한국도로포장공학회지
第1券 2號 1999年 12月
pp. 135 ~ 154

EVALUATION OF SLAG MIXTURE PROPERTIES USING GYRATORY COMPACTOR

Kwanho Lee*

ABSTRACT

Compaction of asphalt pavement is one of the important processes to make good quality one. There are many laboratory-compaction methods to simulate field compaction, including Marshall compaction, Hveem compaction, gyratory compaction, and etc. The most common method used to determine the fundamental properties of asphalt mixture for design is Marshall method which is using impact energy. However, there is major difference between field compaction using kneading compaction and Marshall compaction using impact energy. Therefore, the gyratory compactor, which currently is the best to simulate the field compaction, was employed. The fundamental properties of asphalt specimen compacted by gyratory compactor and Marshall compactor were determined using laboratory test. From the tests, slag mixture with carbon black or pyrolyzed carbon black showed better performances, such as, in low susceptibility to temperature, high resistance against water and rutting, and high resilient modulus and indirect tensile strength.

Key words *: Marshall and gyratory compaction, initial compaction, traffic compaction*

1. INTRODUCTION

The major purpose of compaction is to make asphalt pavement to carry traffic loads applied. In general, compaction of pavements in fields is divided into two stages; during construction and after construction (Paterson et al., 1974). Asphalt pavement is initially compacted to about 8% of air voids during construction. After construction, traffic loads densify the asphalt layer, especially during hot weather, until it reaches ultimate density or failure. According to the research result of Epps et al. (1970), an increasing number of asphalt pavements is not stabilizing at a density equal to that obtained in the laboratory design of a companion paving mixtures. This means that current methods of laboratory compaction are not adequate to simulate field conditions. The properties of the asphalt and aggregate based upon the long term densification of a pavement must be taken into account; that is, consider

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* Assistant Professor, Department of Civil Engineering, Kyungsung Univ., Puasn, Korea

the resistance of the paving mixture to compactive effort (Epps et al., 1970).

Pavements densify with an increased volume of traffic until they stabilize. Traffic will compact pavement to ultimate density and a laboratory compaction needs to be able to simulate final density. The heavier the traffic, the higher the density of the pavement. SHRP (Strategic Highway Research Program), a $150-million research program authorized by the U.S. Congress (1988-1993), provided funds to produce new asphalt binder and mix design specification to improve pavement performance.

Three different compaction methods have been used in common asphalt mixture design, and these include impact compaction, kneading compaction, and gyratory compaction. Impact compaction is the oldest method of laboratory compaction, which was developed by Marshall in the 1930s. The number of blows applied to each face of the specimen (35, 50, 75 blows) was equal to general traffic levels. Higher energy levels were used for higher traffic levels. However, Marshall compaction ranked the last out of five compactors tested in the AAMAS study in simulating field conditions. Hveem method (kneading compactor) was developed in the 1930s and 1940s. Kneading compaction applies force through a roughly triangular-shaped foot that covers only a portion of the specimen face. Tamps are applied uniformly on the specimen face to achieve compaction. The objective of kneading compaction is to achieve specimen density that matches postconstruction mixture density under traffic. Gyratory compaction was developed in the 1930s in Texas. The process involves applying a vertical load while gyrating the mold in a back-and-forth motion. The kneading action is caused by gyrating the specimen through a horizontal angle. The angle of gyration of various compactors ranges from 1.00 to 6.00.

In a recent study of the AAMAS (Consuegra et al., 1989), compaction methods are listed in descending order beginning with those that best simulated field cores in various engineering properties : Texas gyratory shear compactor, California kneading compactor, Mobile steel wheel simulator, Arizona vibratory kneading compactor, and Marshall mechanical hammer.

The main purpose of this paper is to check the possibility of using of furnace slag from iron company as fine and coarse aggregate, and pyrolyzed carbon black from scrap tires as additive in hot mix asphalt, as well as to determine the fundamental properties of asphalt mixture with furnace slag, compacted by gyratory compactor, including percent of compaction, air voids, Gyratory Stability Index, and Gyratory Shear as well as to make a correlation with Marshall stability and flow. The resilient modulus, indirect tensile test and the Hamburg wheel tracking test were conducted.

2. GYRATORY TESTING MACHINE (GTM)

The gyratory testing machine was developed by the Texas Highway Department in 1939. The main purpose was to develop the methods and equipments that would simulate road conditions and to give accurate reproducible results. Different machine models were tested in the laboratory. The Gyratory Molding Machine was the ninth version since been incorporated in a standard procedure by the Texas Highway Department (Ortolani and Sandberh, 1952).

The molding method employing specimen shear consisted of a mold having four equally spaced handles which were individually lifted in succession a prescribed number of times. The molding cylinder has two 60.96cm handles attached to act at an included angle of 75° , by which the gyratory motion is imparted to the specimen (Ortolani and Sandberh, 1952). In 1957, the kneading compactor developed by the Corps of Engineers was introduced to the AAPT (Association of Asphalt Paving Technologists) at the annual meeting in Atlanta. There are four primary reasons to develop the kneading compactor (McRae and McDaniel, 1958) :

- to produce the high density under channelized traffic of the wheel load
- to produce test specimens having stress-strain relationships corresponding to those of actual pavement samples of equivalent density and bitumen content
- to give an indication of how many repetitive load applications a pavement sample can take before flushing
- to give a new approach to overcome the limitations of current pavement mixture design tests.

Two types of gyratory testing machine have been recently used: the U.S. Army Corps of Engineers gyratory shown in Figure 1 and the SHRP (Strategic Highway Research Program) gyratory. The main difference is that the SHRP gyratory machine has a fixed plate, whereas the U.S. Army Corps of Engineers gyratory testing machine is freely rotated. The former is used only for the compaction of the specimen, but the latter is used for the compaction and shear testing of the specimen.

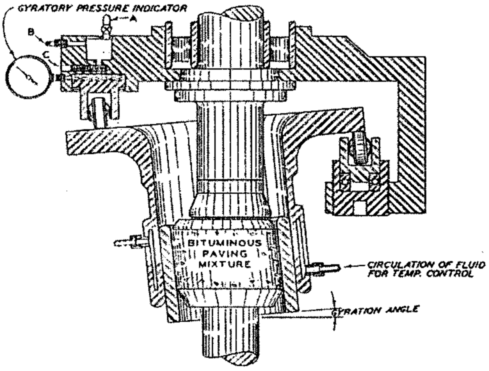

Figure 1. Schematic of U.S. Army Gyratory Testing Machine (U.S. Army Corps of Engineers, 1962)

3. TESTING MATERIALS AND PROCEDURES

3.1 Materials Used

Two grades of asphalt cement, AC-10 and AC-20, which are highly common in the United States, were employed. The physical properties of AC-10 and AC-20 are shown in previous paper (Lee and Park, 1997).

CB (commercial carbon black) and CBp

(pyrolyzed carbon black) were used as additive. CB in this research was purchased from CABOT, Boston, Massachusetts (1994) and CBp used was obtained from pyrolysis of waste tires, and was provided by Wolf Industries, Indiana. More than 90% of CBp passes through the #200 sieve. According to the test results provided by Wolf Industries, CBp is insoluble in water. The particles of CBp are much coarser than commercially available, high-structure and high abrasion furnace (HAF) carbon black; however, most of the coarse particles are easily broken down by normal finger pressure.

Slag from the Levy Company, Portage, Indiana was used as coarse aggregate, and natural sand from Vulcan Materials, West Lafayette, Indiana was used as fine aggregate in the asphalt mixtures. The Indiana Department of Transportation (INDOT) specification for the #9 binder aggregate was adopted for the target gradation (Lee, 1996), which is shown in Figure 2. The specific gravity test for the coarse aggregate and for the fine aggregate were carried out in accordance with ASTM C127 and ASTM C128 (1993), respectively. The bulk specific gravity and apparent specific gravity of the coarse aggregate is 2.420 and 2.587. The bulk specific gravity and apparent specific gravity of the fine aggregate is 2.579 and 2.581.

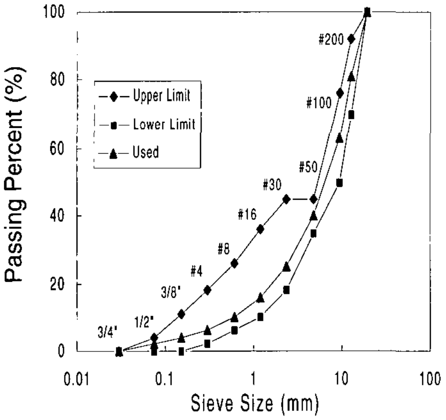

Figure 2. The Target Gradation Used

3.2 Mix Preparation and Compaction

The mix preparation of gyratory compaction specimens followed ASTM D 3387-93 and the manual provided by the Engineering Developments Company Inc. (McRae, 1993). The masses of 1200 grams of aggregate and the optimum binder content which was determined from the Marshall mix design were used to make the size of specimen for 101.6mm diameter and approximately 68.6mm height. The chuck temperature was kept at 140±5℃. A 101.6mm diameter mold was used for the preparation of specimens. A 1.25° angle of gyration and a 828 kPa vertical pressure were employed. Although 1° is most commonly used, the angle of 1.25° was selected to simulate the worst condition. The vertical pressure (ram pressure) simulates the maximum anticipated tire contact pressure, since the theoretical stress for compaction and maximum induced shear are based on the concept of simulating the field conditions for the test (Zhang et al., 1994). A value of 500 revolutions was chosen for the ultimate compaction efforts, although SHRP (1994) recommended 230 revolutions as the ultimate traffic densification. According to McRae's

(1993) recommendation, compaction is completed as the variation in densification of the specimen is not greater than 0.157kN/m3 after an additional 100 revolutions. The variation of roller pressure and height of the sample were monitored and recorded at every 50 revolutions to check the effects of subsequent loads and inclusions of different ratios of pyrolyzed carbon black and carbon black. The roller pressure and the height of sample were measured at four positions differing by approximately 90° . The height of sample, gyratory angle, and applied pressure were recorded by the gyrograph. After the compaction was completed, the sample was extruded from the mold. The compacted samples were cooled down to the laboratory temperature (18℃ to 20℃) for more than 24 hours prior to the bulk specific gravity test. The bulk specific gravity was measured in accordance with ASTM D 2727-93.

3.3 Gyratory Testing

Percent of Compaction and Air Voids

The SHRP compaction protocol would maintain a constant gyration pressure and a specified number of gyration to define two levels of compaction: (1) construction compaction (92 percent of maximum theocratical specific gravity), and (2) traffic compaction (96 percent). Gyration at 89 and 98 percent densities were defined as threshold limits for an acceptable mix. Percent compaction is defined as the ratio of bulk specific gravity to maximum theoratical specific gravity.

Gyratory Stability Index

The Gyratory Stability Index (GSI) is an important parameter used to predict the stability of a mixture, and is related to the potential for the mixture to experience plastic deformation. As the GSI value is closer to unity, the mixture becomes more stable, and less plastic deformation is likely to occur. The GSI is defined as follows:

$$GSI = \frac{\theta_{max}}{\theta_{min}}$$

where θ_{max} : the maximum gyratory angle
θ_{max} : the minimum gyratory angle

According to the recommendation of McRae (1993), a GSI close to unity implies a stable mix. Research conducted by the Maine DOT suggests that GSI should be less than 1.15 after 300 revolutions to prevent rutting, and Illinois DOT (1991) studies suggested that GSI should be less than 1.25 after 300 revolutions (Zhang et al., 1994). Based on the previous research (Park, 1995) on GSI value, a GSI value of 1.15 was selected as a criterion in this study.

Gyratory Shear

Gyratory shear represents the shear resistance of mixture which is a function of the imposed vertical pressure and degree of strain. A decrease of this value during compaction and densification indicates a loss of stability. According to the recommendation of the Maine DOT (1992), 241.3 kPa (35 psi) after 300 revolutions is the minimum Sg value (Zhang et al., 1994). A value of 275.8 kPa (40 psi) after 300 revolutions has been selected for the Sg criteria.

3.4 Resilient Modulus and Indirect Tensile Test

A closed loop, servo-hydraulically controlled loading system was used for the test. The MTS model 643.01 A, resilient modulus fixture, was used to determine the modulus(MTS, 1994). Two different testing temperatures were used, 5°C and 25°C. The tests were carried out on diametrical specimens in the indirect tension mode at both testing temperatures. About 10 percent of the indirect tensile strength was employed as an applied load. The one second repeated loading cycle (0.1 second loading and 0.9 second unloading) was applied along the vertical diameter of the test specimen for 200 seconds. The test procedures followed are in accordance with ASTM D 4123-82.

The 810 Material Testing System (MTS) was employed to determine the indirect tensile strength. Testing was performed at 5°C. A constant 1 second repeated loading cycle with 0.1 second loading and 0.9 second unloading was applied to the specimen for 50 seconds for the initial condition. The compressive loading was applied to the conditioned specimens until failure occurred. The loading stroke rate of 13 mm/min was used in accordance with SHRP recommendation (SHRP, 1994, Park, 1995). The data sampling frequency of 20 Hz was employed.

The resilient modulus (M_R) represents the ratio of an applied stress to the recoverable strain that takes place after the applied stress has been removed. The resilient modulus is calculated by the following equation:

$$M_R = \frac{P \times (0.27 + \nu)}{H \times t} \quad \text{..................................} \quad (1)$$

where M_R = resilient modulus (Pa)
P = load applied (N)
υ = Poisson's ratio(assumed to be 0.35)
H = total recoverable horizontal deformation (mm)
t = thickness of specimen (mm)

The indirect tensile testing provides the tensile strength of the mixtures and the cracking potential of the mixture can be determined through the tensile strength. The ultimate applied load at failure was obtained from the test and the tensile strength was calculated. The tensile strength of mixture is calculated using the following equation.

$$S_t = \frac{2P_{ult}}{\pi t D} \quad \text{..} \quad (2)$$

where S_t = tensile strength of the mixture (kPa)
P_{ult} = ultimate applied load at failure (N)
D = diameter of the specimen (mm)
t = height of the specimen (mm)

3.5 Hamburg Wheel Tracking Test

In general

The wheel tracking device has been used in the Hamburg, Germany area since 1974 for research on asphalt binder course mixes. In 1984, the Hamburg Load Authority began using wheel tracking tests as a specification tool to determine the resistance to moisture damage and permanent deformation (Elf Industries, 1992). The Hamburg wheel tracking device was introduced to the United States in 1990 after the representatives of the American Association of State Highway and Transportation Officials (AASHTO), Federal Highway Administration (FHWA), National Asphalt Pavement Association (NAPA), Strategic Highway Research Program (SHRP), Asphalt Institute (AI) and Transportation Research Board (TRB) made a two week research tour of six European countries (Aschenbrener, 1993). After the European pavement study tour, the Colorado Department of Transportation (CDOT) and the FHWA Turner-Fairbank Highway Research Center demonstrated the Hamburg wheel. The tracking device used in this study was purchased in May 1990, from Helmut Wind Inc. of Hamburg, Germany by Koch Materials, Terre Haute, Indiana. The detail information for this device is shown in Table 1.

Testing Procedures

A total of 8800 grams of aggregate was used to make duplicate slabs. Based upon the results of Marshall and gyratory tests, conventional mixtures and mixtures modified with 10 % and 15 % of CB and CBp were tested. A linear kneading compactor was used for the preparation of sample slabs at 6 percent of targeted air voids. The compacted slab has a length of 320 mm (12.6 in.), width of 260 mm (10.2 in.), and depth of 40 mm (1.6 in.). The bulk specific gravity test according to ASTM D2726-93 was followed. The range of measured air voids is around 8 to 9 percent which is different from the targeted air voids, 6 %. Table 2 shows measured air voids of the

Table 1. Information of the Hamburg Wheel Tracking Device (Elf Ind., 1992)

Type		Subject
Materials of steel wheel		V2A steel, rust resistant
Dimension of wheel	diameter	203.5±1 mm
	width	47.0±0.02 mm
	surface	plane
Wheel load		71±0.1 kg
Side play of each bearing of the load arms		≤0.2 mm
Length of the rolling section		230±10 mm
Rolling frequency		53±2 min^{-1}
Time duration of load pressure		0.1 sec

prepared slab. Table 3 shows the detail testing conditions for the wheel tracking test. A pair of specimens was tested simultaneously and was submerged under water at 50℃ for 30 minutes in order to ensure thermal stability. The deformations at the center of the slab were measured by LVDT automatically. Each sample slab is subjected 20,000 passes of the wheel, unless 20 mm of deformation occurs earlier.

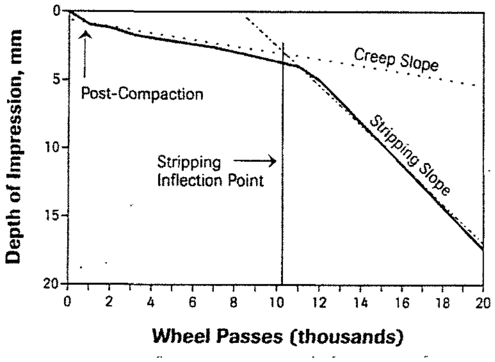

Figure 3. Testing Parameters of Hamburg Wheel Tracking Test

Testing Parameters

The results from the Hamburg wheel tracking test include post compaction consolidation, creep slope, stripping inflection

Table 2. The Air-voids of Prepared Specimens

Modifier		AC-10		AC-20	
	content	air voids	std.	air voids	std.
	0 %	6.0	0.06	7.9	0.08
CB	10 %	9.0	0.27	8.5	0.39
CB	15 %	9.1	0.91	9.0	0.12
CB_P	10 %	---	---	8.6	0.02
CB_P	15 %	8.9	0.21	8.6	0.08

Table 3. Testing Conditions(Lee, 1996)

Type	Subject
Sample	duplicated specimens, fully immersed in water
Wheel	moving steel wheel
Speed	sinusoidal speed reciprocation
Weight	705 N (158.3 lb)
Contact Pressure	1490 kPa (216.9 psi)
Loading Cycle	0.1 sec load, 0.9 sec rest
Temperature	50°C
Deformation	up to 20 mm 0.01 mm
Test duration	20,000 cycles, unless 20 mm deformation is reached first

Table 4. Summary of GTM Revolutions with Percent Compaction

AC-10	92 %	94 %	96 %	AC-20	92 %	94 %	96 %
Straight	29	50	130	Straight	36	70	190
5% CB	32	61	200	5% CB	37	86	240
10% CB	40	90	400	10% CB	47	87	245
15% CB	42	90	280	15% CB	38	74	235
20% CB	55	105	〉500	20% CB	37	75	240
5% CB$_p$	42	79	300	5% CB$_p$	46	90	250
10%CB$_p$	45	100	280	10%CB$_p$	35	78	250
15%CB$_p$	42	78	270	15%CB$_p$	37	74	190
20%CB$_p$	38	88	300	20%CB$_p$	37	73	200
Average	41	82	296	Average	39	79	227

point and stripping slope as shown in Figure 3. The post compaction is defined as the range that the wheel rapidly deforms the pavement. For example, about 1000 passes in Figure 3 is called post compaction consolidation. A low value for post compaction consolidation would indicate that the compaction process during laboratory fabrication or field construction is near optimum levels. After the consolidation effect of the wheel occurs, we are concerned with the rate of permanent deformation in the mix, which is defined as the creep slope. The more rapid the rate of deformation, the more sensitive the mix is to rutting. The unit of creep slope is passes per mm. The stripping inflection point is defined as the number of passes where the curve changes shape and plunges downward. The lower the stripping inflection point, the lower the mechanical energy to make stripping damage occur. The stripping slope is defined as the rate of deformation after the stripping inflection point. In the field, a combination of stripping and rutting failure is seen often, particularly in the southeastern part of the U.S.

4. TESTING RESULTS

4.1 Percent of Compaction and Air Voids

Table 4 summarized all the testing results. The measured number of GTM revolution for AC-10 and AC-20 mixtures is around 40 during the beginning stage (92% of compaction), and more than 100 for traffic compaction. In AC-10 case, compaction to beginning stage took more number of gyratory. This means either more compaction effort or higher compaction temperature is needed to achieve the same level of density. It is necessary to show viscosity data for modified asphalt. The inclusion of

CB and CBp for both asphalt grade increases the number of GTM revolutions to reach 96 percent of compaction. This means that the modified asphalt mixtures is more durable than straight asphalt mixtures.

The air voids in the mixture is one of the most important parameters in asphalt concrete, since the physical properties and performance of mixtures during the service life of the pavement can be predicted from the air voids. Figure 4 shows the relationship between air voids and GTM revolutions for AC-10 mixtures. As the GTM revolutions increase, air voids at the optimum binder content correspondingly decrease. The air voids at the same number of revolutions increase as the content of CB is increased. Considering the decreasing rate of air voids, the initial compaction would be completed in less than about 100 GTM revolutions and the traffic densification would start after about 100 GTM revolutions. The same trend for initial compaction and traffic densification for AC-10 CBp mixtures was obtained. The variation of the air voids at the same value of GTM revolutions for AC-20 mixtures is less than that in AC-10 mixtures. Also, there is no general trend of the change of air voids due to the inclusion of CB and CBp. The traffic densification determined might occur near the 100 GTM revolution value. Considering the whole testing result, the final air voids were about 2 percent to 4 percent. The decreasing rate of air voids after 100 GTM revolutions was relatively small. The main reason is the high strength of the slag as a coarse aggregate. The aggregate provided a

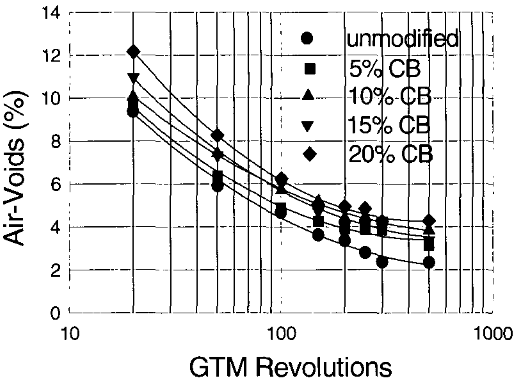

Figure 4. Air-Voids of AC-10 with CB_p

Table 5. Summary of GSI for Asphalt Specimens

Rev.	100	200	300	400	500	Rev.	100	200	300	400	500
AC-10	1.038	1.009	1.009	1.019	1.038	AC-20	1.009	1.009	1.009	1.000	1.028
5% CB	1.020	1.000	1.010	1.030	1.040	5% CB	1.000	1.029	1.049	1.039	1.069
10% CB	1.000	1.019	1.019	1.038	1.086	10% CB	1.019	1.029	1.029	1.029	1.058
15% CB	1.000	1.019	1.028	1.056	1.084	15% CB	1.010	1.000	1.010	1.048	1.125
20% CB	1.018	1.009	1.018	1.182	1.309	20% CB	1.009	1.000	1.038	1.094	1.226
5% CB_p	1.029	1.010	1.029	1.010	1.000	5% CB_p	1.029	1.010	1.000	1.010	1.029
10%CB_p	1.010	1.020	1.020	1.010	1.000	10%CB_p	1.000	1.019	1.029	1.038	1.048
15%CB_p	1.010	1.030	1.030	1.030	1.040	15%CB_p	1.000	1.029	1.020	1.049	1.108
20%CB_p	1.031	1.000	1.021	1.031	1.031	20%CB_p	1.020	1.010	1.010	1.069	1.127

strong, stone skeleton to resist the applied loads. The compaction using Gyratory Testing Machine should minimize crushing of the aggregate during the compaction. Both grades of asphalt mixtures might be permeable to air and water due to high air voids in the initial stage of construction. The potential for premature cracking, raveling, and freezing and thawing of the AC-10 mixtures with CB or CBp might be more significant than that in AC-20 mixtures with CB or CBp. In the case of the AC-10 mixture, the inclusion of CB or CBp will decrease the rutting potential, because when the air voids of the in-place mixture are less than 3 percent, permanent deformation is likely to occur due to plastic flow (Brown and Cross, 1989).

4.2 Gyratory Stability Index

The relationship between GSI and GTM revolution for AC-10 and AC-20 mixtures with CB and CBp is provided in Table 5. The inclusion of CB showed positive results except for the inclusion of 20 percent of CB. Most of GSI values were less than 1.1, which indicates stability. After long loading duration, more than 400 GTM revolutions, the GSI value is apt to increase slightly. Judging from Table 5, the mixture with a large amount of CB might be unstable. In case of CBp mixtures, the GSI value was significantly uniform, (between 1.00 to 1.05) which indicates reasonable stability.

Considering the selected criterion of GSI, the AC-20 mixtures with CB or CBp were reasonably stable, except mixtures with 20 percent of CB. Large amounts of CB or CBp (more than 15 percent) are inclined to be unstable after long loading duration, although mixtures with 15 percent of CB, and 15 and 20 percent of CBp remained within the criterion.

Table 6. Summary of Gyratory Shear, S_g (kPa)

AC-10 Asphalt Binder						AC-20 Asphalt Binder					
Rev.	100	200	300	400	500	Rev.	100	200	300	400	500
0%	401	388	382	373	470	0%	409	369	397	355	319
5% CB	360	358	335	337	355	5% CB	407	385	352	349	313
10% CB	422	379	367	364	333	10% CB	380	347	345	342	365
15% CB	323	332	314	283	267	15% CB	394	376	359	351	336
20% CB	381	363	378	337	425	20% CB	365	347	293	263	333
5% CB$_p$	409	352	387	389	408	5% CB$_p$	357	335	349	351	326
10%CB$_p$	396	374	400	370	362	10%CB$_p$	369	277	305	313	345
15%CB$_p$	384	378	366	374	370	15%CB$_p$	376	348	325	332	291
20%CB$_p$	421	378	366	363	448	20%CB$_p$	434	362	355	399	541

(criteria : minimum 275kPa after 300 GTM revolutions)

4.3 Gyratory Shear

Table 6 show the relationship between gyratory shear and GTM revolutions. In the case of mixtures with CB, as the GTM revolutions increased, Sg value of mixtures without CB increased, however, Sg of the others decreased slightly. The range of Sg value was between 275.8 kPa to 413.7 kPa (40 psi to 60 psi). Considering the selected criterion, only the mixtures with 15 percent of CB are not acceptable. In the case of CBp mixtures, the range of Sg value was 344.8 kPa to 413.7 kPa (50 psi to 60 psi) and the values were almost uniform, except for the values at 500 GTM revolutions. The variation of the Sg value of CBp mixtures as the number of GTM revolutions increased was less than that of CB mixtures.

Both cases for AC-20 mixtures with CB and CBp show slightly decreased Sg values, as the GTM revolutions increased. Only AC-20 mixtures with 10 percent CBp and 20 percent CB were not acceptable.

4.4 Marshall Stability

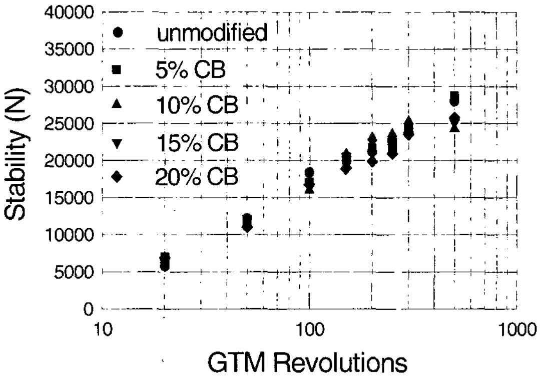

Figure 5. Marshall Stability of AC-10 with CB

The summary of Marshall stability for AC-20 mixtures with CB is shown in Figure 5. As can be seen in the figure, the relationship between Marshall stability and logarithmic GTM revolutions was almost linear which

Table 7. Comparison of Marshall Stability for Marshall Compaction and Gyratory Compaction

Asphalt Cement		AC-10			AC-20		
Additive		Gyratory	Marshall	Stab. Ratio	Gyratory	Marshall	Stab. Ratio
CB	0%	11947	18512	1.55	14920	19224	1.29
	5%	13129	18423	1.40	17526	19090	1.09
	10%	15234	19580	1.29	19847	18156	0.91
	15%	16460	19758	1.20	18010	18957	1.05
	20%	17205	20292	1.18	15260	18868	1.24
CB_p	5%	16759	19269	1.15	19659	21004	1.07
	10%	13746	21138	1.54	17904	18779	1.05
	15%	13847	21223	1.53	17162	22962	1.34
	20%	15772	21223	1.35	15858	21271	1.34

(criteria : maximum 1.15)

means that Marshall stability increased as the GTM revolutions increased. The slope of the mixtures with CBp was larger than that of the mixtures with CB. In the case of CB mixtures, the dispersion velocity during the mixing is very important. When the CB is properly dispersed, the microsize and the hydrophobic property of CB particles, saturated by the asphalt cement, makes CB a part of the asphalt cement. This is called microfiller action of CB, and is in contrast to conventional mineral fillers. Vallerga and Gridley (1980) recommended the use of pelletized CB to improve the dispersing effect and high speed mixing, approximately 15000 rpm, in order to achieve the full development of the dispersing effects in the asphalt mixtures. In our research, relatively lower mixing velocity, about 8000 rpm, was used. This might be the main reason that lower values occur, although the high performance CB was used. However, the differences observed between the slopes are relatively insignificant in engineering terms, and any conclusions drawn should be treated only as indicative rather than definitive.

Table 7 shows the comparison of Marshall stability for asphalt specimen compacted Marshall compactor and Gyratory compactor. The air-void of specimen for both compaction was fixed at 6%±1% because it is not easy to exactly make 6% of air-voids. There is a somewhat difference in Marshall stability for both compactions. The average Marshall stability of AC-10 and AC-20 with Gyratory compactor is 14500N and 17100N, as well as that of AC-10 and AC-20 with Marshall compactor is 19800N and 19500N, respectively. The Marshall stability of Gyratory compacted specimen was less than up to 75% of Marshall-compacted specimen. This represents that Marshall mix design overestimates stability and the effect of additive, CB and CBp, shows more significant for Gyratory compaction than Marshall compaction. The possible reason to make such a big difference of stability is the arrangement of coarse and fine aggregate, and particle orientation. From this result, the compaction method significantly affects the Marshall stability.

4.5 Flow

Figure 6 showed the summary of flow for AC-10 mixtures with CB. According to ASTM criteria, the range of acceptable flow is 0.152cm to 0.406cm, in the range 3% < air voids < 5%. As the GTM revolutions increased, the flow value tended to stabilize.

In the case of AC-10 CB mixtures, straight mixtures showed a lower bound and mixtures

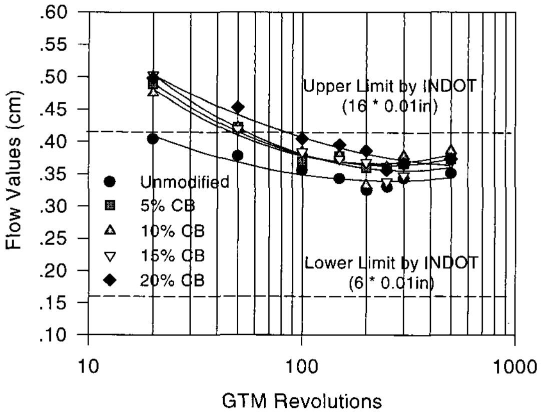

Figure 6. Flow Values of AC-10 with CB

with 20 percent of CB represented the higher bound. On the other hand, mixtures with 20 percent CBp indicated a lower bound and mixtures with 5 percent of CBp showed the upper bound. After a long loading duration (after 100 GTM revolutions), the flows for AC-10 mixtures with CB or CBp were within the criteria.

In the case of AC-20 mixtures, the flow values of CB mixtures were higher than that of CBp mixtures at the initial stage of compaction. At the final stage of compaction, the range of flow values for both mixtures were almost identical, about 0.35cm to 0.45cm. In both cases, the mixtures without CB and CBp represented a lower bound, while the mixtures with 20 percent of CB and with 10 percent of CBp represented the upper bound. Judging from the INDOT criteria, only mixtures without CB and CBp and with 15 percent of CBp were acceptable. The others did not meet the criteria.

4.6 Marshall Stiffness Index (MSI)

The Marshall Stiffness Index (MSI) is defined as Marshall Stability divided by Flow. This is an empirical stiffness value and is used by some engineers, especially in Europe, to evaluate the quality of asphalt mixtures. A higher value of stability divided by flow indicates a stiffer mixture and, hence, indicates the mixture is likely more resistant to permanent deformation. There is ver little performance data to indicate that the Marshall stability/flow is related to performance.

Table 8 represents the MSI of mixtures at 6% of air-void using different compaction methods. Also, the second-order regression results are represented, which shows the relationship between MSI and additive percents. There is a big difference between Marshall-compacted mixtures and Gyratory-compacted mixtures. In case of Marshall-compacted mixtures, the unmodified mixtures are generally higher MSI than modified mixtures. However, in case of Gyratory-compacted mixtures, the MSI of modified mixtures are higher than that of unmodified mixtures. This means that the compaction method is a significant factor to affect the resistant to permanent deformation.

4.7 Resilient Modulus (M_R) Test

The summary of test results is shown Table 9. In this study, two different testing temperatures, 5˚C and 25˚C, were employed. The M_R at 5˚C for both compacted specimens

Table 8. The Comparison of MSI using Different Compaction Method

Additive		CB					CB_p				
Percent		0	5	10	15	20	0	5	10	15	20
Marshall	AC-10	375.8	339.8	359.5	338.8	369.0	375.8	362.0	388.5	384.1	394.9
	AC-20	392.4	342.7	305.8	318.1	336.1	392.4	387.8	360.5	418.9	393.1
Gyratory	AC-10	315.2	325.1	392.9	429.8	427.8	315.2	453.6	380.5	383.1	453.8
	AC-20	370.2	419.8	432.6	404.3	313.1	370.2	493.3	382.2	387.0	413.1

Table 9. The Summary of MR Tests

Aggregate		Slag							
Compaction		Marshall				Gyratory			
Asphalt		AC-10		AC-20		AC-10		AC-20	
Add.	%	5°C	25°C	5°C	25°C	5°C	25°C	5°C	25°C
No	0	11.4	4.4	9.2	5.3	12.8	4.2	13.9	4.4
CB	5	10.8	5.2	13.8	5.7	13.2	4.2	14.5	5.8
CB	10	12.7	5.2	14.0	6.3	13.3	5.2	13.1	4.9
CB	15	14.8	7.1	15.6	5.5	13.3	5.3	12.5	4.9
CB	20	11.0	4.2	12.2	6.3	11.8	5.4	14.9	6.7
CB$_P$	5	13.9	5.2	11.1	6.3	12.3	2.7	14.5	5.0
CB$_P$	10	14.3	5.1	14.4	6.2	11.1	4.3	14.8	5.5
CB$_P$	15	15.9	5.0	15.8	8.7	14.6	3.5	13.9	5.3
CB$_P$	20	12.4	4.8	10.9	6.2	14.0	3.9	12.9	4.8

increases up to 15%, and then decreases, as the content of CB or CBp increases. The M_R at 25°C shows a similar trend to M_R at 5°C. The measured average M_R for slag mixtures at both temperatures is around 13 GPa at 5°C and 5 GPa at 25°C, respectively. Figure 7 shows an example for the M_R as the testing temperature change. The Marshall compacted samples show larger rates of changes for M_R than the gyratory compacted specimens.

Table 10 shows the effect of different compaction method for M_R. The M_R for Marshall compacted specimens is higher than

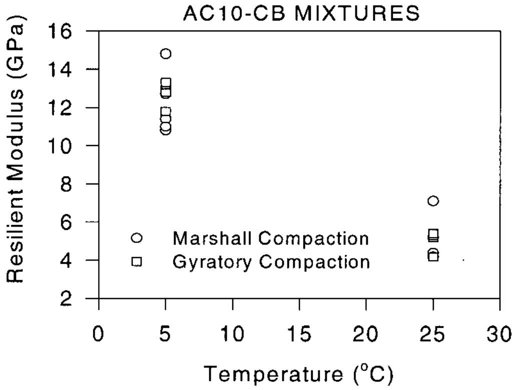

Figure 7. Temperature Change of M_R for AC10-CB Mixtures

Table 10. Summary of the Effect of the Compaction Method for Slag Mixtures

Additive	AC-10		AC-20	
	5°C	25°C	5°C	25°C
CB	M 〈 G	M 〉 G	M 〈 G	M 〉 G
CB$_P$	M 〉 G	M 〉 G	M 〈 G	M 〉 G

M : Marshall Compaction, G : Gyratory Compaction

Table 11. The Summary of Tensile Strength

Aggregate		Slag			
Compaction		Marshall		Gyratory	
Additive	%	AC-10	AC-20	AC-10	AC-20
	0	2056	3120	2720	3109
CB	5	2827	3004	2905	3562
CB	10	2848	3293	3234	3231
CB	15	3422	3550	3368	3209
CB	20	3290	3509	3390	3302
CB_p	5	2766	3328	2992	3344
CB_p	10	3048	3309	3172	3379
CB_p	15	3051	3241	3059	3253
CB_p	20	3086	3446	2827	2987

the gyratory compacted specimens at high temperature, 25℃. The possible reason would be the effect of crushed aggregate, which can make higher friction in the mixtures, during the compaction. On the other hand, the M_R for gyratory compacted specimens, except AC-10 CB_p mixtures, is higher than for Marshall compacted specimens. The possible reason would be the orientation of aggregate particles, which can make for tighter mixtures, during compaction. According to the recent study of Asphalt-Aggregate Mixture Analysis System (AAMAS), (Von Quintus and Kennedy, 1988), the gyratory compaction proved to simulate field condition, especially field particle orientations. Considering these results, the use of M_R for Marshall compacted specimens is overestimated at high temperature and underestimated at low temperature.

The effect of the Gyratory compaction done by Busching and Goetz (1964) shows different particle orientation of the mixtures. The major advantage of using the gyratory compactor is to simulate the particle orientation of compaction in the field. The particle orientation would be the key effect to determine the strength of the asphalt mixtures.

4.8 Indirect Tensile Strength

The test results are shown in Table 11. The variation of tensile strength for the gyratory compacted specimens is less than that for the Marshall compacted specimens. This relation is similar to resilient modulus tests. It means that gyratory compaction shows better reproducibility than the Marshall compaction. For AC-10 mixtures, the tensile strength for the gyratory compacted specimens is slightly higher than that for the Marshall compacted specimens. However, in the case of AC-20 mixtures, the tensile strength is not significant different for either compaction method.

The tensile strength of CBp mixtures for both asphalt grade and compaction method is higher than that of CB mixtures at relatively low additive content, up to 10%. On the other hand, the tensile strength of CB mixtures is higher than that of CBp mixtures at high content of additives. The possible reason would be that a large amount of CBp could reduce the effective asphalt film thickness in the mixtures because CBp with large particle size acts like mineral filler and fine aggregate. However, CB becomes a part of asphalt cement due to its small particle size when it added into asphalt cement. Therefore, the inclusion of CB would not change the effective asphalt film thickness.

4.9 Hamburg Wheel Tracking Test

Creep Slope

One of test results is shown in Figure 8. Table 12 shows each testing parameter for Hamburg wheel tracking. The higher value of the creep slope means a lower potential for permanent deformation. The creep slope of pure AC-10 mixtures and AC-20 mixtures is 3195 passes/mm and 5208 passes/mm, respectively. The inclusion of CB into AC-10 mixtures produces a significant effect on increasing the creep slope. On the other hand, AC-10 modified CBp decreases the creep slope. The inclusion of CB and CBp for AC-20 mixtures indicate the decrease of creep slope of the mixtures. Based on the results of testing, dynamic confined creep test, the inclusion of CB and CBp decreases permanent deformation of the mixtures at high testing temperature. Although the testing temperature for the dynamic confined creep test and the Hamburg wheel tracking test is same (50℃), the effect of the inclusion of additives is different. The effect of the water is very significant for rutting of the pavement.

Stripping Inflection Point

In the case of AC-10 mixtures, the inclusion of CB and CBp increases the stripping inflection points of the mixtures. The CB mixtures are slightly better for stripping resistance than CBp ones. Table 13 shows the comparison of stripping inflection point of slag mixtures. In the case of AC-20 mixtures, the

Table 12. Testing Parameters

Asphalt		AC-10				AC-20			
Add.	Cont.	Creep slope	Strip. In. Po.	Strip. slope	Poten. resis.	Creep slope	Strip. In. Po.	Strip. slope	Poten. resis.
CB	0 %	3195	7200	235	93	5208	15600	645	87
	10 %	409	10200	267	93	3817	14500	885	77
	15 %	5263	14500	437	92	3003	9600	375	88
CB_p	10 %	2000	7200	364	82	3185	8600	617	80
	15 %	3096	13300	361	88	4132	15300	505	88

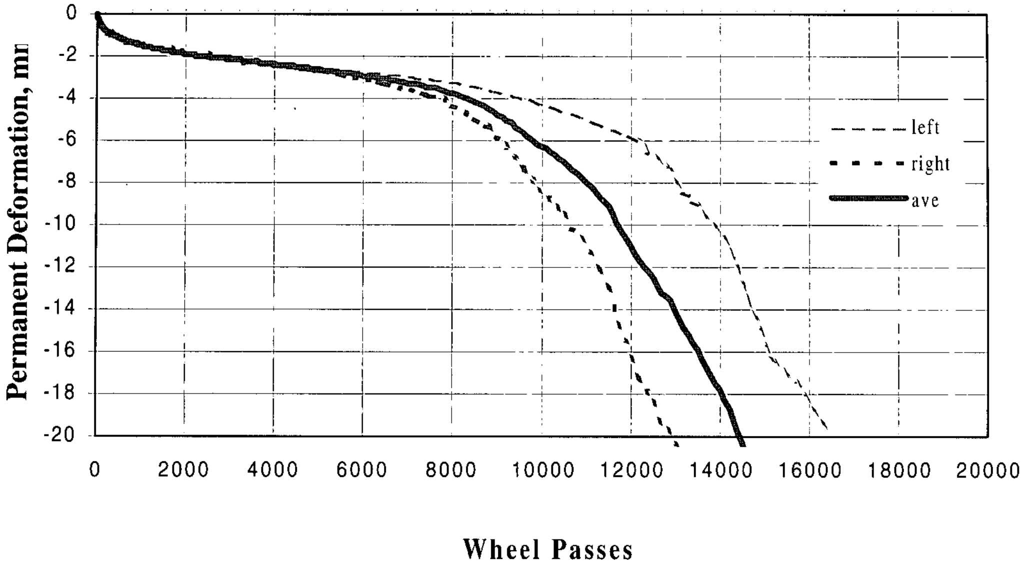

Figure 8. Test Result for AC-10 Mixture with 10% CBp

inclusion of CB and CBp decreases the stripping inflection point of the mixtures. The possible reason would be the high viscosity of AC-20 asphalt.

Table 13. Comparison of Stripping Inflection Point

Binder		AC-10	AC-20
Additive	0 %	7200	15600
CB	10 %	10200	14500
	15 %	14500	9600
CBp	10 %	7200	8600
	15 %	13300	15300

5. Conclusion

Within the limited laboratory testing in this study, the following principal conclusions can be drawn:

(1) As the GTM revolutions increased, air voids deceased. The air voids of AC-10 mixture increased with increasing percent of CB and CBp, but AC-20 mixtures did not show a similar trend. Judging from the change of air voids, about 100 GTM revolutions divided the initial compaction and the traffic densification of the mixtures.

(2) Considering the value of GSI, AC-10 CBp mixtures represented very stable mixtures. The inclusion of CBp had the effect of producing a very stable mixture during long loading application. Only AC-10 mixtures and AC-20 mixtures with 20 percent of CB indicated instability for long loading application due to the flushing of binder.

(3) The AC-10 CBp mixtures represented the best performance of retaining the shear resistance for long loading applications. The

others showed a slight decrease of the shear resistance for long loading applications.

(4) The Marshall stability and logarithm of GTM revolutions showed a linear relationship. The compaction method significantly affects the Marshall stability. The Gyratory compaction is better than Marshall compaction to simulate field condition and to be recommended. The flow of AC-10 mixtures with CB and CBp remained in an acceptable range after long loading application, but that of AC-20 mixtures with CB and CBp was out of range. In all the mixtures, the flow stabilized after long loading applications.

(5) The M_R for slag mixtures at low temperature, 5℃, is around 2 to 3 times larger than at higher temperature, 25℃. The rate of change of M_R is larger for Marshall compacted specimens than for gyratory compacted specimens. The effect of compaction method for the M_R is relatively significant. The Marshall compaction shows relatively poor reproducibility, however, gyratory compaction does not. The use of M_R for Marshall compacted specimen is overestimated at high temperature and underestimated at low temperature. The grade of asphalt has a significant effect on the M_R and tensile strength of the mixtures. The higher asphalt grade, the higher M_R and tensile strength. The inclusion of CB and CBp produces an increase of M_R and tensile strength. In the case of AC-10 mixtures, CBp can produce a more dominant difference than CB at low temperature, however, CB is better than CBp at high temperature.

(6) AC-10 mixtures modified with CB produce higher creep slopes than with CBp. However, the inclusion of CB and CBp in AC-20 mixtures reduces the creep slope, which means that AC-20 mixtures modified by CB and CBp are more sensitive to rutting than unmodified AC-20 mixtures.

(7) The additives, CB and CBp, for AC-10 mixtures increase the stripping inflection point. However, for AC-20 mixtures a poor effect is produced, because AC-20 asphalt has a high viscosity. The inclusion of CBp in AC-10 mixtures and AC-20 mixtures shows better performance than that of CB for retaining its original rutting resistance after the mixtures are stripping.

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