

# The Effects of using Styrene-Butadiene-Styrene and Fly Ash Together on the Resistance to Moisture-Induced Damage, Permanent Deformation and Fatigue of Hot Mixture Asphalt

Taner Alataş\* and Mustafa Ethem Kızırgil\*\*

Received December 14, 2011/Revised May 10, 2012/Accepted September 12, 2012

## Abstract

In this study, the effects of combined utilization of Styrene-Butadiene-Styrene (SBS) in bitumen modification and fly ash in modification of mixtures on the mechanical properties of hot mix asphalts were investigated. Within the scope of this study, 12 different mixtures were obtained by combination of three different proportions of SBS additive relative to the total bitumen mass (0, 3 and 6 wt.%) with four different proportions of fly ash replacement relative to the total aggregate mass (0, 2, 4 and 6 wt.%). As a result of these tests, the use of fly ash was found to reduce the Optimum Bitumen Content (OBC), while the use of SBS increased the OBC. It was determined that the individual utilization of SBS and fly ash improved the stability of the mixtures, resilience at normal temperatures, resistance against moisture-induced damage, fatigue life and strength against permanent deformation. In addition, it was found that using only SBS in bitumen modification at 3 wt.% without using fly ash and the use of only fly ash as filler at a proportion of 6 wt.% with pure bitumen yielded similar results. The combined usage of SBS and fly ash was ascertained to boost the associated positive effects, while a comparison of separate additions showed that SBS is more effective than fly ash. Besides, it was also detected that as the SBS content in the mixture increased, the effectiveness of fly ash decreased.

Keywords: *hot mix asphalt, additive, fly ash, SBS, mechanical properties*

## 1. Introduction

Highway pavements can be constructed in either flexible or rigid forms. Flexible pavements in which bituminous materials are used as binder are substantially preferred to stiff pavements due to their advantages like higher level of comfort and ease of construction. In recent years, demand on highway utilization increased rapidly throughout the world, road traffic became more intense, and axle loads as well as tire pressures escalated. However, pure bitumen and high grade classic asphalt concrete fail to satisfy these rising demands and the expected level of performance. This insufficiency resulted in excessive rutting, fatigue and thermal cracking and hence resulting in shorter service life (Isikyakar, 2009).

A variety of admixtures can be utilized to extend the service life of pavements by preventing or retarding the collapse of pavements without adverse effect to performance parameters of asphalts (Al-Hadidy and Yi-qiu, 2009; Ahmadiania *et al.*, 2011). In this context, a number of appropriate admixtures are available, which can either be directly entrained into the Asphalt Cement (AC) as a binder modifier (Roque *et al.*, 2005), or rather be added into the aggregate containing mixture (Lee *et al.*, 2010). Polymers are the most widely utilized class of materials for the

modification of bitumen, which can be classified into four general categories as plastics, fibers, elastomers, and admixtures/coatings. To improve the properties of bitumen, selected polymer must be able to either change the balance system within the bitumen by entering into a chemical reaction with the binder, or alternatively, generate a secondary network by the assistance of molecular interactions. For this purpose, Styrene-butadiene-Styrene (SBS) thermoplastic elastomer is a commonly preferred block copolymer (Kok and Yilmaz, 2009). According to several studies, the strengths of hot mixture asphalts (HMAs) against permanent deformation, (Ozen, 2011; Wong *et al.*, 2004; Khodaii and Mehrara, 2009) fatigue (Birliker, 1998) and moisture induced damages (Gorkem and Sengoz, 2009; Yilmaz and Kok, 2009) were improved after the use of SBS in bitumen modification.

Fly ash is a type of waste material produced by incineration of ground coal in power plants, obtained by the collection of fine grains in chimney gasses through a dust collection system prior to their release into the atmosphere. It reacts with calcium ions in moist environments to form semi-stable aluminum silicates. It is effectively used in cement industry as pozzolanic admixture. The total annual fly ash output worldwide is about 450 million tons, however merely 6% of this amount is used as cement replacement in concrete products. There are eleven coal-fired power plants in

\*Assistant Professor, Dept. of Civil Engineering, Firat University, Elazığ 23119, Turkey (Corresponding Author, E-mail: talatas@firat.edu.tr)

\*\*Lecturer, Dept. of Civil Engineering, Firat University, Elazığ 23119, Turkey (E-mail: mkizirgil@firat.edu.tr)

Turkey, corresponding to a cumulative annual fly ash generation of 15 million tons, of which only a tiny portion is currently utilized. The recycling of fly ash is important in terms of both economic and environmental aspects. Exploiting fly ash leads to savings of other scarce materials and also saving on landfill space. In various studies, fly ash was employed as an admixture in hot mix asphalts and encouraging results on stability, permanent deformation and fatigue life were obtained (Tapk n, 2008; Tapk n, 2009; Cabrera and Zoorob, 1994; Kumar *et al.*, 2008; Sharma *et al.*, 2010).

Although a number of studies was published regarding the use of SBS for bitumen modification in hot mix asphalts as well as fly ash as filler for mixture modification, little work investigating the combined utilization of these two materials was performed. In this investigation, the effects of combined as well as separate additions of fly ash and SBS on the mechanical properties of hot mix asphalts were evaluated in a comparative way.

## 2. Experimental Materials

The asphalt cement B 160-220 (B<sub>160/220</sub>) was supplied from Batman Refinery of TUPRAS. SBS (Kraton D 1101), a product of Shell Chemical Co., was used as an asphalt modifier, see

Table 1. The Properties of Kraton D 1101 Polymer

| Composition                     | Kraton D 1101         |
|---------------------------------|-----------------------|
| Molecular structure             | Linear                |
| Styrene/rubber ratio            | 31/69                 |
| Specific gravity                | 0.94                  |
| Tensile strength at break (MPa) | 31.8                  |
| Shore hardness (A)              | 71                    |
| Physical form                   | Porous pellet, powder |
| Melt index                      | < 1                   |
| Elongation at break (%)         | 880                   |

Table 1 for various properties. In the previous studies, it was recorded that 2-6 wt.% of SBS in bitumen should be used to improve the properties of base bitumen significantly (Lu and Isacsson, 1997). In this investigation, 3 and 6 wt.% SBS in bitumen were used for bitumen modification. The propeller mixer was used to prepare SBS modified bitumen. Pure bitumen and SBS were mixed for 60 minutes at 180°C inside a mixer with a rotating rate of 1,000 rpm in order to prepare the modified binder. Physical properties of the base and modified binders are presented in Table 2.

Rotational viscosimeter tests were conducted on unaged B<sub>160/220</sub> bitumen, 3 wt.% SBS modified binder (MB<sub>3%SBS</sub>) and 6 wt.% SBS modified binder (MB<sub>6%SBS</sub>) in order to determine the mixing and compaction temperatures of hot mixture asphalts (HMAs) at 135°C and 165°C, respectively. The viscosity values were plotted on the derived temperature-viscosity graph and a regression line was drawn. It is desired that the bitumen binder exhibits viscosities of 170 ± 20 cP for mixing and 280 ± 30 cP for compaction (Zaniewski and Pumphrey, 2004). The temperatures for the corresponding viscosity values were then selected as the mixing and compaction temperatures. To maintain workability, the viscosity value at 135°C should not exceed 3 Pa.s (3000 cP) (McGennis *et al.*, 1994). The results obtained from viscosity tests are given in Table 2, showing that the binder fulfilled the workability requirement. Additionally, viscosity of the binders was found to be increasing with increasing SBS content, hence escalating the required mixing and compaction temperatures.

A crushed limestone aggregate obtained from Karayazi Region of Elazig Province was utilized in the mixture as the aggregate, whose physical properties are summarized in Table 3, and gradation used is presented in Table 4.

The type-F fly ash obtained from Tun bilek Thermal Power Plant was used as the filler, i.e., as the replacement for limestone compound. The chemical composition and physical properties of the fly ash gathered from this plant are listed in Table 5 (Turk and

Table 2. Fundamental Properties of Neat and SBS Modified Binders (MB)

| Properties                                | Standard   | Binder Types         |                     |                     |
|-------------------------------------------|------------|----------------------|---------------------|---------------------|
|                                           |            | B <sub>160/220</sub> | MB <sub>3%SBS</sub> | MB <sub>6%SBS</sub> |
| Penetration (0.1 mm), 100 g, 5 s          | ASTM D5    | 183                  | 112                 | 76                  |
| Softening point (°C)                      | ASTM D36   | 41.7                 | 54.8                | 63.5                |
| Penetration index (PI)                    | -          | 0.28                 | 2.33                | 2.89                |
| Viscosity (cP, 135°C)                     | ASTM D4402 | 212.5                | 562.5               | 825.0               |
| Viscosity (cP, 165°C)                     | ASTM D4402 | 75.0                 | 162.5               | 276.5               |
| Mixing temperature range (°C)             | -          | 132.1-139.1          | 162.2-168.5         | 173.4-181.1         |
| Compaction temperature range (°C)         | -          | 121.0-126.1          | 149.8-155.1         | 158.5-164.9         |
| After Rolling Thin Film Oven Test (RTFOT) |            |                      |                     |                     |
| Mass Loss (%)                             | ASTM D2872 | 0.872                | 0.683               | 0.569               |
| Penetration (0.1 mm), 100 g, 5 s          | ASTM D5    | 89                   | 73                  | 53                  |
| Retained Penetration, (%)                 | -          | 49                   | 65                  | 70                  |
| Softening point (°C)                      | ASTM D36   | 50.5                 | 60.9                | 67.2                |
| Increase in Softening Point (°C)          | -          | 8.8                  | 6.1                 | 3.7                 |
| Penetration index (PI)                    | -          | 0.45                 | 2.25                | 2.52                |

Table 3. Physical Properties of the Aggregate

| Properties                                               | Standard    | Specification limits | Coarse | Fine  | Filler |
|----------------------------------------------------------|-------------|----------------------|--------|-------|--------|
| Abrasion loss (%) (Los Angeles)                          | ASTM D 131  | Max 30               | 29     | -     | -      |
| Frost action (%) (with Na <sub>2</sub> SO <sub>4</sub> ) | ASTM C 88   | Max 10               | 4.5    | -     | -      |
| Flat and elongated particles (%)                         | ASTM D 4791 | Max 10               | 4      |       |        |
| Water absorption (%)                                     | ASTM C127   | Max 2                | 1.37   |       |        |
| Specific gravity (g/cm <sup>3</sup> )                    | ASTM C127   |                      | 2.613  | -     | -      |
| Specific gravity (g/cm <sup>3</sup> )                    | ASTM C128   |                      | -      | 2.622 | -      |
| Specific gravity (g/cm <sup>3</sup> )                    | ASTM D854   |                      | -      | -     | 2.711  |

Table 4. Combined Aggregate Gradation

|                 |     |      |     |      |      |      |     |     |      |       |
|-----------------|-----|------|-----|------|------|------|-----|-----|------|-------|
| Sieve size (mm) | 19  | 12.5 | 9.5 | 4.75 | 2.36 | 1.18 | 0.6 | 0.3 | 0.15 | 0.075 |
| Passing (%)     | 100 | 95   | 88  | 65   | 35   | 23   | 15  | 11  | 8    | 6     |

Table 5. Physical Properties and Chemical Combination of Fly Ash (Turk and Karatas, 2011)

|                 | SiO <sub>2</sub><br>(%) | Al <sub>2</sub> O <sub>3</sub><br>(%) | Fe <sub>2</sub> O <sub>3</sub><br>(%) | CaO<br>(%) | MgO<br>(%) | SO <sub>3</sub><br>(%) | HL<br>(%) | SSA<br>(cm <sup>2</sup> /g) | SG<br>(g/cm <sup>3</sup> ) |
|-----------------|-------------------------|---------------------------------------|---------------------------------------|------------|------------|------------------------|-----------|-----------------------------|----------------------------|
| F class fly ash | 58.82                   | 19.65                                 | 10.67                                 | 2.18       | 3.92       | 0.48                   | 0.91      | 3812                        | 2.08                       |

HL: Heating loss SSA: Specific surface area SG: Specific gravity

Karatas, 2011).

### 3. Testing Methodology

#### 3.1 Determination of Optimum Bitumen Contents

In this study, three different binders (B<sub>160/220</sub>, MB<sub>3%</sub>SBS, MB<sub>6%</sub>SBS) and four different proportions of fly ash (0, 2, 4 and 6 wt.%) were used to produce 12 different mixtures. The optimum bitumen contents of the mixtures containing any one of the binders and 0 or 6 wt.% fly ash were calculated in accordance with Marshall Method. The optimum bitumen contents of remaining mixtures with intermediate fly ash contents were determined on a pro-rata basis. According to General Directorate of Highways of Turkey, the optimum bitumen content is the amount of bitumen at which the stability and bulk specific gravity reach the maximum level, the air void equals 4% and voids filled with asphalt equals 70%. The stability, flow and the ratio of stability (kN) to flow (mm), which is defined as the Marshall Quotient (MQ) and is an indication of stiffness of the mixtures, were determined. It is known that, for a material, MQ is a measure of resistance to shear stress, permanent deformation and hence rutting. High MQ values indicate a mixture with high stiffness, high capability to distribute the applied load and high resistance to creep deformation (Zoorob and Suparna, 2000). For each mixture, three specimens were prepared at the calculated or experimentally determined optimum bitumen content, and the obtained values were compared with the criteria indicated in the specification.

#### 3.2 Resistance to Moisture-induced Damage Test

The resistances of mixtures against moisture-induced damage were determined in accordance with AASHTO T 283 standard test procedure. According to this standard, the specimens were compacted with an air void content of  $7 \pm 0.5$  percent. Out of these specimens, two separate groups were assigned, each

consisting of 36 mixtures, such that the mean specific gravities of the specimens in each group would be equal. The first group is composed of unconditioned specimens (immersed in water at a temperature 25°C for 2 h), while the second group includes conditioned ones, i.e., specimens kept in freezer at -18°C for 16 h then immersed in water at 60 °C for 24 h and finally immersed in water at 25°C for 2 h. Prior to the application of conditioning procedure, the specimens were vacuum-saturated such that 70 to 80% of the encompassed air voids were filled with water. Cylindrical specimens were exposed to compressive loads at a constant loading rate of 50.8 mm/min by Marshall loading equipment. These loads act in parallel to the vertical diametral plane. Depending on the maximum load, leading to the point of failure, the Indirect Tensile Strength (ITS) in units of kPa was calculated by the equation given below:

$$ITS = 2F / \pi LD \quad (1)$$

where F denotes peak value of the applied vertical load (kN); L is the mean thickness of the test specimen (m); and finally D is the diameter of the specimen (m). The indirect Tensile Strength Ratio (TSR) was calculated in accordance with the equation below:

$$TSR = 100 \times (ITS_{cond.} / ITS_{uncond.}) \quad (2)$$

where  $ITS_{cond.}$  denotes the indirect tensile strength of the conditioned specimens and  $ITS_{uncond.}$  stands for the indirect tensile strength for the unconditioned specimens.

#### 3.3 Indirect Tensile Stiffness Modulus ( $S_m$ ) Test

The Indirect Tensile Stiffness Modulus (ITSM) test is a non-destructive testing method that can be used for the assessment of relative qualities of materials and investigating the impact of temperature and loading rate on the stiffness of asphalt mixtures. The repeated load indirect tensile stiffness modulus test as

specified by BS DD 213 standard is known as a potential technique for the measurement of this property. The value of  $S_m$  in units of MPa can be calculated by the equation below:

$$S_m = F(R + 0.27)/LH \quad (3)$$

where  $F$  denotes the peak value of vertically applied load cycles,  $H$  is the mean amplitude of the horizontal deformation in mm observed after 5 repetitions of the load pulse,  $L$  is the mean thickness of the test specimen (mm), and  $R$  stands for the Poisson's ratio, assumed to be 0.35 in this case. The test was performed at 25°C by Universal Testing Machine (UTM) operating under deformation-controlled mode. The magnitude of the applied load was calibrated by the system itself for the five initial conditioning pulses such that they would produce the specified peak transient diametral deformation. An appropriate level of deformation was selected to ensure the generation of sufficiently high amplitude of signal by transducers, and thereby perform reliable and accurate measurements. For this particular test, the deformation was chosen to be 5 micrometers and the rise time, which denotes the time interval measured from the initiation of load pulse to the completion of the applied load, increasing from zero to the maximum value. The rise time was determined as 124 ms, and the applied load pulse was adjusted to 3.0 seconds.

### 3.4 Indirect Tensile Fatigue Test

One of the constant stress tests is the Indirect Tensile Fatigue (ITF) test, which generally characterizes the fatigue behavior of the mixture (Nejad *et al.*, 2008). Within the scope of this study, the fatigue tests were performed under controlled stress conditions in accordance with BS DD AFB standard, by Universal Testing Machine (UTM). UTM possesses a servohydraulic test system, where the loading frame is nested in an environmental chamber for temperature control during the course of the experiment. The desired load level, the load rate and load duration were all computer controlled. Deformations of the specimens were traced through Linear Variable-differential Transducers (LVDTs), which were vertically attached onto the diametrical side of the specimen. A dynamic compressive load was repetitively applied to the specimens across the vertical cross-section along the depth of the specimen utilizing two loading strips each has a width of 12.5 mm. The total induced deformation for each level of applied force was measured as a final stage. The indirect tensile fatigue test was carried out at a temperature of 25°C and stress level of 300 kPa. The loading period was taken as 1.5 seconds, of which 0.124 seconds was calibrated to be the load action time similar to the ITSM test.

### 3.5 Dynamic Creep Test

Dynamic creep test is one of the most commonly preferred tests to determine the resistance of hot mix asphalts against permanent deformation. In this test, performed by UTM, a constant load is applied dynamically to a cylindrical specimen at a particular periodic rate. The plastic strains resulting from the

load cycles are then analyzed by LVDT vertically clamped onto the metal plate, which is fixed onto the specimen's surface. The creep modulus values could then be calculated as per the formulas given below:

$$\varepsilon_c = (L3_n - L1)/G \quad (4)$$

$$\sigma = F/A \quad (5)$$

$$E_c = \sigma/\varepsilon_c \quad (6)$$

In the equations given above,  $\varepsilon_c$  denotes the total permanent (plastic) strain (%),  $E_c$  is the creep modulus (MPa),  $G$  is the initial specimen height (mm),  $L3_n$  is the plastic displacement before applying the (n+1)<sup>th</sup> load pulse (mm),  $L1$  is the initial reference displacement for LVDT (mm),  $\sigma$  is the maximum vertical stress (kPa),  $F$  is the maximum level of vertical load (N), and  $A$  denotes the cross-sectional area of the sample (cm<sup>2</sup>). As Eq. (6) implies, the plastic strain is inversely proportional to creep modulus. Consequently, when plastic strain is high, creep modulus is low; hence a high creep modulus value for a hot mixture asphalt specimen shows that the specimen demonstrates a strong resistance against permanent deformation.

The temperature and the stress level for dynamic creep test were selected as 50°C and 500 kPa, respectively. The specimens were exposed to static preloading at a stress level of 10 kPa for duration of 90 seconds prior to testing. The loading period was taken as 1.0 seconds, a half of which was adjusted as the load action time and other half as the resting time.

## 4. Results and Discussions

### 4.1 Volumetric properties and Marshall test results

The Optimum Bitumen Content (OBC), bulk specific gravity (Gmb), air void (Va), Voids in Mineral Aggregate (VMA), Voids Filled with Asphalt (VFA), Marshall stability, flow and Marshall Quotient (MQ) values belonging to the specimens prepared at their respective optimum bitumen contents are presented in Table 6.

As seen in Table 6, it was observed that the optimum bitumen content in HMAs decreased with increasing amount of fly ash, while it increased with the amount of SBS content. It was determined that the mixtures prepared with B<sub>160/220</sub> and using 4 wt.% or 6 wt.% fly ash as filler did not satisfy VMA and VFA conditions. Furthermore, the mixture prepared with MB<sub>6%SBS</sub> bitumen and using 6 wt.% fly ash also did not meet the specification criterion pertaining to VFA. These mixtures were evaluated in this study in order to investigate the effects of admixture types in a wider scope.

As a result of stability and flow tests, it was determined that the use of both SBS and fly ash augment the stability values of the mixtures. It was found that the stability improved by 15.5% after using 6 wt.% SBS in bitumen modification without addition of fly ash; whereas the increase in stability was only 5.5% when B<sub>160/220</sub> pure bitumen was used in conjunction with adding 6 wt.% fly ash. Thus, it can be inferred from these results that

Table 6. Volumetric Properties and Marshall Test Results of Mixtures

| Binder type          | FA content (%) | OBC (%) | Gmb (gr/cm <sup>3</sup> ) | Va (%) | VMA (%) | VFA (%) | Flow (mm) | Stability (kgf) | MQ (kgf/mm) |
|----------------------|----------------|---------|---------------------------|--------|---------|---------|-----------|-----------------|-------------|
| B <sub>160/220</sub> | 0              | 4.85    | 2.356                     | 3.86   | 14.38   | 73.18   | 3.40      | 1571            | 4.62        |
|                      | 2              | 4.77    | 2.348                     | 3.76   | 14.09   | 73.29   | 3.61      | 1617            | 4.48        |
|                      | 4              | 4.69    | 2.350                     | 3.28   | 13.45   | 75.64   | 3.33      | 1624            | 4.88        |
|                      | 6              | 4.61    | 2.346                     | 3.04   | 13.03   | 76.66   | 3.45      | 1657            | 4.80        |
| MB <sub>3%SBS</sub>  | 0              | 5.18    | 2.338                     | 4.15   | 15.30   | 72.87   | 3.54      | 1673            | 4.73        |
|                      | 2              | 5.1     | 2.336                     | 3.84   | 14.81   | 74.08   | 3.48      | 1681            | 4.83        |
|                      | 4              | 5.02    | 2.327                     | 3.82   | 14.58   | 73.83   | 3.4       | 1742            | 5.12        |
|                      | 6              | 4.94    | 2.320                     | 3.69   | 14.27   | 74.16   | 3.30      | 1764            | 5.35        |
| MB <sub>6%SBS</sub>  | 0              | 5.38    | 2.325                     | 4.41   | 15.90   | 72.28   | 3.51      | 1815            | 5.17        |
|                      | 2              | 5.29    | 2.323                     | 4.11   | 15.42   | 73.34   | 3.30      | 1798            | 5.45        |
|                      | 4              | 5.21    | 2.322                     | 3.77   | 14.91   | 74.74   | 3.50      | 1835            | 5.24        |
|                      | 6              | 5.13    | 2.317                     | 3.59   | 14.55   | 75.35   | 3.42      | 1847            | 5.40        |
| Specification limits | -              | 4-7     | -                         | 3-5    | Min. 14 | 65-75   | 2-4       | Min. 900        | -           |

bitumen modification with only SBS is more effective compared to modifying the mixture with only fly ash in terms of stability values. On the other hand, mixture prepared with MB<sub>6%SBS</sub> bitumen and using 6 wt.% fly ash as filler has 17.6% higher stability compared to the mixture prepared with B<sub>160/220</sub> pure bitumen and using limestone as filler. The test results further showed that mixtures prepared with MB<sub>3%SBS</sub> bitumen and without using any fly ash exhibited similar stability values compared to those prepared with B<sub>160/220</sub> bitumen and using 6% fly ash by weight as filler. No regular variation was observed in the yield values due to employing SBS and fly ash and the values were found to be in general proximity with each other. It was determined that utilizing SBS and fly ash generally increased Marshall Quotient (MQ) values.

#### 4.2 Resistance to Moisture-induced Damage Test Results

The results of the Indirect Tensile Strength (ITS) tests for the mixtures before (ITS<sub>BC</sub>) and after (ITS<sub>AC</sub>) conditioning are presented in Fig. 1 and Fig. 2, respectively. Each value represents to the mean value obtained from testing of three specimens.

As seen in Fig. 1 and Fig. 2, using either SBS or fly ash improved the indirect tensile strength values both prior to and after the conditioning. Because of conditioning, ITS values of mixtures decreased. If strength values of mixtures before conditioning are

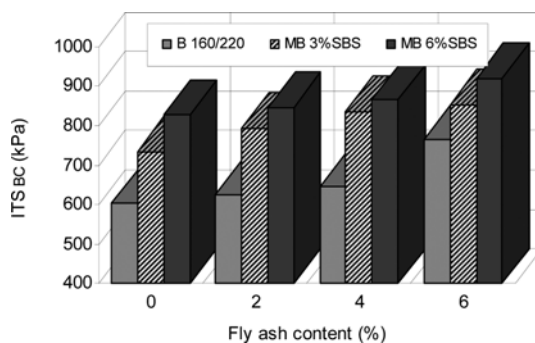


Fig. 1. ITS Values of Mixtures before Conditioning

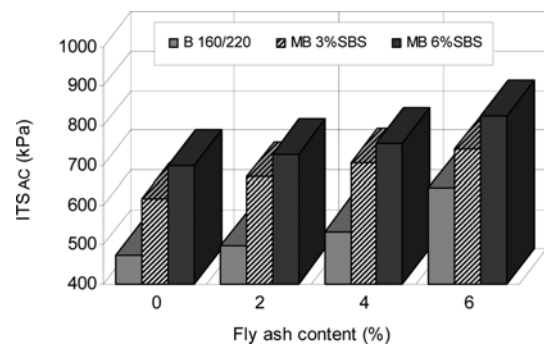


Fig. 2. ITS Values of Mixtures after Conditioning

compared, it can be seen that for mixtures prepared with B<sub>160/220</sub> bitumen, those using 4 wt.% fly ash as filler had a tensile strength 6.9% higher than that of the mixture including entirely limestone as the filler; while the corresponding increase in ITS was 26.5% for the mixture using 6 wt.% fly ash. Similarly, among the mixtures containing MB<sub>3%SBS</sub> bitumen, those using 4% fly ash as filler had an ITS value 13.8% higher than that of the mixtures without fly ash; while the corresponding increase in ITS was 16.1% for the mixture using 6 wt.% fly ash. Finally, among the mixtures containing MB<sub>6%SBS</sub> bitumen, those using 4 wt. % fly ash as filler had an ITS value 4.8% higher than that of the mixtures without fly ash; with the corresponding increase in ITS measured to be 11.3% for the mixture using fly ash at a proportion of 6 wt.%.

After conditioning, for the mixtures prepared with B<sub>160/220</sub> bitumen, those using 4 wt.% fly ash as filler had an indirect tensile strength 12.7% higher than that of the mixture utilizing entirely limestone as filler; while the corresponding increase in ITS was 35.7% for the mixture containing 6 wt.% fly ash. Among the mixtures containing MB<sub>3%SBS</sub> bitumen, those using 4% fly ash as filler had an ITS value 14.1% higher than that of the mixtures without fly ash; while the corresponding increase in ITS was 20.1% for the mixture using 6 wt.% fly ash. Finally, among the mixtures containing MB<sub>6%SBS</sub> bitumen, those using 4

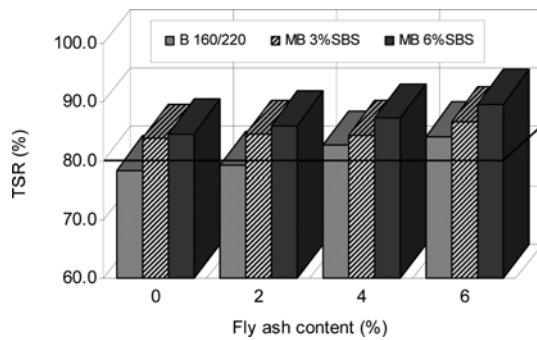


Fig. 3. Variation of TSR Values with SBS and FA Contents

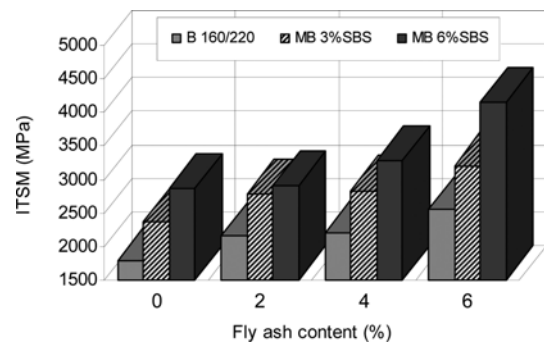


Fig. 4. ITSM Values of Mixtures

wt.% fly ash as filler had an ITS value 8.1% higher than that of the mixtures without fly ash; while the corresponding increase in ITS was 17.9% for the mixture containing fly ash at a proportion of 6%. The obtained results showed that similar to the unconditioned mixtures, in conditioned ones the addition of fly ash had a greater influence on ITS values of the mixtures prepared with pure bitumen ( $B_{160/220}$ ), and this influence tended to decrease with increasing proportion of SBS in binder modification. Besides, after conditioning, effects of SBS and fly ash were found to be increasing. Additionally, SBS was found to be more effective material among these two admixtures. The indirect tensile strength ratios of mixtures prior to and after conditioning are presented in Fig. 3.

Similar to the ITS values, the Tensile Strength Ratios (TSRs) of the mixtures increased with increasing SBS and fly ash contents, see Fig. 3. According to various specifications, such as Superpave method, TSR must be greater than 80%. Analyzing the obtained values, it can be seen that TSR value is lower than 80% threshold for the mixtures prepared with  $B_{160/220}$  bitumen and consist of either limestone entirely as filler or containing 2% fly ash as filler. Using 6% SBS in bitumen modification combined with adding 6% fly ash as filler raised the TSR value by 14.3% compared to the unadulterated mixture. The obtained results also showed that separate utilization of SBS and fly ash improved the resistance against moisture-damage of hot mix asphalts. According to the test results, it was determined that the mixtures prepared with  $MB_{3\%SBS}$  bitumen and without fly ash displayed similar levels of resistance against moisture-damage with those prepared with  $B_{160/220}$  bitumen and contain 6% fly ash as filler. Superior than this, the combined utilization of these two increased the resistance against moisture-damage even further.

#### 4.3 Indirect Tensile Stiffness Modulus Test Results

The results for ITSM test are given in Fig. 4, where each value indicates the mean value obtained from testing of three specimens.

As seen from Fig. 4, ITSM values of the mixtures increased with the utilization of SBS in bitumen modification and fly ash in mixture modification. Among the mixtures prepared with  $B_{160/220}$  bitumen, those using 4 wt.% fly ash as filler had an ITSM value 22.6% higher than that of the mixture consisting entirely of limestone as filler; while the corresponding increase in ITSM

was 42.4% for the mixture containing 6 wt.% fly ash. Mixtures containing  $MB_{3\%SBS}$  bitumen, with 2 wt.% fly ash as filler had an ITSM value 17.7% higher than that of the mixtures without fly ash; while the corresponding increase in ITSM were 20% and 35.6% for mixtures containing 4 wt.% and 6 wt.% fly ash, respectively. Finally, among the mixtures containing  $MB_{6\%SBS}$  bitumen, those using 4% fly ash as filler had an ITSM value 14.4% higher than that of the mixtures without fly ash; while the corresponding increase in ITSM was 44.0% for the mixture containing 6% fly ash. It can be inferred from results of the ITSM tests that the separate uses of SBS and fly ash both increases the stiffness of asphalts at normal temperatures, and the combined utilization of these two admixtures compounds the associated rise in stiffness.

#### 4.4 Indirect Tensile Fatigue Test Results

In order to determine the strength of hot mix asphalts against fatigue cracks induced by repeated loads, three specimens were subjected to ITF tests for each mixture. These tests were continued until the point of failure in the specimens was reached. The vertical deformation versus load cycle number graphs for the mixtures prepared with  $B_{160/220}$  bitumen and 6 wt.% fly ash are given Fig. 5 and Fig. 6.

As seen in these figures, both SBS and fly ash extended fatigue life of the mixtures. In order to evaluate the impact of admixtures more clearly, the number of load cycles causing 4 mm of vertical deformation, given in Fig. 7, was compared against the vertical deformation level at 2000 load cycles, given in Fig. 8.

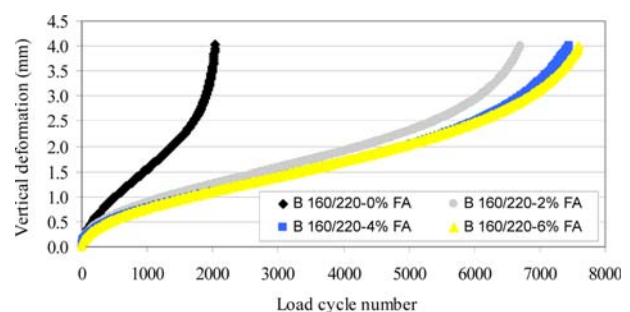


Fig. 5. Vertical Deformation-load Cycle Number Relationship of Mixtures Prepared with  $B_{160/220}$

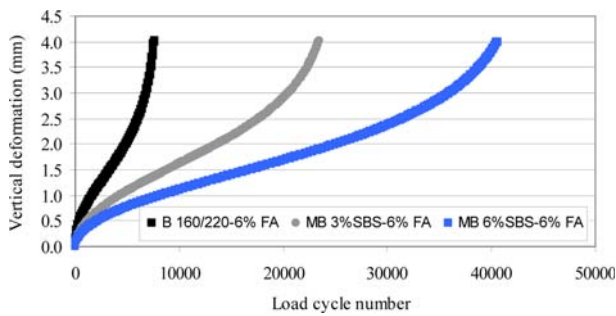


Fig. 6. Vertical Deformation-load Cycle Number Relationship of Mixtures Including 6% FA

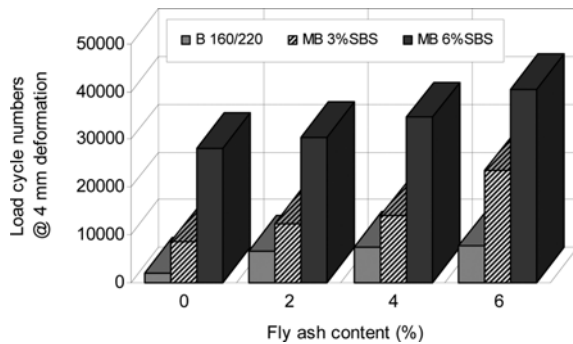


Fig. 7. Load Cycle Numbers of Mixtures at 4 mm Deformation Value

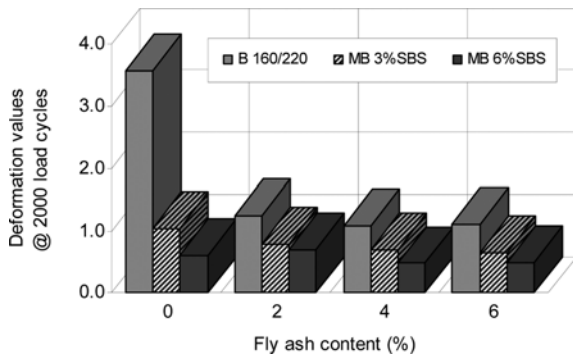


Fig. 8. Deformation Values of Mixtures at 2000 Load Cycles

Assessing the mixtures as a whole, the earliest failure associated with repeated loading was observed in the mixture prepared with B<sub>160/220</sub> bitumen and do not contain any fly ash. Analyzing the number of load cycles causing 4 mm vertical deformation in mixtures given in Fig. 7, it was determined that both SBS and fly ash increased the number of load cycles. Among the mixtures prepared with B<sub>160/220</sub> bitumen, the number of load cycles increased by 3.7 times when 4 wt.% or 6 wt.% fly ash was added. For mixtures prepared with MB<sub>3%SBS</sub> and MB<sub>6%SBS</sub> bitumen, the addition of 4 wt.% fly ash increases the load cycle by 1.6 and 1.2 times while the addition of 6 wt.% fly ash increases the load cycle by 2.8 and 1.4 times, respectively. The obtained results showed that in the combined addition of fly ash and SBS, the influence of fly ash on the number of load cycles decreased as the proportion of SBS increased. In the mixtures

without fly ash, using 3 wt.% SBS in bitumen modification boosted the number of load cycles by 4.2 times and using 6 wt.% SBS escalated the number of load cycles by 13.9 times. As for the mixtures consisting of fly ash by 2, 4 and 6 wt.% as filler, the use of 3 wt.% SBS increased the number of load cycles by 1.8, 1.9 and 3.1 times, respectively. Similarly, the utilization of 6 wt.% SBS increased the number of load cycles by 4.5, 4.6 and 5.3 times, respectively. It can be inferred from these results that SBS is more effective on mixtures that do not contain any fly ash. Moreover, assessing these results as a whole, SBS was found to be more influential on the number of loads compared to fly ash.

As seen in Fig. 8, the deformation values decreased as the content of SBS and fly ash in the mixtures increased. In mixtures prepared with B<sub>160/220</sub> bitumen, the deformation level at 2000 load cycles dropped by 3.3 times when 4 wt.% or 6 wt.% fly ash was used compared to mixtures without fly ash. The corresponding reductions in vertical deformation in cases of using fly ash by 4% and 6% for the mixtures compared to those containing no fly ash were approximately 1.6 times and 1.3 times for the mixtures prepared with MB<sub>3%SBS</sub> bitumen and MB<sub>6%SBS</sub> bitumen, respectively.

In the mixtures without fly ash, the deformation level plunged by 3.4 times by using 3 wt.% SBS in bitumen modification, while an SBS proportion of 6 wt.% reduced the deformation by 5.8 times. As for the mixtures containing fly ash by 2, 4% and 6 wt.%, using 3 wt.% SBS reduced the number of load cycles by 1.6, 1.5 and 1.7 times, respectively. The corresponding decreases in case of using 6 wt.% SBS were 1.8, 2.3 and 2.3 times, respectively. The results showed that separate utilization of SBS and fly ash reduced the level of deformation, while the combined use of these admixtures decreased the deformation even greater extent. Furthermore, similar to the other tests conducted, it was determined that the mixtures prepared with MB<sub>3%SBS</sub> bitumen and do not contain any fly ash exhibited similar indirect tensile fatigue test results compared to those prepared with B<sub>160/220</sub> bitumen and using 6 wt.% fly ash as filler.

#### 4.5 Dynamic Creep Test Results

Three specimens from each type of mixture were subjected to dynamic creep test and the means of the values obtained from these specimens were compared. Similar to the fatigue test, the experiment was continued until reaching the point of failure for the specimens. The permanent strain vs. load cycle number graph for the mixtures prepared with B<sub>160/220</sub> bitumen is given in Fig. 9, while the creep modulus vs. load cycle number plots for the mixtures containing 6 wt.% fly ash are given in Fig. 10.

In order to determine the strength of the mixtures against permanent deformation more reliably, the numbers of load cycles inducing 2 or 3% permanent strain were further compared with the creep moduli at 1000 and 2000 load cycles. The obtained values are summarized in Table 7.

Analyzing the number of load cycles yielding  $\varepsilon_c$  values of 2 and 3% for the mixtures, it was found that using SBS or fly ash both increased the number of load cycles. Among the mixtures

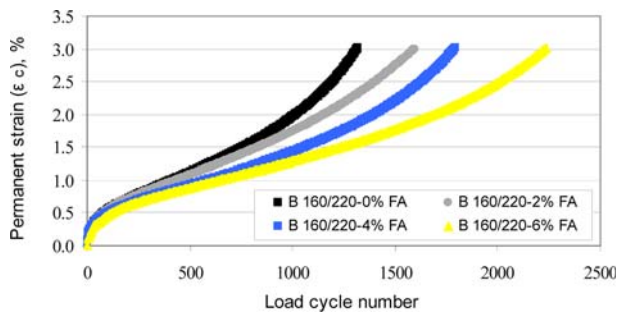


Fig. 9. Permanent Deformation-load Cycle Number Relationship of Mixtures Prepared with B<sub>160/220</sub>

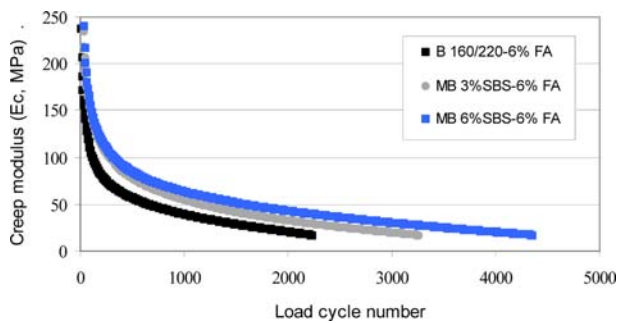


Fig. 10. Creep Modulus-load Cycle Number Relationship of Mixtures including 6% FA

prepared with B<sub>160/220</sub> bitumen, using 6 wt.% fly ash increased the number of load cycles resulting in a  $\epsilon_c$  value of 2 or 3% by 65.9% and 69.1%, respectively. For the mixtures prepared with MB<sub>3%SBS</sub> bitumen, using 6 wt.% fly ash increased the number of load cycles resulting in an  $\epsilon_c$  value of 2 or 3% by 34.9% and 37.8%, respectively, compared to the mixture prepared with the same binder but without fly ash. The mixtures prepared with MB<sub>6%SBS</sub> bitumen and consisting of 6 wt.% fly ash displayed increased number of load cycles resulting in an  $\epsilon_c$  value of 2 or 3% by 23.6% and 25.4%, respectively in comparison with the mixture without fly ash. The obtained results showed that using SBS or fly ash both increased the number of load cycles resulting in a  $\epsilon_c$  value of 2 or 3%. Furthermore, it was determined that the impact

of adding fly ash on the number of load cycles resulting in an  $\epsilon_c$  value of 2 or 3% grows with rising levels of SBS content.

For the mixture without fly ash and containing 6 wt.% SBS, the number of load cycles inducing a permanent strain of 2% and 3% are 174.7% and 163.2% higher than those of the unadulterated mixture, i.e. the mixture prepared with B<sub>160/220</sub> bitumen and containing no fly ash respectively. Similarly, the corresponding increases compared to the mixture prepared with B<sub>160/220</sub> bitumen and contain 6 wt.% fly ash are 65.9% and 69.1%, respectively. In case of using 6 wt.% SBS in bitumen modification combined with using 6 wt.% fly ash as filler, the number of load cycles inducing a permanent strain of 2% or 3% soared by 3.4 times. This phenomenon demonstrates that the combined utilization of fly ash and SBS has a more pronounced contribution to the rise in the number of load cycles that would cause a permanent strain of 2% and 3% compared to the addition of these admixtures separately.

At the end of 1000 and 2000 load cycles, the  $\epsilon_c$  values were found to be decreasing with the use of SBS and fly ash. Since the mixtures prepared with B<sub>160/220</sub> bitumen and do not contain any fly ash, as well as those containing 2 and 4 wt.% fly ash failed prior to the completion of 2000 load cycles, their  $\epsilon_c$  values could not be obtained at this particular number of load cycle. In case of using 6 wt.% fly ash in the mixtures prepared with B<sub>160/220</sub> bitumen, the  $\epsilon_c$  value at the completion of 1000 load cycles reduced by 34.4% compared to the mixture prepared with the same binder but containing no fly ash. Compared to the mixtures using MB<sub>3%SBS</sub> bitumen but contain no fly ash for the mixtures prepared with MB<sub>3%SBS</sub> bitumen and 6 wt.% fly ash, the  $\epsilon_c$  values at the completion of 1000 and 2000 load cycles dropped by 21.3% and 29.3%, respectively. In case of using 6 wt.% fly ash in the mixtures prepared with MB<sub>6%SBS</sub> bitumen, the  $\epsilon_c$  values at the completion of 1000 and 2000 load cycles decreased by 13.6% and 15.9%, respectively, compared to the mixtures using the same binder but without fly ash.

Analyzing the  $\epsilon_c$  values at the completion of 1000 and 2000 load cycles, which are indications of strength against permanent deformation of the mixtures, it was seen that these values regularly increased with the use of SBS and fly ash. The  $\epsilon_c$  value

Table 7. Dynamic Creep Test Results

| SBS Content (%) | FA Content (%) | Load cycle number @2% $\epsilon_c$ | Load cycle number @3% $\epsilon_c$ | $\epsilon_c$ @ 1000 load cycles (%) | $E_c$ @ 1000 load cycles (MPa) | $\epsilon_c$ @ 2000 load cycles (%) | $E_c$ @ 2000 load cycles (MPa) |
|-----------------|----------------|------------------------------------|------------------------------------|-------------------------------------|--------------------------------|-------------------------------------|--------------------------------|
| 0               | 0              | 1020                               | 1320                               | 1.958                               | 25.54                          | -                                   | -                              |
|                 | 2              | 1164                               | 1596                               | 1.737                               | 28.79                          | -                                   | -                              |
|                 | 4              | 1398                               | 1791                               | 1.427                               | 35.04                          | -                                   | -                              |
|                 | 6              | 1692                               | 2232                               | 1.285                               | 38.79                          | 2.491                               | 20.15                          |
| 3               | 0              | 1872                               | 2364                               | 1.170                               | 42.74                          | 2.192                               | 22.81                          |
|                 | 2              | 1890                               | 2598                               | 1.214                               | 41.19                          | 2.131                               | 23.46                          |
|                 | 4              | 2112                               | 2856                               | 1.121                               | 44.60                          | 1.891                               | 26.44                          |
|                 | 6              | 2526                               | 3258                               | 0.921                               | 54.29                          | 1.550                               | 32.26                          |
| 6               | 0              | 2802                               | 3474                               | 0.916                               | 54.59                          | 1.401                               | 35.69                          |
|                 | 2              | 2946                               | 3738                               | 0.868                               | 57.60                          | 1.355                               | 36.90                          |
|                 | 4              | 3138                               | 4140                               | 0.865                               | 57.80                          | 1.335                               | 37.45                          |
|                 | 6              | 3462                               | 4356                               | 0.791                               | 63.21                          | 1.178                               | 42.48                          |

at the completion of 1000 load cycles for the mixture using 6 wt.% SBS in bitumen modification and contain no fly ash increased by 2.14 times compared to the unadulterated mixture. On the other hand, the  $\varepsilon_c$  value at the completion of 1000 load cycles for the mixture prepared with B<sub>160/220</sub> bitumen and contains no fly ash increased by 1.52 times compared to the unadulterated mixture. Finally, the  $\varepsilon_c$  value at the completion of 1000 load cycles for the mixture using 6 wt.% SBS in bitumen modification and also containing 6 wt.% fly ash increased by 2.48 times compared to the unadulterated mixture.

As a result of the dynamic creep tests, it was determined that the separate utilization of SBS and fly ash both increased the strengths of hot mix asphalts against permanent deformation. It was also established that the combined utilization of these admixtures is more effective compared to their separate uses. A comparison of the mixtures showed that the use of SBS is more effective than fly ash, and the effectiveness of fly ash decreased with increasing levels of SBS content for the combined additions.

## 5. Conclusions

In this study, the effects of using SBS in bitumen modification and fly ash in mixture modification both in separate and combined forms on the mechanical properties of hot mix asphalts were investigated. While SBS was used at 0, 3 and 6 wt.% in bitumen, fly ash was added at 0, 2, 4 and 6 wt.% in aggregate mass, resulting in a total of 12 different mixture compositions. It was determined that the optimum bitumen content decreased with rising proportions of fly ash, however, the same parameter increased at higher SBS contents.

In all mixtures, the weakest performances were displayed in mixtures containing B<sub>160/220</sub> bitumen, while the single best performance was demonstrated by the mixture containing fly ash by 6 wt.% as filler and consisting of MB<sub>6%SBS</sub> bitumen. Additionally, using only SBS by 3 wt.% in bitumen led to similar outcomes compared to using only fly ash by 6 wt.% as filler. To conclude, it can be said that SBS and fly ash enhanced the stability, resistance against moisture-damage, fatigue life, permanent deformation strengths and stiffness of the mixtures at normal temperatures. Accordingly, it was also determined that the combined use of these admixtures improved the results further. The influence of fly ash dwindled with rising levels of SBS content for the admixtures. SBS is found to be more effective compared to fly ash when they are utilized separately.

## Acknowledgements

The financial contribution of FUBAP (Firat University Scientific Research Projects Unit) is gratefully acknowledged.

## References

Ahmadinia, E., Zargar, M., Karim, M. R., Abdelaziz, M., and Shafigh, P.

- (2011). "Using waste plastic bottles as additive for stone mastic asphalt." *Mater. Design*, Vol. 32, No. 10, pp. 4844-4849.
- Al-Hadidy, A. I. and Yi-qiu, T. (2009). "Mechanistic approach for polypropylene-modified flexible pavements." *Mater. Design*, Vol. 30, No. 4, pp. 1133-1140.
- Birlikci, R. Y. (1998). *Additives can be added to bituminous mixtures and investigation of behavior of this mixtures and a prediction model for fatigue curve*, PhD Thesis, Istanbul Technical University, Istanbul, Turkey.
- Cabrera, J. G. and Zoorob, S. (1994). "Design of low energy hot rolled asphalt." *In Proceedings of the 1st European Symposium*, The Civil Engineering Materials Unit, Department of Civil Engineering, University of Leeds, pp. 289-308.
- Gorkem, C. and Sengoz, B. (2009). "Predicting stripping and moisture induced damage of asphalt concrete prepared with polymer modified bitumen and hydrated lime." *Constr. Build. Mater.*, Vol. 23, No. 6, pp. 2227-2236.
- Isıkaykar, G. (2009). *Employment of fluorescent microscopy technique in determination of the rheological and mechanical properties of polymer modified asphalts*, MSc Thesis, Dokuz Eylül University, Izmir, Turkey.
- Khodaii, A. and Mehrara, A. (2009). "Evaluation of permanent deformation of unmodified and SBS modified asphalt mixtures using dynamic creep test." *Constr. Build. Mater.*, Vol. 23, No. 2, pp. 2586-2592.
- Kok, B. V. and Yilmaz, M. (2009). "The effects of using lime and styrene-butadiene-styrene on moisture sensitivity resistance of hot mix asphalt." *Constr. Build. Mater.*, Vol. 23, No. 5, pp. 1999-2009.
- Kumar, P., Mehndiratta, H. C., and Singh, V. (2008). *Use of fly ash in bituminous layer of pavement*, Indian Highways, New Delhi, India, pp. 41-50.
- Lee, S., Seo, Y., and Kim, Y.R. (2010). "Effect of hydrated lime on dynamic modulus of asphalt-aggregate mixtures in the state of North Carolina." *KSCE J. Civ. Eng.*, Vol. 14, No. 6, pp. 839-843.
- Lu, X. and Isacson, U. (1997). "Rheological characterization of styrene-butadiene-styrene copolymer modified bitumens." *Constr. Build. Mater.*, Vol. 11, No. 1, pp. 23-32.
- McGennis, R. B., Shuler, S., and Bahia, H. U. (1994). *Background of Superpave asphalt binder test methods*, Report No: FHWA-SA-94-069, US Department of Transportation, USA.
- Nejad, F. M., Aflaki, E., and Mohammadi, M. A. (2010). "Fatigue behavior of SMA and HMA mixtures." *Constr. Build. Mater.*, Vol. 24, No. 7, pp. 1158-1165.
- Ozen, H. (2011). "Rutting evaluation of hydrated lime and SBS modified asphalt mixtures for laboratory and field compacted samples." *Constr. Build. Mater.*, Vol. 25, No. 2, pp. 756-765.
- Roque, R., Birgisson, B., Drakos, C., and Sholar, G. (2005). *Guidelines for use of modified binders*, Florida Department of Transportation, Project Number: 4910-4504-964-12, USA.
- Sharma, V., Chandra, S., and Choudhary, R. (2010). "Characterization of fly ash bituminous concrete mixes." *J. Mater. Civil Eng.*, Vol. 22, No. 12, pp. 1209-1216.
- Tapkın, S. (2008). "Mechanical evaluation of asphalt-aggregate mixtures prepared with fly ash as a filler replacement." *Can. J. Civil Eng.*, Vol. 35, No. 1, pp. 27-40.
- Tapkın, S. (2009). "Investigation of variation of mechanical properties of hot mix asphalts including fly ash as filler." *In Proceedings of the Izmir Transportation Symposium*, Izmir, Turkey.
- Türk, K. and Karatas, M. (2011). "Abrasion resistance and engineering properties of self-compacting concrete with different dosage fly ash/

- silica fume.” *Indian J. Eng. Mater. S.*, Vol. 18, No. 1, pp. 49-60.
- Wong, W. G., Han, H., He, G., Wang, K. C. P., and Lu, W. (2004). “Rutting response of hot-mix asphalt to generalized dynamic shear moduli of asphalt binder.” *Constr. Build. Mater.*, Vol. 18, No. 6, pp. 399-408.
- Yilmaz, M. and Kok, B. V. (2009). “Effects of *ferrochromium slag* with neat and polymer modified binders in hot bituminous mix.” *Indian J. Eng. Mater. S.*, Vol. 16, No. 5, pp. 310-318.
- Zaniewski, J. P. and Pumphrey, M. E. (2004). *Evaluation of performance graded asphalt binder equipment and testing protocol*, Asphalt Technology Program, The University of Texas at Austin, USA.
- Zoorob, S. E. and Suparna, L. B. (2000). “Laboratory design and investigation of the properties of continuously graded asphaltic concrete containing recycled plastics aggregate replacement (plastiphalt).” *Cement Concrete Comp.*, Vol. 22, No. 4, pp. 233-242.