Evaluation of the Asphalt Mixture Performance with Waste Materials

Lee, Kwan-Ho*[1]

Lovell, C, W*[2]

요 지

본 논문의 주된 목적은 폐자원(첨가제로서 pyrolyzed carbon black과 굵은 골재로서 air-cooled iron blast furnace slag)을 사용한 아스팔트 콘크리트의 기본특성을 설명하는 것이다. 최적의 아스팔트 함유량을 결정하기 위하여 Marshall Mix Design 방법을 이용하였고, 최적의 아스팔트 함유량은 첨가제의 양에 따라 변하며, 그 범위는 6.7%에서 7.57%로 나타났다. 최적의 아스팔트 함유량을 이용하여 아스팔트 콘크리트 시편을 제작하였고, dynamic creep 실험을 수행하였다. Pyrolyzed carbon black과 Furnace slag의 사용은 Marshall stability를 증가시켰고, 비교적 높은 온도(50℃)와 137.9kPa의 구속 압력하에서 아스팔트 콘크리트의 시간에 따른 변형률을 감소시켰고, 또한 시간에 따른 아스팔트 콘크리트의 stiffness감소 비율을 줄여주는 역할을 하였다.

본 실험결과로 부터 첨가제로서의 pyrolyzed carbon black과 굵은 골재로서의 slag의 사용은 Marshall stability, stiffness, rutting resistance에 좋은 결과를 나타내는 것으로 밝혀졌다.

Abstract

The objective of this paper is to evaluate the asphalt mixture performance with pyrolyzed carbon black(CB_p) and air-cooled iron blast furnace slag. Marshall mix design was performed to determine the optimum binder content. The optimum binder content ranged from 6.3 percent to 7.75 percent. Dynamic creep testing was carried out using mixtures at the optimum binder content. Based on the test results, the use of pyrolyzed carbon black and slag in the asphalt pavement showed a positive result, such as the increase of Marshall stability, the decrease of the strain rate and the decrease in the mix stiffness rate at high temperature(50℃) and 137.9 **kPa** confinement. Within the limits of this research, it was concluded that pyrolyzed carbon black as an additive and slag as a

*[1] Member, Research Assistant, Geotechnical Engineering, Purdue University, W. Lafayette, IN 47907

*[2] Professor, Emeritus, Geotechnical Engineering, Purdue University, W. Lafayette, IN 47907

coarse aggregate could be used to produce an asphalt paving mixture that has good stability, stiffness, and rutting resistance.

Keywords : Pyrolyzed Carbon Black, Slag, Scrap Tires, Marshall Mix Design, Dynamic Confining Creep Test, Strain Rate, Mix Stiffness

1. Introduction

Scrap tires which are generated at the rate of over 242 million each year in the United States are recognized as one of the most significant environmental problems. Most of these scrap tires have been stored on or in the ground as landefiling, stockpiling material, and illegal dumping(EPA, 1991). Therefore, an economical and useful technology is needed to deal with the scrap tire problems. Research has been conducted for the utilization of the scrap tires. Especially, the use of scrap tires for asphalt pavement has received major attention. However, this use of scrap tires may be technologically complicated due to the complex behavior of asphalt.

Commercial carbon black(CB) is an intensely black, fine powdery substance. Due to the excellent properties of carbon black, it has been used as a fundamental raw material for rubber, plastic products, printing ink, and so on. Tire companies are one of the large consumers of carbon black, and use two thirds of the commercial carbon black as a reinforcing agent. Pyrolyzed carbon black (CB_p)is one of byproducts of the pyrolysis of scrap tires which typically yields 55% oil, 25% carbon black, 9% steel, 5% fiber, and 6% gas. Pyrolyzed carbon black includes 75% carbon black, a maximum of 9% ash, 4% sulfur, and 12% of minimum butadiene copolymer(Roy et al, 1990).

Slag is a non−hazardous industrial waste which is generated in the amount of about 350 million metric tons per year(Emery, 1982). In this research, the air−cooled blast furnace slag was used for the advantages of low compacted density, high friction angle, good resistance to weathering and erosion, and so on(Ahmed, 1991).

The main purpose of this paper is to evaluate the asphalt mixture performance with waste materials, slag and pyrolyzed carbon black. In order to establish the suitability of the asphalt mixtures, several laboratory tests were conducted at the Indiana Department of Transportation(INDOT). Marshall mix design was performed to determine the optimum binder content and to check the fundamental characteristics of the mixtures, such as air void, unit weight, VMA, VFA, Marshall stability, and flow. Dynamic creep testing using the MTS device was performed to determine the permanent deformation, creep strain rate and mix stiffness rate, and creep strain components.

2. The Properties of Materials Used

2.1 Aggregates

In this paper, air−cooled blast furnace slag from the Levy Company(at Portage, IN) was used as coarse aggregates, and natural sand from the Vulcan Materials(at W. Lafayette, IN) was used as fine aggregates. The air-cooled blast furnace slag produced in North America is used in concrete, asphalt, road base, ballast, and as an all-purpose construction aggregate and fill material(Ahmed, 1991). The relatively low cost and high performance are the major advantages. The main components of iron blast furnace slags are calcium oxide and silicon dioxide. The typical characteristics of air-cooled blast furnace slags are shown in Table 2.1.

Table 2.1 Typical Characteristics of Steel Slag and Air-Cooled Blast Furnace Slag(Noureldin and McDaniel, 1990)

Property	Air-Cooled Blast Furnace Slag	Steel Slag
Bulk Sp. Gravity	2.1~2.5	3.2~3.6
Porosity	up to 5%	up to 3%
Rodded Unit Weight(ASTM C28), kN/m^3	11.8~14.1	15.7~18.8
Los Angeles Abrasion(ASTM C131), %	35~45	20~25
Sodium Sulfate Losses(ASTM C88), %	≤12	≤12
Angle of Internal Friction	40°~45°	40°~50°
Hardness(measured by Moh' scale)	5~6	6~7
California Bearing Ratio(top zize 3/4 inch)	up to 250%	ut to 300%
Unit Weight(kN/m^3)	19.6~22.8	25.1~29.8
Polarity	Alkaline, pH 8~10	Alkaline, pH 8~10
Asphalt Cement Requirements in Dense Grade Mixes	up to 8%	up to 6.5%

* Hardness of dolomite measured on same scale is 3~4.

** Typical CBR value for crushed limestone is 00%.

Table 2.2 The Gradation of Aggregate and Specification for #9 Binder(INDOT, 1993)

Sieve Size	% Passing(Used)	Specific % Passing Range
3/4″(19mm)	100	100
1/2″(12.5mm)	81	70~92
3/8″(9.5mm)	63	50~76
#4(4.75mm)	40	35~45
#8(2.36mm)	32	18~45
#16(1.18mm)	23	10~36
#30(0.6mm)	16	6~26
#50(0.3mm)	10	2~18
#100(0.15mm)	6	0~11
#200(0.075mm)	2	0~4

The Indiana Department of Transportation(INDOT) specification(1993) for #9 binder aggregate was adopted for the target gradation. The upper limit and lower limit gradation for #9 binder and the target gradation are shown in Table 2.2.

The specific gravity test for the coarse aggregate and for the fine aggregate were carried out in accordance with ASTM C127 and ASTM C128 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.

2.2 Binder

In this research, grade AC−10 and AC−20 were used. The main reason is that AC−10 has been used in northern Indiana, and AC−20 has been used in southern Indiana. Also, these two types of asphalt are used very widely in the USA. The physical properties of AC−10 and AC−20 are summarized in Table 2.3

Table 2.3 The Physical Properties of AC−10 and AC−20(INDOT, 1993)

Test	AC−10 (Requirement of Specification)	AC−20 (Requirement of Specification)
Penetration @ 77°F(25℃) (0.1mm), 100g, 5sec	87~106 (70~140)	53~65 (50~110)
Kinematic Viscosity @ 275°F (135℃), Centistokes, Min.	316 (250)	406 (300)
Absolute Viscosity @ 140°F (60℃), Poise, Max.	2670 (4000)	5497 (8000)
Flash Point, Cleveland Open Cup, ℃), Min.	99,9 (99.0)	99.95 (99.0)
Ductility @ 25℃, 5Cm/min Cm, Min.	60 (60)	60 (40)

2.3 Additive

Pyrolyzed Carbon Black(CB_p)

Vacuum pyrolysis is an established concept. Pyrolysis of tires involves the application of heat to produce chemical changes and to derive various products such as oil and carbon black. Vacuum pyrolysis minimizes secondary reactions such as thermal cracking, repolymerization and recondensation reactions, gas phase collision, oxidation reductions, and so on(Roy et al, 1990).

The pyrolyzed carbon black used in this research was provided by an industry in Indiana.

The information provided by Wolf Industries specified that pyrolysis is a method of decomposing tires by a cooking process in order to break down the tire rubber into salable byproducts.

Pyrolyzed carbon black contains 9% ash, 4% sulfur, 12% butadiene copolymer(nitride rubber), and 75% carbon black. This carbon black could partially replace commercial blacks for the preparation of low-grade rubber parts(Roy et al, 1990). More than 90% of the pyrolyzed carbon black passes through the #200 sieve. According to test results provided by Wolf Industries, pyrolyzed carbon black is insoluble in water.

The main characteristics of a representative carbon black sample produced under vacuum at 525℃ are summarized in Table 2.4. Pyrolyzed carbon black is blended with asphalt. The particles of pyrolyzed carbon black are much coarser than commercially available high structure HAF(High Abrasion Furnace)type carbon black ; however, most of the coarse particles are easily broken down by normal pressure. The color is lighter black than HAF type carbon black.

Table 2.4 General Properties of Carbon Black Produced during Vacuum Pyrolysis of Used Tires(Roy et al, 1990, Park, 1995)

Property	Value
Iodine Index(mg/g)	144.2~151.4
DPB Absorption(ml/100g)	84.6~93.0
Heat Loss at 105℃(%)	0.4~1.0
Tint Strength(% ITRB)	57.1~60.6
ASH(%)	15.5~17.0
Volatile Matter	3.3~4.9
S(%)	2.5~3.0

Note : Ultimate temperature was 525℃ and total pressure varied between 1.5 and 4.5 kPa. (Feedstock included both regular and belt used tire samples.)

Carbon Black

Carbon black is the sole product formed in a vapor phase from the decomposition of vaporized hydrocarbons. As defined by Powell(1968), carbon black is formed by incomplete combustion of many organic substances such as solid, liquid, and gas. The major distinct characteristics are small particle size(the mean diameter of 100 to 500 nanometers) and large specific surface(15 to over $100m^2/g$), hydrophobic materials, and irregular particle shapes(from clustered to branched forms).

Carbon black used in this research was purchased from an industry in Boston, Massachusetts. The analytical specifications of this carbon black are given in Table 2.5.

As can be seen in Table 2.5, densities are 0.21 ± 0.048 g/cm^3, ash content is a maximum of 1.0 percent, iodine index is 76 ± 5 mg/g, Dibutyl Phthalate absorption is 85 ± 5 cc/100g, and tint strength is $113 \pm 5\%$ ITRB.

Table 2.5 Analytical Specifications for Carbon Black(CABOT, 1994, Park, 1995)

Property	Test Method	Specification
Density(g/cm^3)	ASTM D1513	0.21±0.048
Ash(%)	ASTM D1506	1.0 max
Iodine Index(mg/g)	ASTM D1510	76±5
Tint Strength(% ITRB)	ASTM D3265	113±3.0
Dibutyl Phthalate Absorption(cc/100g)	ASTM D2414	85±5

3. Experimental Background

3.1 Marshall Mix Design

The prepared asphalt cement in 5 quart cans was heated between 145℃ and 150℃ for an hour in order to get good coated mixtures. The content of pyrolyzed carbon black and carbon black is based on the weight of asphalt. 5%, 10%, 15%, and 20% of CB_p and CB were adopted for the research, because previous carbon black modified asphalt concrete study (Yao and Monismith, 1986) showed that carbon black contents between 10% and 15% have resulted in enhanced rutting resistance and less cracking. The Hobart mechanical mixer was used at the low speed setting. The mass of 1200 grams of the blended aggregate for one batch was heated more than 3 hours in the oven in order to eliminate the moisture in the aggregate. Three samples were prepared for each asphalt content with additive(carbon black and pyrolyzed carbon black). After mixing with asphalt and aggregate, the mixtures were put into the oven(145℃) for about 3 hours to produce absorption of asphalt cement.

Table 3.1 INDOT Marshall Specifications(1993)

Mix Criteria	Min.	Max.
Compaction(No. of blows each side of specimen)	75	75
Stability(KN)	5338	–
Flow(*0.254mm)	6	16
Percent of Air Voids	4.0	8.0
Perecent Voids in Mineral Aggregate(VMA)		
• 3/8"(9.5mm) of Nominal Maximum Particle Size	16	–
• 1/2"(9.5mm) of Nominal Maximum Particle Size	15	–
• 3/4"(19.0mm) of Nominal Maximum Particle Size	14	–
• 1/0"(25.0mm) of Nominal Maximum Particle Size	13	–
Base 5D Mixtures	12	–

Note 1) The nominal maximum particle size is the largest sieve upon which any material will be permitted to be retained.
2) The percent air voids for base 5D mixture shall be 3.0 to 5.0.
3) The optimum bitumen content shall be the bitumen content that procedure 6.0% air voids for all mixtures except base 5D[401.04(b)].

A number of 75 blows per side, which represented high traffic volume, was used for compacting effort. The other procedures followed were ASTM D−1557 and MS−2(1988). In this project, the INDOT criteria were used to determine the optimum binder content, as shown in Table 3.1.

3.2 Dynamic Confining Creep Test

Concept of the Creep Deformation in Asphalt Concrete

Asphalt concrete is usually defined as viscoelastic material. With viscoelastic materials, the longer the time to reach the final value of stress(lower stress rate), the larger is the coresponding strain. The Burgers model is.considered as the best representation for the behavior of asphalt concrete. The creep behavior in the Burgers model is described in Equation 3-1.

$$\varepsilon(t)=\frac{\sigma_0}{E_1}+\frac{\sigma_0 {}^{*}t}{\eta_1}+\frac{\sigma_0}{E_2}\left(1-e^{\frac{-E_2{}^{*}t}{\eta 2}}\right) \qquad (3\text{-}1)$$

where σ_0 : applied stress

E_1 and E_2 : spring constant

η_1 and η_2 : Newtonian dashpot

Equation 3-1 shows that the application of a stress, σ_0 induces an instantaneous elastic strain, σ_0/E_1, followed by an additional retarded elastic strain and an indefinite viscous flow. If the stress is released at some time t_1, an immediate elastic recovery equal to σ_0/E_1 takes place, followed by gradual decrease in the strain to a permanent value of $(\sigma_0\ t_1/\eta)$. The Brugers model is thought to give the best model representation for the behavior of sol−gel asphalt.

With the Burgers model as a background, Perl et al(1983) suggested that the total strain(ε_t) of asphalt concrete is composed of four components : elastic strain(ε_e), plastic strain(ε_p), viscoelastic strain(ε_{ve}), and viscoplastic strain(ε_{vp}).

Each strain component is shown in Figure 3.1.

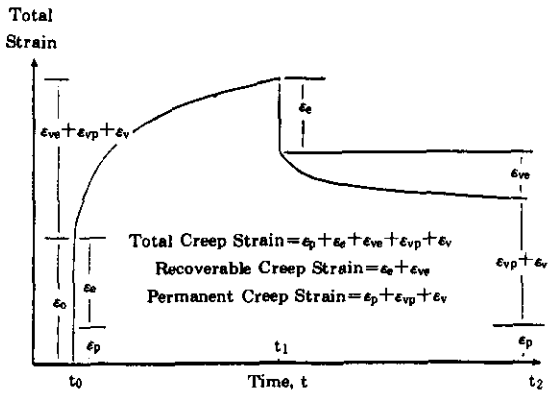


Fig. 3.1 Creep Behavior of Asphalt Concrete (Perl et al, 1983)

Mix stiffness of Mixtures

The creep modulus is calculated, based on the recorded deformation and applied stress, as a function of loading time and temperature using the following equation(Hill, 1974).

$$S_{mix}(T, t) = \frac{\sigma}{\varepsilon_t} \quad (3\text{-}2)$$

where S_{mix} : mix stiffness at a specifed temperature(T) and loading time(t)

σ : applied stress(psi), and

ε_t : axial strain at, t, and is defimed $\Delta h/h$ where Δ h is change in height of specimen, and h is original height of speciemen.

Testing Equipment and Procedure

Creep testing was carried out on a Material Test System(MTS, 1994) and a feed back control hydraulic tester with a temperature controlled environmental chamber. A MTS model 810 was employed as a loading and measuring device. An Automated Testing System(ATS) software collected and analyzed the testing data. The testing procedure is shown in Figure 3.2.

According to the Marshall testing results, the testing specimens were prepared at each optimum asphalt content and at 6% of air voids. The testing specimens with 4 inch diameter were compacted with 75 blows per each face, which simulates high traffic volume. However, it was very difficult to make specimens with exactly 6% of air voids owing to the relatively poor reproductibility of Marshall method. The deviation of voids was limited to ± 1.0%.

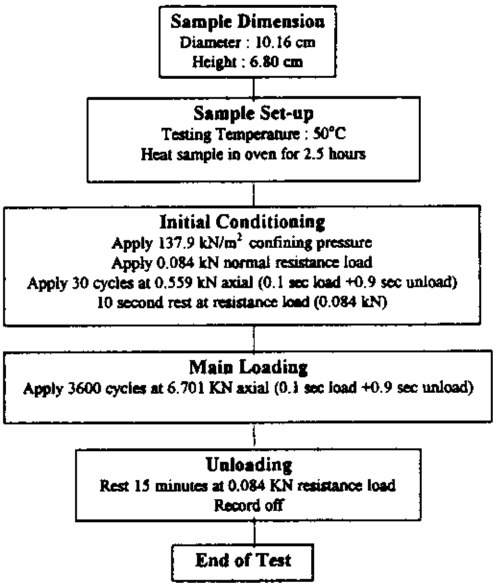


Fig. 3.2 Testing Procedure for Dynamic Confining Creep

4. Result and Discussion

4.1 Marshall Mix Design

4.1.1 Air Voids

Figure 4.1 represents the relationship between air voids and CB content for AC−10 and AC−20. It is noted that air voids increase slightly as the carbon black content increases for both bitumen grades and as the binder content decreases. This is the similar trend to the one reported by Khadaywi(1988) using oil−shale−ash modified binder.

In general, the trend of variation for CB_p mixtures was similar to CB mixtures. However, the changing rate of air voids in CB_p mixtures is larger than that of CB mixtures. The main reason for this difference was due to the particle size of CB_p and CB, and the resultant degree of dispersion in asphalt cement. The non−uniformity in particle shape of CB_p also plays a key role in the increase of the air voids of the mixtures.

4.1.2 Marshall stability

Figure 4.2 represents the relationship between stability and CB and CB_p content for AC−10 and AC−20 mixtures. The average stability of each case was about 17792 kN to

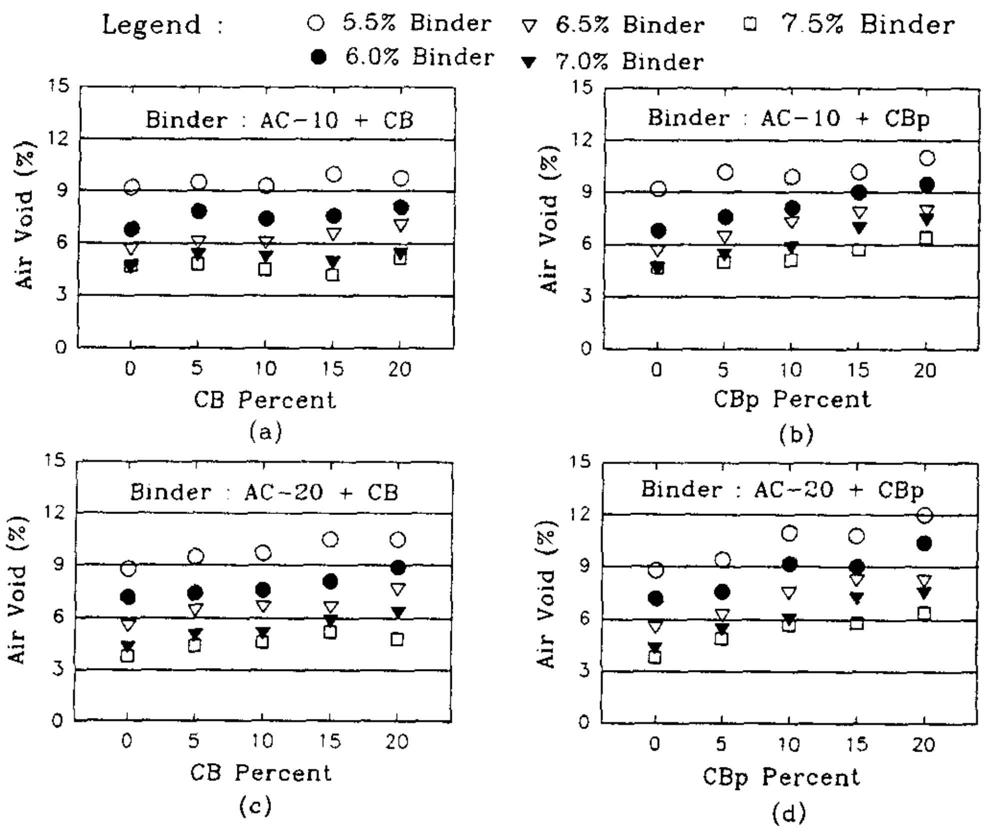


Fig. 4.1 The Relationship between Air-Voids and CB and CB_p Content

19571 kN. The recommended minimum stability is 5338 KN by INDOT, 2224 kN by the US Army Corps of Enginers, and 8006 kN by the Asphalt Institute. The effect on stability by adding CB varies case by case(Figure 4.2(a) and (c)), but the stability increase of AC−10 mixtures as CB content increases, was larger than that of AC−20 mixtures. Considering the binder content, 7% of binder content for AC−10 and AC−20 mixtures showed a relatively higher stability. Also, 10%, 15% and 20% of CB content for AC−10 mixtures showed some increase in stability. This result agrees with the general trend reported by Rostler et al(1977), and Vallerga et al(1957).

The test results for AC−10 and AC−20 mixtures with CB_p are inconsistent(Figure 4.2 (b) and (d)). The average stability is about 18682 kN to 21350 kN for AC−10 mixtures, and about 19126 kN to 22685 kN for AC−20. The variation of stability for both cases was about 20%. The 7.0% and 7.5% of binder contents for both cases showed relatively good results. The effect of incluaing CB_p was more significant for AC−10 mixtures than for AC−20 mixtures. The increase of Marshall stability showed at 10%, 15%, and 20% of CB_p for AC−10 mixtures and 15% and 20 of CB_p for AC−20 mixtures.

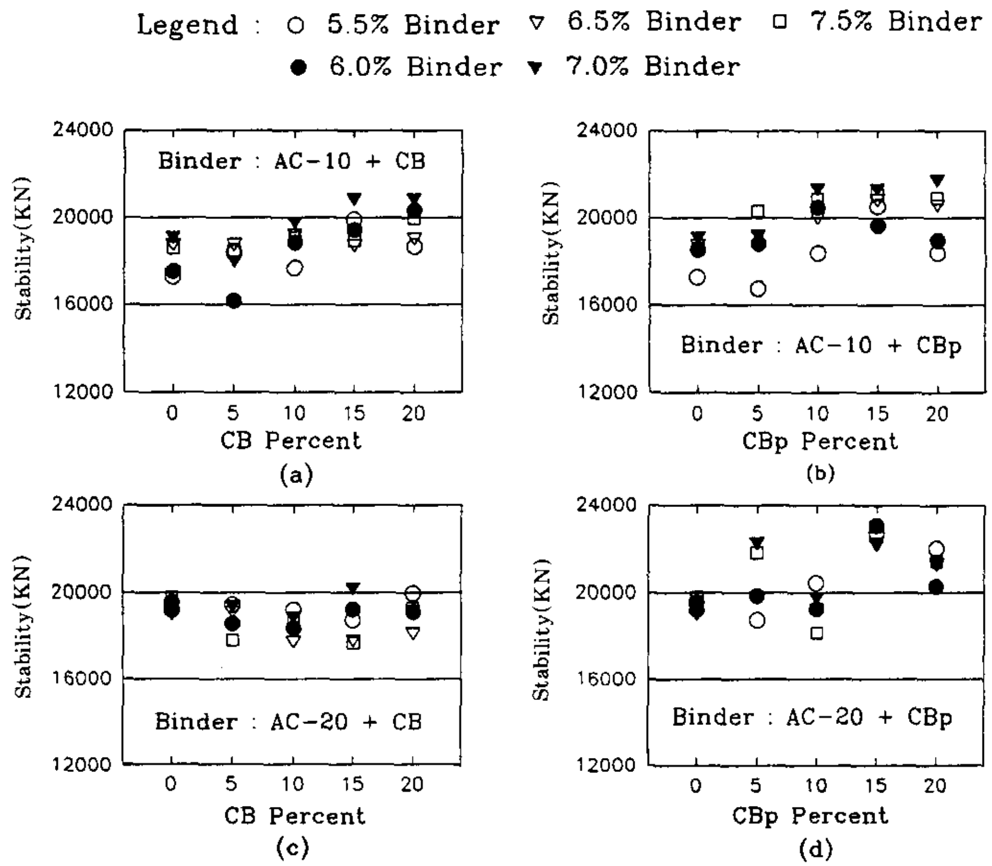


Fig. 4.2 The Relationship between Marshall Stability and CB/CB_p Content

4.1.3 The Optimum Binder Content

The Indiana Department of Transportation(INDOT) specification(1993) was used to determine the optimum binder content. Table 4.1 shows the optimum binder content at 6% of air voids by INDOT specification and the other characteristics at the optimum binder content. The optimum binder contents for AC－10 and AC－20 mixtures increase as the pecent of CB and CB_p increases. The increase is caused by the absorption of asphalt by CB and CB_p.

For AC－10 mixtures, the optimum binder content with CB was lower than that with CB_p at the same content. The main cause is the difference of the particle size of CB and CB_p. In the case of CB, carbon black would become a part of the asphalt cement. On the other hand, some of the CB_p should be a part of the asphalt cement, and the others should act like the fine aggregate or mineral filler. The same phenomena were noted for AC－20 mixtures. It was noted that the optimum binder content for the AC－20 mixtures was slightly higher than that for AC－10 mixtures at the same content of CB and CB_p.

Table 4.1 Summary of the Optimum Binder Content

Binder	Optimum Binder Content	Unit Weight (kN/m³)	Stability (kN)	Flow (*0.254mm)	VMA (%)	VFA (%)
AC－10	6.3	38410	18503	10.9	13.7	57
5%CB	6.6	38410	18414	12.1	15.1	60
10%CB	6.6	38573	19571	11.9	14.4	58
15%CB	6.7	38437	19749	13.3	16.8	64
20%CB	6.87	38518	20282	13.3	14.4	57.5
5%CBp	6.67	38464	19259	12.0	16.2	63
10%CBp	7.0	38328	21128	12.5	14.6	58
15%CBp	7.33	38274	21217	13.1	16.3	60.3
20%CBp	7.7	38111	21217	12.3	16.0	61.5
AC－20	6.4	38437	19215	11.6	14.8	60
5%CB	6.6	38437	19081	12.6	14.6	58
10%CB	6.7	38545	18005	13.5	15.8	62
15%CB	6.85	38464	18948	13.5	15.8	62
20%CB	7.1	38464	18859	14.4	17.5	65
5%CBp	6.7	38328	20994	12.8	13.7	57
10%CBp	7.2	38247	18770	13.2	17.4	66
15%CBp	7.45	38220	22951	12.3	17.7	65
20%CBp	7.75	38111	21251	13.4	18.7	67.5

4.2 Dynamic Confining Creep Test

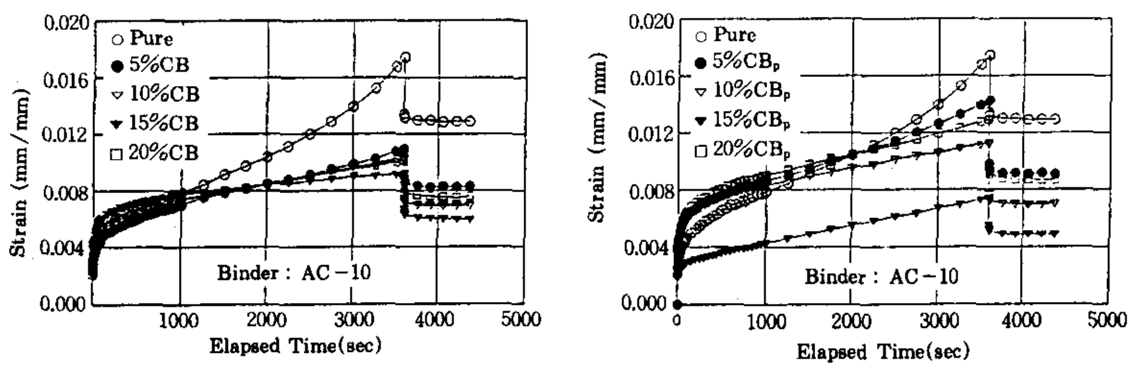
4.2.1 Strain of Mixture

- AC − 10 Mixtures

Figure 4.3 shows the summary of the strain for AC−10 mixtures with carbon black (CB) and pyrolyzed carbon black (CB_p). As shown in Figure 4.3(a), the testing results showed two different types of strain curve. The result for AC−10 mixtures without CB shows almost ideal behavior of a viscoelatic material, which can be simplified and classified into elastic behavior, plastic behavior, and viscoelastic behavior. The other results for AC−10 mixtures with CB are almost identical. The maximum strain that the mixtures experienced at 1 hour was 0.0174(mm/mm). According to Garbrielson(1992), the strain less than 0.1 mm/mm represents a good performance for pavement and the strain larger than 0.1 m/mm predicts a rutted pavement. Considering these criteria, all of the test results showed a good quality and performance, although the testing results indicated some variation.

As can be seen in Figure 4.3 (b), the results for AC−10 mixtures with CB_p showed almost identical trends, except for the initial strain between 0 sec to 100 sec. Only the AC−10 mixture with 15% of CB_p showed smaller intial strain than AC−10 mixtures without CB_p. The maximum strains which the specimens experienced are still small, about 0.075 to 0.0174 mm/mm. Those mixtures with CB_p can be considered as mixtures with good quality and performance.

Table 4.2 shows the strain rate for the AC−10 mixtures. The strain rate of an AC−10 mixture without CB was $3.36*10^{-4}$ mm/mm/sec. The strain rates for AC−10 mixtures with CB were in the range from $0.66*10^{-6}$ mm/mm/sec. The inclusion of CB for AC−10 mixtures has a significant effect, reducing the creep strain rate more than 100%. The AC−10 mixture with 15% of CB shows the smallest strain rate.



(a) (b)

Fig. 4.3 The Relationship between Creep Strain and Elapsed Time(AC−10 Mixture)

The strain rate of the mixtures with CB_p were in the range form $1.22*10^{-6}$ to $2.08*10^{-6}$mm/mm/sec as shown in Table 4.2. Similarly, the inclusion of CB_p had significant effect on reducing the creep rate. The mixtures with 10% and 15% of CB_p showed the lower creep rates than others.

Table 4.2 Summary for the creep strain rate

Type	Creep Strain Rate (mm/mm/sec)	Type	Creep Strain Rate (mm/mm/sec)
AC-10	$3.34*10^{-6}$	AC-20	$2.44*10^{-6}$
5% CB	$1.55*10^{-6}$	5%CB	$2.44*10^{-6}$
10% CB	$1.64*10^{-6}$	10%CB	$0.79*10^{-6}$
15% CB	$0.66*10^{-6}$	15%CB	$1.07*10^{-6}$
20% CB	$1.04*10^{-6}$	20%CB	$0.89*10^{-6}$
5% CB_p	$2.08*10^{-6}$	5%CB_p	$0.97*10^{-6}$
10% CB_p	$1.22*10^{-6}$	10%CB_p	$0.77*10^{-6}$
15% CB_p	$1.23*10^{-6}$	15%CB_p	$0.81*10^{-6}$
20% CB_p	$1.51*10^{-6}$	20%CB_p	$0.68*10^{-6}$

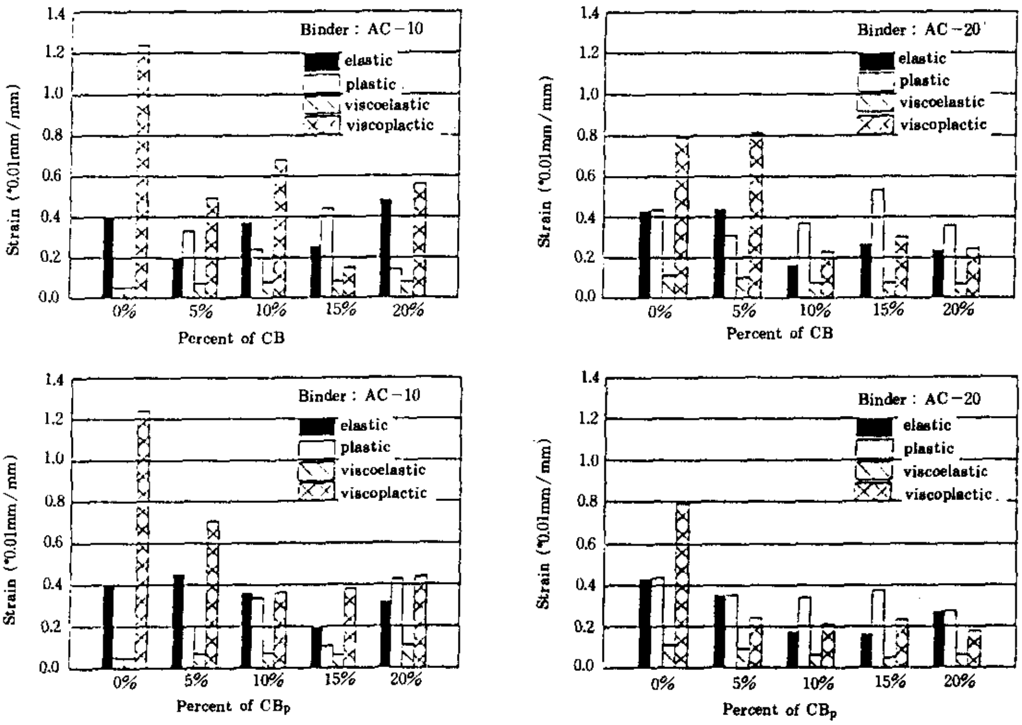


Fig. 4.4 Creep Strain Component(AC-10 and AC-20 Mixtures)

Strain components for each mixture is shown in Figure 4.4. The principal strains for the AC－10 mixture without CB are the elastic strain and the viscoplastic strain. The plastic strain and the viscoelastic strain are very small. The viscoelastic strain is independent of the CB content. In all the mixtures, the viscoelastic strain is a very small portion, less than about 0.001 mm/mm. The change in elastic strain owing to inclusion of CB is not significant. However, it is noted that the plastic strain increased and the viscoplastic strain decreased very much owing to the inclusion of CB. From this Figure, the inclusion of CB has a significant effect on the decrease of the viscoplastic strain. The viscoplastic strain is time－dependent, and this long term strain can be reduced by inclusion of CB. From Figure 4.4, elastic strain and viscoelastic strain are almost the same for every mixture. In particular, the viscoelastic strain is independent of the inclusion of CB_p

• AC－20 mixtures

As shown in Figure 4.5(a), the results for AC－20 mixtures without CB and with 5% of CB show ideal behavior for a viscoelastic material. The inclusion of a small amount of CB did not have an effect on the creep strain. The results for AC－20 mixtures with 10%, 15%, and 20% of CB showed almost identical trends except for the amount of the initial creep strain.

As shown in Figure 4.5(b), the results for AC－20 mixtures with CB_p showed almost identical trends. The effect caused by the inclusion of CB_p was significant for all cases. The permanent deformation at 1 hour decreased more than about 0.005 mm/mm.

Considering the creep rate shown in Table 4.2, the inclusions of CB_p had a great effect on the strain rate. On the other hand, the result for AC－20 mixture with 5% of CB, and the inclusion of a small amount of CB_p, about 5% by asphalt weight, showed a relatively good performance in the creep test.

The summary of the creep strain rate is shown in Table 4.2. Except for AC－10 mixtures with 5% of CB, all cases indicated a benefit owing to the inclusion of CB. The creep rate was decreased, owing to the inclusion of CB, more than 100%.

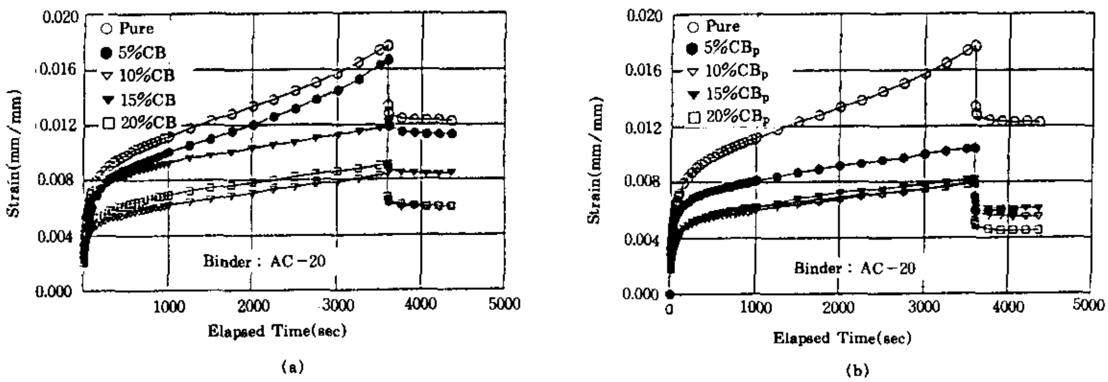


Fig. 4.5 The Relationship between Creep Strain and Elapsed Time(AC－20 Mixture)

The strain components for each mixture are shown in Figure 4.4. The major strains for AC−20 mixtures are the elastic strain, the plastic strain, and the viscoplastic strain. On the other hand, for AC−10 mixtures without CB, the plastic strain is one of major strains. The elastic strain decreased owing to the inclusion of CB except for the mixtures with 5% of CB. The change of the plastic strain does not show a specific trend. The main effect caused by the inclusion of CB is the decrease of the viscoplastic strain. The situation is similar for AC−10 mixtures.

Each strain component for the AC−20 mixtures with CB_p is similar to AC−20 mixtures with CB. The effect of the inclusion of CB_p is also similar to that of AC−20 mixtures with CB.

4.2.2 Mix Stiffness

• AC−10 Mixtures

Figure 4.6 shows the summary for the mix stiffness of AC−10 mixtures with CB and CB_p. As shown in Figure 4.6, there was some difference for initial mix stiffness at 1sec, but the trend for the change of stiffness with time was quite similar. In fact, rutting problems are mainly dependent on time and temperature. Therefore, the change of stiffness with time is more important than the initial mix stiffness. With this concept as a background, the mix stiffness rate(dS_{mix}/dt) was calculated and is shown in Table 4.3. The mix stiffness rate with time for pure AC−10 mixtures is $-3.93*10^{-3}$ kPa/sec. The inclusion of CB for AC−10 mixtures resulted in slightly decreasing mix stiffness rates, $-3.86*10^{-3}$ kPa/sec. for 10% of CB to $-2.21*10^{-3}$ kPa/sec for 15% of CB. Among then, the mixtures with 15% of CB had better mix stiffness rates than the others. After 1000 sec in the creep test, the mix stiffness rate rapidly decreased for all cases except the mixtures with 15% of CB. The CB mixtures are generally more stable than the mixtures without CB.

The mixtures with CB_p showed almost identical trends for each CB_p content, although the initial mix stiffness is different. As shwon in Figure 4.6(b), the mix stiffness for the

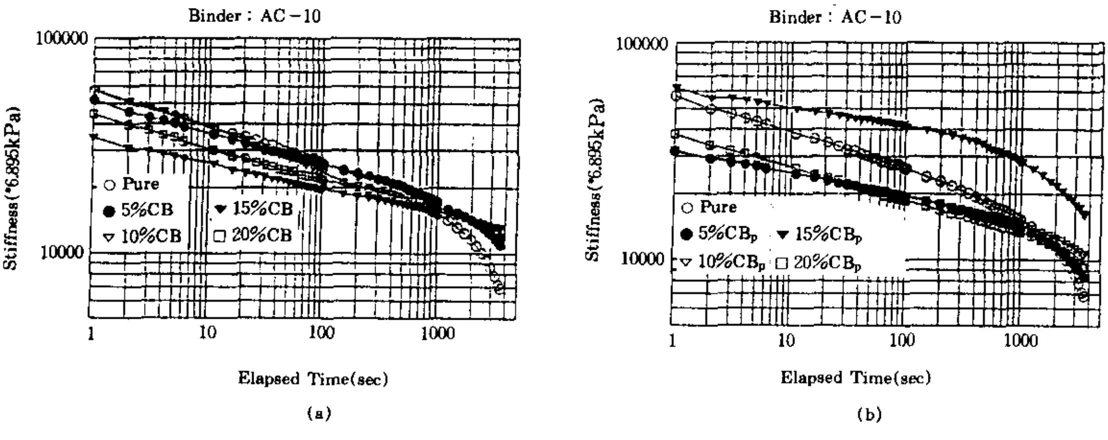


Fig. 4.6 The Relationship between Mix Stiffness and Elapsed Time(AC−10)

mixtures without CB_p decreased more rapidly than the mixtures with CB_p, as time elapsed. Among the test results, the mixtures with 15% of CB_p show best performance for the creep test. Also, the inclusion of CB_p decreased the mix stiffness rate as shown in Table 4.3. This means that the mixtures with CB_p reatined their initial mix stiffness longer than the mixture without CB_p. The main reason that the mixtures with CB_p show better performance is that the CB_p serves as a microfiller to improve the gradation effect and mineral filler to reinforce the binder stiffness. Larger particles work as mineral filler, and smaller particles work as microfiller. However, the mix stiffness decreased rapidly for all cases after 2000 sec of creep testing. This means that the viscoplatic strain may increase with time.

Table 4.3 Summary for the Mix Stiffness Rate

Specimen	Mix Stiffness Rate (kPa / sec)	Specimen	Mix Stiffness Rate (kPa / sec)
AC−10	$-3.93 * 10^{-3}$	AC−20	$-4.07 * 10^{-3}$
5% CB	$-3.03 * 10^{-3}$	5%CB	$-4.55 * 10^{-3}$
10% CB	$-3.86 * 10^{-3}$	10%CB	$-3.03 * 10^{-3}$
15% CB	$-2.21 * 10^{-3}$	15%CB	$-3.10 * 10^{-3}$
20% CB	$-2.76 * 10^{-3}$	20%CB	$-3.45 * 10^{-3}$
5% CB_p	$-2.41 * 10^{-3}$	5%CB_p	$-2.69 * 10^{-3}$
10% CB_p	$-2.28 * 10^{-3}$	10%CB_p	$-2.90 * 10^{-3}$
15% CB_p	$-2.28 * 10^{-3}$	15%CB_p	$-3.45 * 10^{-3}$
20% CB_p	$-3.03 * 10^{-3}$	20%CB_p	$-3.27 * 10^{-3}$

- AC −20 Mixtures

The mixtures with CB show similar trend to AC−10 mixtures with CB(Figure 4.7 (a)). The inclusion of CB produced a slightly decreased mix stiffness ratio. Mixtures with 10%

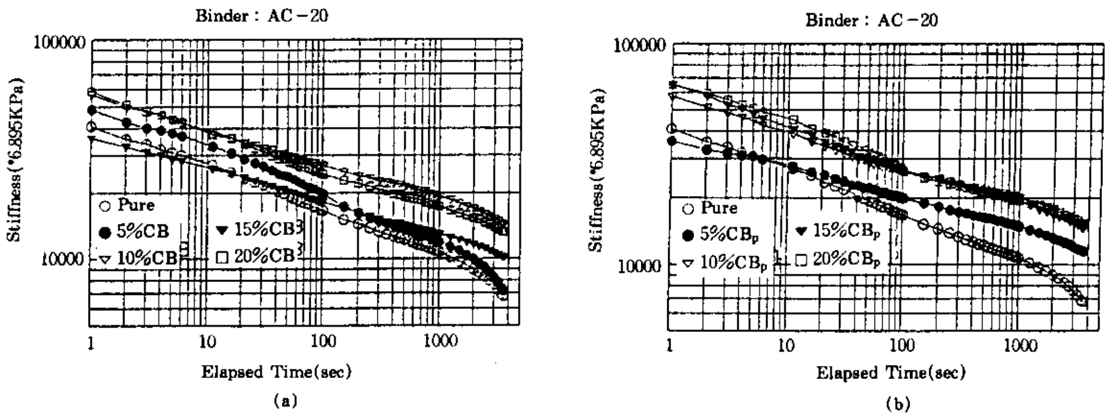


Fig. 4.7 The Relationship between Mix Stiffness and Elapsed Time(AC−20)

of CB showed better performance than the others. On the other hand, the mixtures with 5% of CB were similar to mixtures without CB. Thus, the inclusion of small amount of CB had no effect.

As shown in Figure 4.7(b), the inclusion of CB_p showed significant effects on the mix stiffness for the mixtures with 5% and 10% of CB_p. Considering the mix stiffness rate shown in Table 4.3, mixtures with CB_p showed better performance than mixtures without CB_p.

6. Conclusions

Based on the laboratory testing in this study, the following principal conclusions were drawn :

- There is little doubt that carbon black(CB) as a microfiller becomes an integral part of the asphalt cement owing to its small particle size, about 100 to 150 nanometer. Large particle size of pyrolyzed carbon black(C_p) acts as mineral filler and small particle size acts as microfiller.
- The increase of the content of carbon black or pyrolyzed carbon black tends to increase the air-voids of the mixtures. The variation of air-voids in CB_p mixtures was larger than in CB mixtures owing to the non-uniformity of the particles.
- The use of iron blast furnace slag as an aggregate for binder course of pavement represents a high Marshall stability, on average of 17792 kN owing to the high strength of slag, the high friction angle, and the use of crushed slag(#8 sieve size). Also, as the inclusion of CB or CB_p increases, the Marshall stability increases. However, the effect on the Marshall stability for AC-20 mixtures with carbon black is not as significant as the other cases.
- The inclusion of CB or CB_p has an effect of decreasing the long term viscoplastic strain. The viscoelastic strain is independent of the amount of CB or CB_p. The plastic strain for AC-10 mixtures with CB or CB_p increases as the amount of CB or CB_p added increases. The plastic strain for AC-20 mixtures with CB or CB_p, except for 5% CB, decreases as the content of CB or CB_p increases.
- The inclusion of CB or CB_p tends to decrease the mix stiffness rate. It means that the mixtures with CB or CB_p are more stable than those without CB or CB_p for a long loading duration.
- Within the limited laboratory testing results, the additive content to show better performance is 15% for AC-10 mixtures with CB, 10% for AC-20 mixtures with CB, 10% for AC-10 and AC-20 mixtures with CB_p.

7. Acknowledgement

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