74.4	71.5	89.5	81
CZMW1	148.0	3.79	265.27		211.04		79.5		111.5	
CZMW2	148.2	3.40	259.00		213.63		82.4		111.1	
CZMW3	148.5	3.80	263.6	262.62	234.72	219.8	89.0	83.7	119.4	114
Test temp. (F)			73°		73°				73°	
Loading rate			20 pulse/min		20 pulse/min				2 in/min	
Loading duration			0.1 sec.		0.1 sec.					

CC: Conventional oven heating MW: Microwave oven heating
CZMW: Conventional heating plus zapping in microwave oven

TABLE 3 SUMMARY OF TEST RESULTS FOR VIRGIN MIXTURES WITH ANTISTRIPPING AGENT

Specimen no.	Density p/cf	Voids %	M_R Dry 1,000 psi	Avg. 1,000 psi	M_R Cond. 1,000 psi	Avg. 1,000 psi	% M_R Retained	Avg. % M_R Retained	S_t psi	Avg. S_t psi
CC-T 1	146.70	4.45	214.50		186.60		87.00		99.70	
CC-T 2	146.84	4.23	195.70		175.60		89.70		106.20	
CC-T 3	147.51	3.97	205.50	205.20	202.50	188.23	98.50	91.70	110.30	105.40
MW-T1	147.66	3.93	249.05		211.30		84.80		114.10	
MW-T2	147.28	4.24	237.50		183.90		77.40		110.00	
MW-T3	146.99	4.31	219.30	235.30	188.00	194.40	85.70	82.60	116.40	113.50
CZMW(0.5)-T1	145.62	5.32	201.80		203.30		100.70		105.10	
CZMW(0.5)-T2	146.95	4.50	229.20	215.50	241.80	222.50	105.50	103.20	114.90	110.00
CZMW(2)-T1	145.25	3.79	215.40		209.90		97.40		114.20	
CZMW(2)-T2	147.13	4.18	222.80		222.20		99.70		117.00	
CZMW(2)-T3	147.16	4.33	225.20	221.10	233.00	221.70	103.50	100.30	116.00	115.70
CZMW(5)-T1	147.77	3.94	264.20		260.50		98.60		132.70	
CZMW(5)-T2	148.44	3.48	258.80	261.50	256.78	258.64	99.20	98.90	131.60	132.20
Test Temp. °F			73°		73°				73°	
Loading Rate			20 pulse/min		20 pulse/min				2 in/min	
Load Duration			0.1 Sec.		0.1 Sec.					

CC-T: Conventional oven heating
MW-T: Microwave oven heating
CZMW-T(n): Conventional heating plus zapping in microwave oven. Number in parentheses indicates zapping time.

appear to be widely scattered. One of the points is high, causing the mean value to be to the high side. However, after conditioning, M_R suffered about 29 percent loss, which made M_R after conditioning even lower than that of conventionally prepared mixtures. The split tensile test results correspond very closely with M_R results after conditioning. The uncertainty of uniform heating of aggregate with microwaves and the presence of aggregate particles that were not sufficiently hot when hot asphalt was added and mixed did not facilitate good coating and adhesion. Steps that were taken to ensure uniform temperature through the aggregate mix probably were not adequate. The scattering of points in Figure 2 indicates that uniform heating was not achieved. In addition to probable defects in coating, the alignment of charges on the aggregate surface that were not satisfied by asphalt cement may have increased the affinity of aggregate to water. Examination of the failure surface after the split tension test revealed severe stripping.

Mixtures with Antistripping Agent

Test results show that mixtures made with microwave-heated aggregate had a higher dry M_R. This is believed to be due to the improved orientation of aggregate surface charges. Again, lack of uniform microwave heating is considered the major reason for the greater loss of strength after water conditioning. However, M_R and S_t after the freeze-thaw cycle are slightly higher than for conventional mixing.

In the case of zapped mixtures, M_R before and after the freeze-thaw cycle, percentage of M_R retained, and S_t are higher than those of conventionally prepared mixtures. In this case the entire mixture, including the antistripping agent that had been incorporated in asphalt cement, was exposed to microwave radiation. The test values were in direct proportion to zapping time. The increase in test values of zapped mixtures is thought to have been caused by the mechanisms described earlier. First,

TABLE 4 SUMMARY OF TEST RESULTS FOR RECYCLED MIXTURES

Specimen no.	Density p/cf	Voids %	M_R Dry 1,000 psi	Avg. 1,000 psi	M_R Cond. 1,000 psi	Avg. 1,000 psi	% M_R Retained	Avg. % M_R Retained	S_t psi	Avg. S_t psi
VM1	142.99	8.49	264.30		103.10		39.00		44.20	
VM2	142.47	8.79	268.30	266.30	91.80	97.50	34.20	36.60	42.10	43.20
AM1	140.67	10.00	1018.50		660.30		64.80		143.30	
AM2	139.70	10.30	1072.70		750.60		69.90		153.30	
AM3	140.10	10.18	1006.30	1032.50	772.90	727.93	76.80	70.50	137.30	144.63
CC-R1	144.66	4.80	664.30		579.30		87.20		195.50	
CC-R2	143.99	5.10	665.50		603.60		90.70		190.10	
CC-R3	145.18	4.56	587.30	639.00	600.30	594.40	102.20	93.02	197.20	194.27
MW-R1	145.60	4.30	595.50		588.20		98.70		206.70	
MW-R2	146.00	4.00	616.50		587.00		95.20		205.90	
MW-R3	145.48	4.30	534.10	582.00	580.50	585.23	108.60	100.56	207.20	206.60
CZMW-R1	145.70	4.10	694.30		775.69		111.70		223.50	
CZMW-R2	144.90	4.78	645.70		656.00		101.60		208.70	
CZMW-R3	145.50	4.26	579.79	639.93	675.50	702.40	116.50	109.76	207.10	213.10
CSMW-R1	145.28	4.27	533.50		479.20		89.80		181.60	
CSMW-R2	145.10	4.42	665.20		597.20		89.80		203.10	
CSMW-R3	144.95	4.27	589.30	596.00	591.90	556.10	100.30	93.30	208.80	197.80
Test Temp. (F)			74°		74°				74°	
Loading Rate			20 pulse/min		20 pulse/min				2 in/min.	
Loading Duration			0.1 sec.		0.1 sec.					

VM: Virgin materials. AM: Aged materials. CC-R: Conventional recycle. MW-R: Microwave recycle.
CZMW-R: Conventional plus microwave zapping recycle. CSMW-R: Conventional plus microwave supplemental recycle.

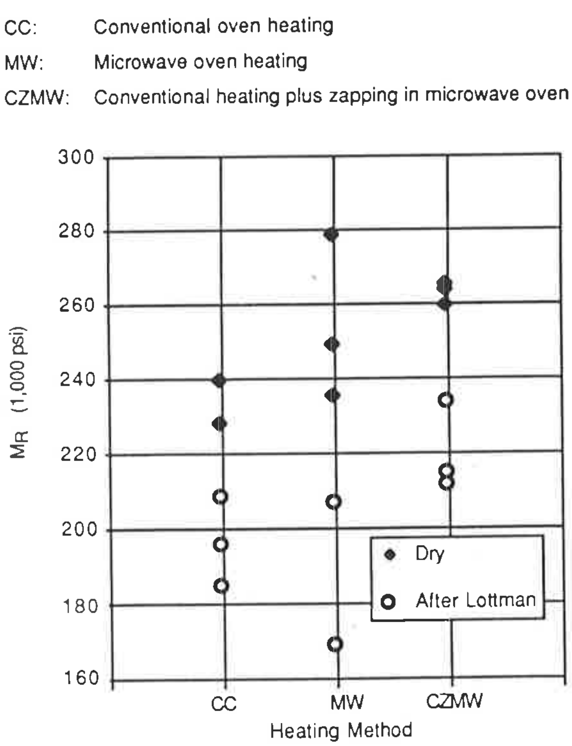


FIGURE 2 Effect of heating method on resilient modulus of virgin asphalt mixtures.

microwave heating might have facilitated uniform coating. Second, the polarization effect of microwaves improved polar molecule orientation and then increased the rate of migration of the antistripping agent toward the aggregate interface. Finally, the extra heating and mixing of these materials aged and stiffened them more. However, the extra heating did not appear to have great impact on stiffness at short zapping times. For example, in the case of zapping for 0.5 min, the temperature actually decreased, which resulted in greater air voids. Yet all test values (i.e., M_R before and after the freeze-thaw cycle, percentage of M_R retained, and S_t) are higher than those for conventional mixtures. At a longer zapping time of 5 min, during which the temperature increases by an average of 41°F, the extra heating effect might be more significant.

Recycled Mixtures

Results show that there was no major difference among dry M_R of all recycled mixtures subjected to the different heating methods.

Unlike that of fresh mixtures, dry M_Rs for both conventionally recycled and zapped recycled mixtures are almost identical. However, the M_R of zapped mixtures after Lottman's conditioning exhibited a slight increase for all samples tested. It is true that the number of samples may not be large enough to make an inference about this behavior, but zapped mixtures were exposed to microwave energy after the addition and mixing of the recycling agent. It is possible that some structuring or polarization of the asphalt cement and the recycling agent had taken place and that, in the presence of water and exposure to a temperature of 140°F for 24 hr, aging or strengthening resulted. If that is the case, the selection of a recycling agent that is compatible with microwave treatment ought to be of concern when designing microwave-heated recycled mixtures. Split tensile strength is shown to be the highest for zapped mixtures (about 10 percent higher than that of conventionally recycled mixtures); split tensile strength of

CC: Conventional oven heating
MW: Microwave oven heating
CZMW (0.5): Conventional heating plus zapping in microwave oven for 0.5 minutes
CZMW (2): Conventional heating plus zapping in microwave oven for 2 minutes
CZMW (5): Conventional heating plus zapping in microwave oven for 5 minutes

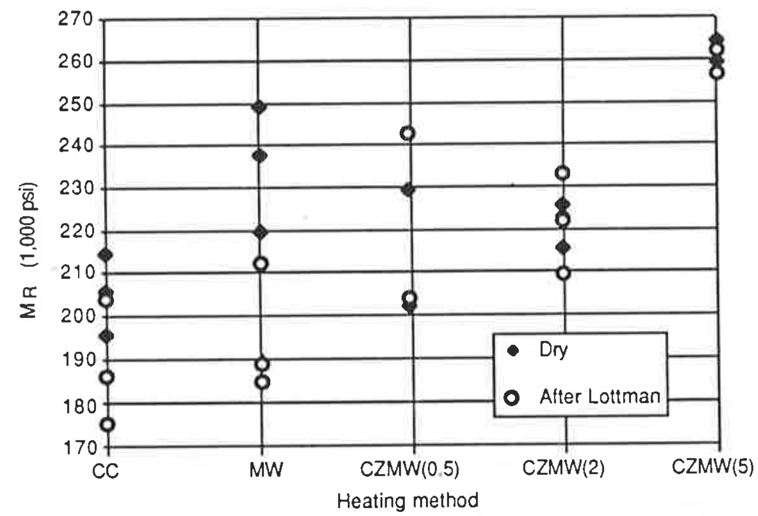


FIGURE 3 Effect of heating method on resilient modulus of virgin mixtures with antistripping additive.

VM: Virgin materials
AM: Aged materials
CC-R: Conventional recycle
MW-R: Microwave recycle
CZMW-R: Conventional plus microwave zapping recycle
CSMW-R: Conventional plus microwave supplemental recycle

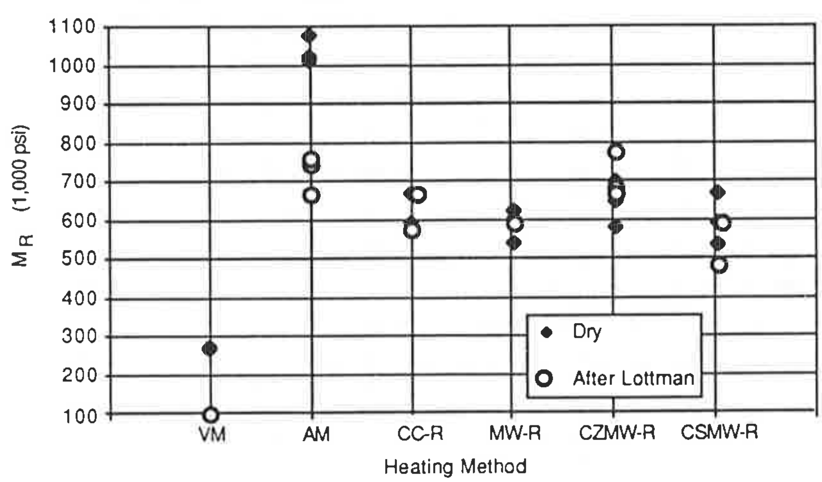
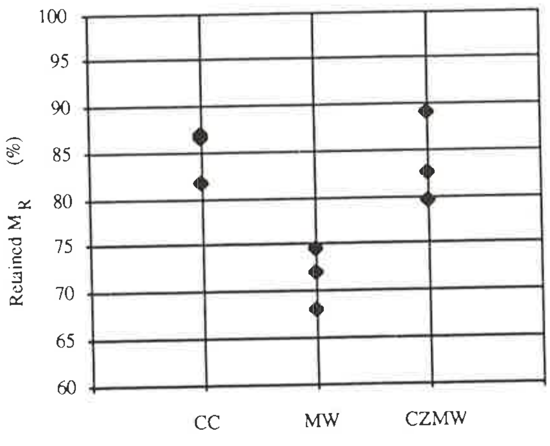


FIGURE 4 Effect of heating method on resilient modulus of recycled mixtures.



CC: Conventional oven heating
MW: Microwave oven heating
CZMW: Conventional heating plus zapping in microwave oven

FIGURE 5 Effect of heating method on percentage of resilient modulus retained for virgin mixtures after Lottman conditioning.

CC: Conventional oven heating
MW: Microwave oven heating
CZMW (0.5): Conventional heating plus zapping in microwave oven for 0.5 minutes
CZMW (2): Conventional heating plus zapping in microwave oven for 2 minutes
CZMW (5): Conventional heating plus zapping in microwave oven for 5 minutes

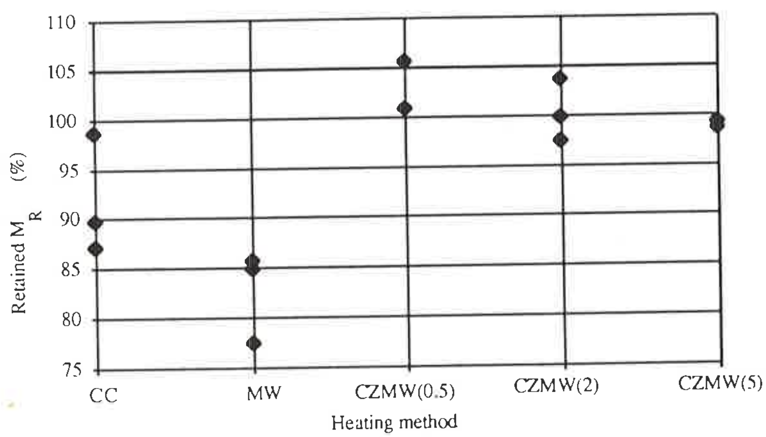
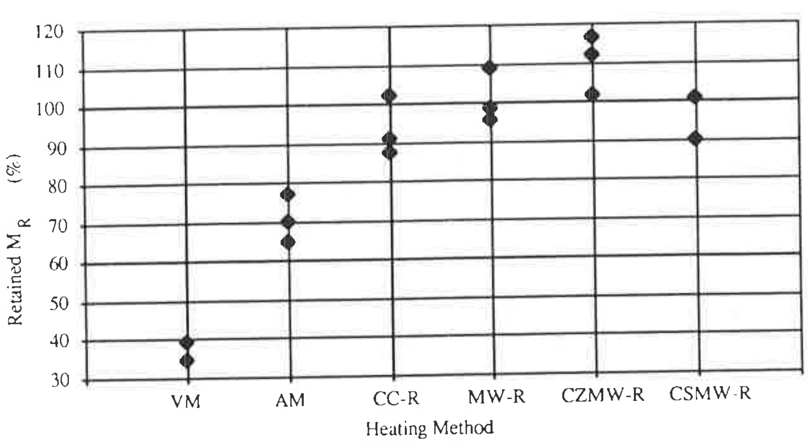


FIGURE 6 Effect of heating method on percentage of resilient modulus retained for virgin mixtures with antistripping agent after Lottman conditioning.



VM: Virgin materials
AM: Aged materials
CC-R: Conventional recycle
MW-R: Microwave recycle
CZMW-R: Conventional plus microwave zapping recycle
CSMW-R: Conventional plus microwave supplemental recycle

FIGURE 7 Effect of heating method on percentage of resilient modulus retained for recycled mixtures after Lottman conditioning.

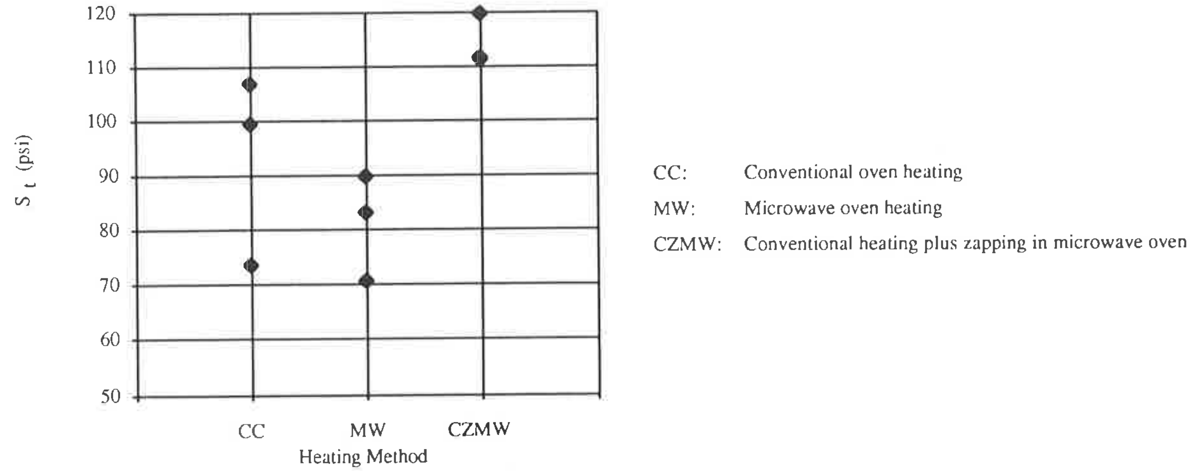


FIGURE 8 Effect of heating method on split tensile strength of virgin mixtures after Lottman conditioning.

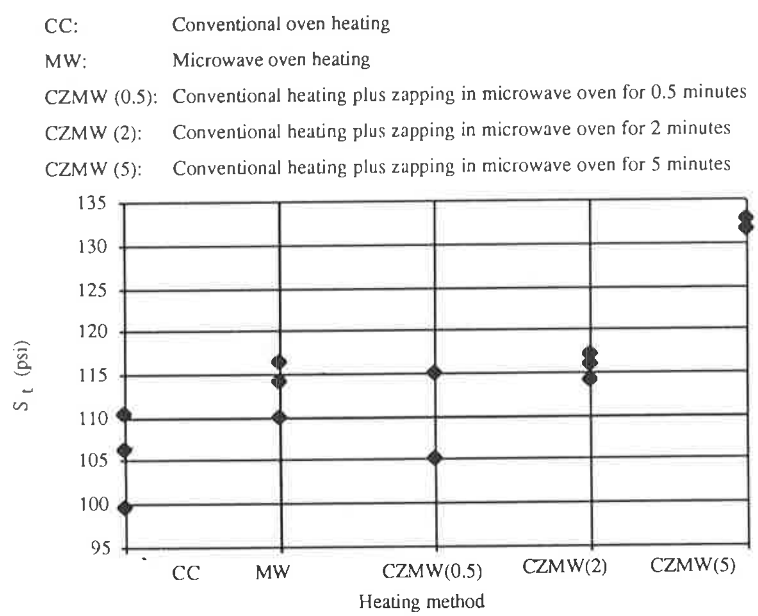


FIGURE 9 Effect of heating method on split tensile strength of virgin mixtures with antistripping additive after Lottman conditioning.

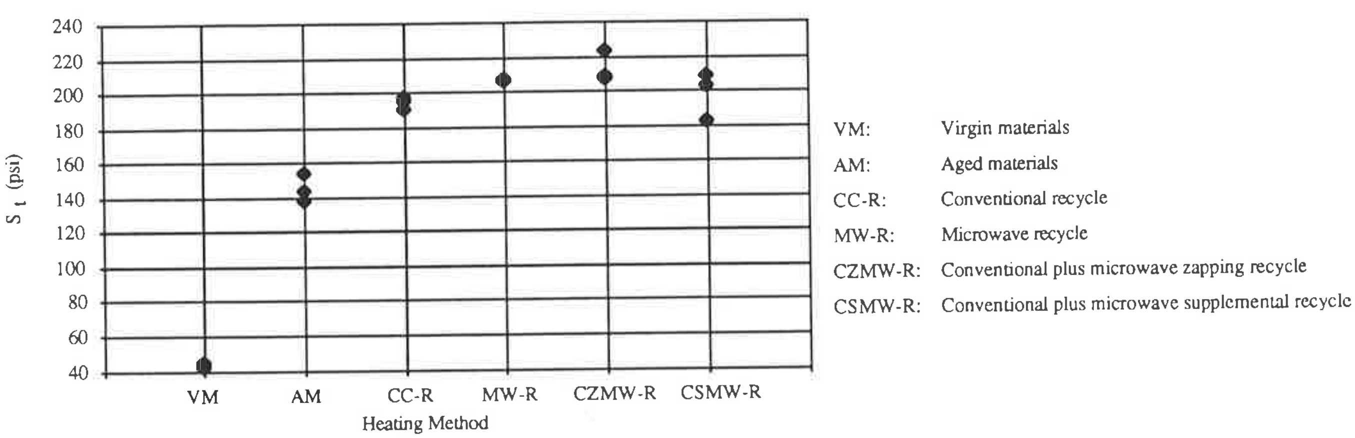


FIGURE 10 Effect of heating method on split tensile strength of recycled mixtures after Lottman conditioning.

microwave-heated mixtures is only 7 percent higher. Examination of samples after split tensile strength tests reveals that none of the recycled mixtures suffered any stripping.

CONCLUSIONS

On the basis of the results of this study, it appears that two conclusions are warranted:

- The zapping of hot asphalt mixtures, virgin or recycled, in the microwave oven has resulted in higher M_R and S_t indicating an improvement in asphalt bonding to aggregate. The resistance to stripping of zapped mixtures is as good as or better than that of conventionally heated mixtures.
- However, heating of plain aggregate in the microwave oven alone does not produce a uniform temperature. Consequently, adhesion of asphalt to aggregate may not be uniform, and stripping and reduction in strength may occur even with the use of polar antistripping additives.

These findings appear to support the hypothesized mechanisms of microwave treatment's role in improving the adhesion of asphalt to aggregate.

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