# Effects of Waste Fibers Stabilizers on the Draindown and Moisture Damage Sensitivity Properties of SMA Mixtures

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*Received: 11.01.2014 Accepted:27.09.2014*


## Abstract:

Waste fibers produced from manufacturing processes are a byproduct commonly deposited in storing yards and/or landfills and thus results in many serious environmental problems in Iran. If these waste materials could be advantageously put to practical use in any application, it would reduce the burden on the environment and landfills. This paper compares the performance of the stone matrix asphalt (SMA) mixes containing commonly used cellulose fibers (here jute) with SMA mixtures made with the various waste fibers. Three types of waste fibers from automotive carpet manufacturing process namely: two synthetic fibers (acrylic and polyester) and one cellulose fibers (viscose) were considered. The performance tests including, draindown, Marshall stability, Marshall stability ratio, tensile strength, tensile strength ratio, compressive strength and loss of compressive strength were carried out on the SMA mixes. Also, toughness, percentage of toughness loss and cohesion and internal friction angle were calculated. Test results showed that the cellulose fibers do better than those of synthetic in stabilizing the binder content of the SMA mixtures. Results of Marshall, indirect tensile strength and cohesion and internal friction angle test, revealed that the addition of synthetic fibers improved these parameters and also increased toughness of the SMA mixes. In addition, SMA mixtures containing the synthetic fibers, particularly those of acrylic, have better resistance to moisture damage than control mixtures.


**Keywords:** Fibers stabilizers, iIndirect tensile strength, compressive strength, toughness, cohesion and internal friction angle.

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## 1. Introduction

Stone Matrix Asphalt (SMA) is a gap-graded mixture that relies on stone to stone contact to provide strength and a rich mortar binder to provide durability. SMA was developed in Germany during the mid-1960s and it has been used in Europe for more than 20 years to provide better rutting resistance and to resist studded tire wear [Kumar et al. 2005]. Following the successful experiments in Europe, some States constructed SMA pavements in the United States in 1991. Since that time, the use of SMA in the US has increased significantly [Brown et al. 1997b]. Japan has started to use SMA paving mixtures as well with good success [Brown et al. 1997a; Ibrahim M 2006].

The fibers are generally used to prevent draindown of the binder during transport and placement of the bituminous mixture. The fibers commonly used are synthetic (e.g., polypropylene, polyester), mineral and cellulose. Cellulose fibers are broadly used in SMA in Europe and USA. Depending on their origin, natural fibers can be categorized as bast (jute, banana, flax, hemp, kenaf, mesta), leaf (pineapple, sisal, henequen, screw pine), seed or fruit fibers (coir, cotton, palm). Different fiber arrangements, such as short-randomly oriented, long-unidirectional and woven fabrics have been fabricated for natural fiber composites [Abiola et al. 2014]. The main functions of fiber reinforcement in asphalt mixes are to deliver additional tensile strength in the resulting asphalt concrete and to increase strain energy absorption of the asphalt mix in order to inhibit the formation and propagation of cracks which can decrease the structural integrity of the road pavement [Huaxin et al. 2009; Abiola et al. 2014]. The fibers improve the service properties of the mixture by forming micromesh in the asphalt mixture to prevent the draindown of the asphalt so as to increase the stability and durability of the mixture [Ibrahim M 2006; Kumar et al. 2005]. It was also reported that fiber modifiers had a better effect on draindown reduction than polymer modifiers [Kumar et al. 2005]. Chen and Lin reported that polyester fibers should be used if the strength reinforcement of bitumen-fiber mastics are found necessary at higher temperatures [Chen and Lin 2005]. In addition, the use of polyester fibers was also found to increase the toughness of the SMA mix compared with the cellulose fibers[Wu et al. 2006]. Furthermore, fibers improve the performance of asphalt mixtures against permanent deformation and fatigue cracking [Huaxin et al. 2009; Abiola et al. 2014].

In some parts of Iran, the removal of waste fibers produced from copious manufacturing processes is an economic and environmental problem for companies and municipalities (e.g., costs, landfill space, etc.). These fibers occasionally find other applications, but normally they are disposed of in landfills. The most important industries that produce such waste fibers are the tire processing industry and the automotive carpet and fabric/textile industry. If these fibers could be constructively utilized in any application, it would reduce the burden on diminishing landfill space. Also, using such waste materials could be economically valuable compared to fibers manufactured for a specific application [Putman and Amirkhanian 2004].

It can be stated as a fact that the utilization of this by-product is relatively low in Iran. The majorities of them are deposited in storing yards and/or landfills, and in turn result in a plethora of serious environmental problems. On the other hand, there is a considerable demand for additives in civil engineering industry, such as highway paving, concrete technology etc. The present study intends to explore the feasibility of utilizing three main waste carpet fibers, i.e. synthetic acrylic and polyester fibers and also cellulose viscose fibers as SMA mixture stabilizers and compare them with commonly used cellulose fibers (here jute) as the control stabilizer.

## 2. Materials

### 2.1. Aggregates

The crushed silicate stone aggregate in this study was obtained from the city of Mashhad, located in Khorasan Razavi Province of Iran. Gradation of aggregates in this research was selected in the middle of the recommended gradation limits by the TWG for SMA mixtures (Figure 1). Properties of aggregate are shown in Table 1. In SMA recommended mixtures, 8–10% of the total amount of aggregate in the mixture passes the 0.075-mm sieve. This large amount of filler plays an important role in the properties of SMA mixture, particularly in terms of air voids, voids in the mineral aggregate and optimum asphalt content [Davidson JK and Kennepohl

GJ 1992].

### 2.2. Asphalt cement

The asphalt cement used in this study was obtained from Isfahan Oil Refinery. Penetration of asphalt cement was, 66 (0.1mm at 25 °C 100g and 5s) and softening point was 49 °C.

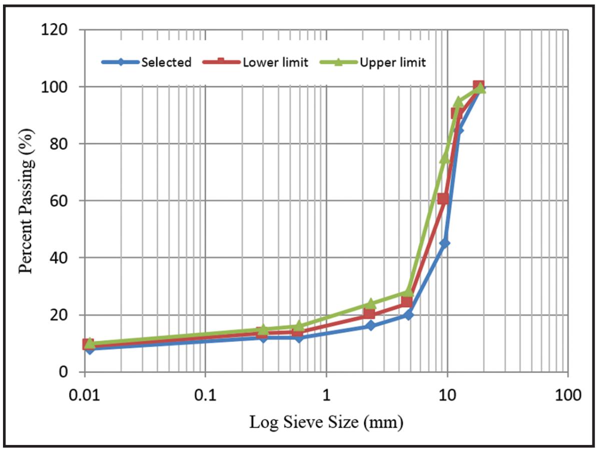


Figure. 1. Selected aggregate distribution on gradation chart

### 2.3. Fiber Stabilization

One of the major problems commonly encountered in SMA mixtures is the draindown of the binder during mixing, transportation and compaction. To overcome this problem, fibers are usually added to SMA mixtures. Organic fibers, such as cellulose, and mineral fibers are used as stabilizing agents in SMA mixtures, at the rate of 0.3% and 0.4% by weight of mixture, respectively [Ibrahim M 2006; National Asphalt Pavement Association 1994]. The fibers that were included in the study were placed in two groups; the first group was waste fibers including acrylic, polyester, viscose and the second group embraced a sort of widely used cellulose fiber, namely jute, as the control stabilizer. The fibers properties are included in Table 2.

### 2.4 Mix design

The aggregate and asphalt binder sources remained constant for this study. The fiber content was also held constant at 0.3% by weight of total mixture and uniformly combined with the dry aggregate before the asphalt cement was added. The mixing and compaction temperatures were kept at 165°C and 150°C, respectively. This fiber percentage was selected after reviewing the literature of SMA practices. The fiber type was varied, yielding four different mixture designs. The requirements for SMA mixtures developed by the FHWA sponsored SMA Technical Working Group (TWG) in Publication IS 118 [National Asphalt Pavement Association 1994] were followed in this study for the design of SMA mixtures. Marshall mixture design procedure is generally used for SMA mix design in Iran. Hence, Marshall design procedure was used in order to find the optimum asphalt contents by varying the asphalt content from 5.5 to 7.5% by weight of mix. Since SMA mixtures' optimum binder content is normally selected as that which produces 3.0–4.0% air voids [Brown and Mallick 1997], the optimum binder content of each

Table 1. Physical properties of aggregate group

| Item | Bulk density (gr/cm3) | Fractured faces | | Water absorption (%) | L.A. Abrasion (%) |
|---|---|---|---|---|---|
| | | One or more | two or more | | |
| Silicate stone | 2.684 | 100 | 91 | 1.39 | 20.3 |
| Standard Specifications | ---- | 100 | 90 | 2 | 30 |

Table 2. Relevant properties of fibers

| Properties | Acrylic | Viscose | Polyester | Jute |
|---|---|---|---|---|
| Type | synthetic | cellulose | synthetic | cellulose |
| Density (gr/cm$^3$) | 1.16 | 1.52 | 1.39 | 1.50 |
| Average length (mm) | 6 | 6 | 6 | 6 |
| Softening point (°C) | 235 | 210 | 230 | - |
| Melting point (°C) | - | - | 255 | 220 |
| Water absorption (%) | 1 | 13 | 0.4 | 11 |

mixture was determined at 3.5% air voids. The optimum binder content obtained corresponding to the designed air voids was checked for minimum voids in mineral aggregate and stone to stone contact. The final results including the mixtures' properties are presented in Table 3.

## 3. Experimental Program

In order to run a comparison between the four types of fibers for SMA mixtures, at least 30 samples of the SMA mixture for each type of the fibers were fabricated using the gyratory compactor (except for Marshall testing) at their optimum binder content as shown in Table 3. The comparison of these stabilizers was substantiated employing draindown, and moisture damage sensitivity tests including indirect tensile strength, loss of Marshall stability and unconfined compression test. Accordingly, cohesion and internal friction angle were calculated. Following is a discussion of these tests and their results.

## 4. Comparison of the Performance of SMA Mixtures

### 4.1. Draindown Test

This test is deemed to be of more significance to SMA mixtures than to conventional dense graded mixtures. Draindown test was used to determine the efficiency of the fibers and polymers as stabilizers to prevent draindown of the binder and mineral filler. This test is intended to simulate conditions that the mixture is likely to encounter as it is produced, stored, transported, and placed at high temperatures. The loose mixture is placed in a wire basket which is positioned on a preweighed dry paper plate. The entire apparatus is placed in a forced draft oven for one hour at 177°C. After 60 minutes, the basket containing the sample is removed from the oven along with paper plate, and the paper plate is weighed to determine the amount of occurred draindown. The draindown is calculated as the percentage of binder which drained out of the basket compared to the original weight of the sample [Kumar et al. 2005; Putman and Amirkhanian 2004]. Draindown test was conducted according to AASHTO T-305 for all of mixes containing acrylic, polyester, viscose and jute fibers at their optimum binder content. Triplicate samples were tested for draindown test. Also, the draindown sensitivity was determined by measuring the percentage draindown of matrix and should meet the design criterion of 0.3 percent. Figure 2 illustrates the average Draindown by weight of the mixtures for each stabilizer. In addition, at 0.3% fiber by weight of mixture and optimum binder content, the draindown by weight of mixture is found within the limits of 0.3 % by weight of the mixture. This indicates that in all mixtures, at the optimum binder content, each fiber is performing its function as a stabilizing additive. However the draindown of the mixture with cellulose fibers is less than that of the mixture with synthetic fibers when binder and fiber contents are constant. Also, among cellulose fibers, viscose outperforms Jute in preventing binder draindown.

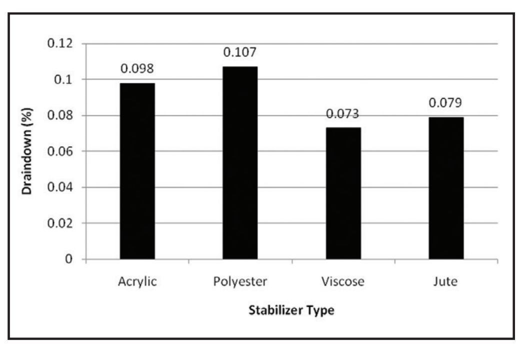


Figure 2. Draindown results for different Stabilizers

Table 3. Summary of Marshall design results

| Mixture type | SMA with acrylic | SMA with viscose | SMA with polyester | SMA with Jute | Specification |
|---|---|---|---|---|---|
| OAC (%) | 6.1 | 6.6 | 6.2 | 6.4 | Min 6% |
| Bulk Specific gravity (gr/cm$^3$) | 2.370 | 2.356 | 2.352 | 2.374 | --- |
| VMA (%) | 17.06 | 18.01 | 17.80 | 17.21 | 17≤ |
| VFA (%) | 79.48 | 80.57 | 80.34 | 77.92 | --- |
| Stability (KN) | 7.792 | 8.286 | 7.997 | 7.063 | --- |
| Flow (mm) | 2.76 | 3.07 | 3.09 | 2.55 | --- |

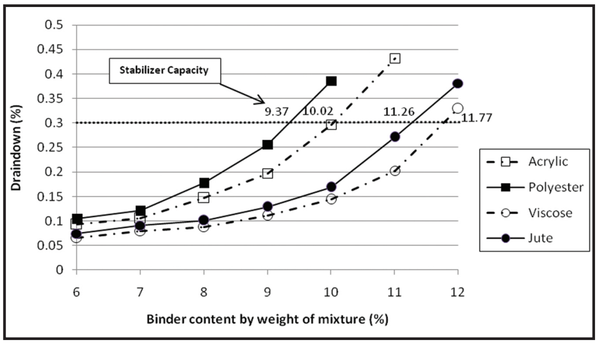


Figure 3. Draindown results at varying binder content for different stabilizers

Draindown was also tested at binder contents above the optimum binder content to determine the stabilizing capacity of each fiber. The binder contents used in this section of the study started at 6% (by weight of mixture) and increased by 1.0% increment until a draindown of 0.3% was reached. The stabilizing capacity of each fiber was determined as the binder content reached a draindown of 0.3%.The stabilizing capacity results are shown in Figure 3.

However, some differences can be seen in the performance of each fiber at binder contents greater than the optimum content. In general, the draindown increased with the increase of binder content for all mixtures. It is evident that all of the fibers gave significant stabilization to the mixture in comparison to the mixture containing polyester fibers. All of the fibers exceeded 10% binder before reaching 0.3% draindown except for polyester. The cellulose fibers had the highest stabilizing capacity at 11.77% and 11.26% for viscose and jute, respectively, followed by the acrylic fibers (10.02%), and the polyester fibers reached the draindown limit at 9.37%. These results indicate that the viscose fibers manage the draindown better than those of jute and have much higher stabilizing capacities as compared with the synthetic fibers, especially polyester. In addition, among the waste synthetic fibers, the acrylic fibers exert a higher stabilizing effect than the polyester fibers but lower than the control fibers. This property can be attributed to the absorptive nature of the fibers. As shown in Table 3, cellulose fibers had the highest water absorption values which may explain the its lowest draindown.

### 4.2. Moisture sensitivity tests

#### 4.2.1. Marshall stability/ loss of Marshall stability

To begin with, for each of mixes containing acrylic, polyester, viscose and jute fibers at their optimum asphalt content and corresponding bulk specific gravity, six specimens were fabricated. The specimens were then divided in two groups. First group specimens were placed in water bath at 60 °C for 40 min and then loaded at a ratio of 50.8 mm /min, and the stability and flow values were recorded (unconditioned specimens). The second group of specimens was placed in water bath at 60 °C for 24 h and then the same loading as described above was applied. The Marshall Stability Ratio (MSR) was then calculated by using the average stability of each group via the following formula:

$$MSR = \frac{MS_{con}}{MS_{uncon}} \times 100 \qquad (1)$$

where MSR: Marshall Stability ratio, $MS_{uncon}$: Average Marshall Stability for unconditioned specimens (kN) and $MS_{con}$: Average Marshall Stability for conditioned specimens (kN).

Also, the ratios of average Marshall Stability to flow [Aksoy et al. 2005] for each group of specimens were determined using the formula as follows:

$$MSFR = \frac{(MS/F)_{con}}{(MS/F)_{uncon}} \qquad (2)$$

where MSFR, Marshall Stability flow ratio; $(MS/F)_{con}$: Ratio of average Marshall Stability to flow for conditioned specimens (kN/mm) and $(MS/F)_{uncon}$; Ratio of average Marshall Stability to flow for unconditioned specimens (kN/mm).Table 4 shows the test results and the percent loss in Marshall stability of the mixtures.

It can be observed that although the stability of SMA samples containing viscose fibers is higher than the other SMA samples, the loss in Marshall stability is higher in the viscose mixtures. There is a difference in the average MSR values between the synthetic and cellulose fibers as well. As evidenced in Table 4, it can be found that the mix with synthetic fibers shows the highest MSFR, whereas the cellulose mix shows the lowest one. This means that the mixes with cellulose fibers, especially viscose fibers, suffer from more moisture induced damage compared to the synthetic mixes. It can be put down to the fact that the use of synthetic, especially acrylic fibers, do better micro-reinforcement of the mixtures, and thus improve the resistance of moisture damage.

Statistical analysis was carried out in order to evaluate the significance difference between testing results. The aim was to control whether the differences in the testing results were due to experimental errors or due to the addition of fibers in mixes. This test was implemented using SPSS software version 16. The results are significant whenever the P value is less than the selected significance level, which is usually 5%.

Statistical analysis showed that differences between MSR values were not significant. However, for specimens containing acrylic fibers, the difference between MSFR values compared with control specimen (jute fiber) was statistically significant.

**4.2.2. Indirect Tensile Strength/Loss of Indirect Tensile Strength**

This test was performed in order to find the moisture susceptibility of SMA mixtures utilizing indirect tensile strength (ITS) and retained tensile strength ratio after vacuum saturation and after Lottman-accelerated moisture conditioning. The test was carried out according to AASHTO T-283 specifications. This test involves loading a cylindrical specimen with vertical compressive loads; this generates a relatively uniform tensile stress along the vertical diametrical plane. This test was performed at 25°C in indirect tension at 50.8 mm/min deformation rate. Failure usually occurs by splitting along this loaded plane[Niazi and Jalili 2009].

Six specimens of each mixture were prepared and divided into two groups as mentioned in *section 4.2.1* to determine the tensile strength values. First group was preconditioned by vacuum saturation. That is, 55–80% of the air voids were filled with water. Specimens showing above 80% saturation after the vacuum soaking were discharged since they were accepted as severely saturated; this process was repeated with a new specimen. If saturation has not reached 55% in a conditioned specimen after the initial vacuum soaking, then the specimen was returned for additional vacuum soaking until a minimum saturation level of 55% is reached. Then specimens were wrapped in plastic bags and put in a freezer for 16 h at -18 °C. Then the specimens were put into a water bath for 24 h at 60°C, finally they were placed in a water bath for 2 h at 25°C. Each specimen was loaded to failure and the following parameters were evaluated:

$$ITS = \frac{2P_{\max}}{\pi tl} \tag{3}$$

where $P_{max}$ is peak load (N), t the average height of specimen (mm) and d the diameter of specimen (mm).

Tensile strength ratio (TSR): $$TSR = \frac{ITS_{con}}{ITS_{uncon}} \times 100 \tag{4}$$

A tensile strength ratio of 0.8 or above has typically been utilized as a minimum acceptable value for HMA. Asphalt mixes with TSR less than 0.8 are moisture susceptible and mixes with ratios higher than 0.8 are relatively resistant to moisture damage [Niazi and Jalili 2009].

Toughness: toughness was defined as the area under the tensile stress–deformation curve up to a deformation of twice that incurred at maximum tensile stress [Freeman et al. 1989]Percentage of toughness loss:

$$PTL = \frac{Toughness_{uncon} - Toughness_{con}}{Toughness_{uncon}} \times 100 \tag{5}$$

Toughnessuncon: the area under the tensile stress–deformation curve up to a deformation of twice that in-

Table 4. Summary of effects of stabilizers on mixture properties for Marshall test.

| Mixture type | Marshal test results | | | | | |
|---|---|---|---|---|---|---|
| | Marshall stability at 60°C, 40 min water immersion (kN) | Flow (mm) | Marshall stability at °٦٠C, ٢٤ h water immersion (kN) | Flow (mm) | MSR (%) | MSFR (%) |
| SMA with acrylic | 7.792 | 2.76 | 7.497 | 2.84 | 96.2 | 93.5 |
| SMA with polyester | 7.997 | 3.09 | 7.753 | 3.24 | 96.9 | 92.5 |
| SMA with viscose | 8.286 | 3.07 | 7.654 | 3.28 | 92.4 | 86.5 |
| SMA with jute | 7.063 | 2.55 | 6.695 | 2.75 | 94.8 | 87.9 |

curred at maximum tensile stress for unconditioned specimens.

Toughnesscon: the area under the tensile stress–deformation curve up to a deformation of twice that incurred at maximum tensile stress for conditioned specimens.

ITS and TSR test results were summarized in Table 5, and Toughness and PTL results were given in Table 6. The mix containing the viscose fibers produced the highest unconditioned ITS followed by the polyester fibers, the jute fibers, and finally, the acrylic fibers produced the lowest unconditioned ITS. The tensile strength ratio (TSR) for all of the mixtures exceeded the minimum value of 80%. This indicates that these fibers do not cause a decrease in the strength of the SMA due to the intrusion of water into the mix. The mixtures containing the acrylic fibers have the highest TSR 90%, followed by the polyester and cellulose fibers (i.e. jute and viscose fibers, respectively). Analysis of the toughness results of both the conditioned and the unconditioned specimens indicates that the mixture containing the waste cellulose fibers have the lower toughness and higher PTL values than the waste synthetic and jute fibers, respectively. This shows that the acrylic and polyester fibers increase the mixture toughness due to their higher ability to prevent crack propagation which normally occurs within the mix during the loading process. This would also indicate that there is a stronger bond between the both acrylic and polyester fibers and the asphalt binder than there are with the jute and viscose fibers.

At 5% significance level, differences between ITS values were not significant. The same results were observed for TSR values except for the specimens containing acrylic fibers in comparison to control specimens. However, for PTL values, differences between specimens containing acrylic and polyester fibers compared with control specimens were significant.

#### 4.2.3. Compressive strength/loss of compressive strength

Compressive strength (CS) test provides a method for measuring the compressive strength of compacted bituminous mixtures. The compressive strength is determined in accordance with ASTM D1074 using 101.6 by 101.6 mm cylindrical specimens for each test. The samples are tested at 25°C.The specimens are tested in axial compression without lateral support at a uniform rate of vertical deformation of 0.05mm/min·mm of height. For specimens 101.6 mm in height, a rate of 5.08 mm/min is applied.

Compressive strength ratio (CSR) is useful as an indicator of the susceptibility to moisture of compacted bitumen-aggregate mixtures. This test method covers measurement of the loss of compressive strength resulting from the action of water on compacted bituminous mixtures containing asphalt cement. A numerical index of reduced compressive strength is attained by likening the compressive strength of molded and cured specimens with the compressive strength of duplicate specimens which have been submerged in water under given conditions in line with ASTM D1075.

For compressive strength conditioning test, six samples of SMA mixture were prepared for each type of the fibers. Then each set of six test specimens were sorted into two groups; the average void content of the speci-

Table 5. Summary of effects of stabilizers on mixture properties for indirect tensile test

| Mixture type | Unconditioned ITS (kPa) | Conditioned ITS (kPa) | TSR (%) |
|---|---|---|---|
| SMA with acrylic | 467.5 | 421 | 90 |
| SMA with polyester | 479.8 | 418.7 | 87.3 |
| SMA with viscose | 500.8 | 401 | 80.1 |
| SMA with jute | 478.3 | 400.5 | 83.7 |

Table 6. Average toughness results

| Mixture type | Unconditioned Toughness (N/mm) | Conditioned Toughness (N/mm) | PTL (%) |
|---|---|---|---|
| SMA with acrylic | 2.16 | 2.01 | 7.1 |
| SMA with polyester | 2.33 | 2.08 | 11.1 |
| SMA with viscose | 2.06 | 1.59 | 22.6 |
| SMA with jute | 1.88 | 1.50 | 20.4 |

mens of each group shall be equal. The first group of specimens was brought to the test temperature 25°C by storing them in an air bath maintained at the test temperature for 24 h (unconditioned) and their compressive strengths were determined. The second group of specimens was immersed in water for 24 h at 60°C. Then it was transferred to the second water bath maintained at 25°C and stored there for 2 h (conditioned) and then the compressive strength of the specimens were also determined. The numerical index of resistance of SMA mixtures to the detrimental effect of water, i.e. CSR, was calculated as the percentage of the original strength that is retained after the immersion period as follows:

$$CSR = \frac{CS_{immersed}}{CS_{dry}} \times 100 \quad (6)$$

where $CS_{dry}$ is compressive strength of dry specimens *(Group 1)*, and $CS_{immersed}$ is compressive strength of immersed specimens *(Group2)*.

Compressive strength test results for different stabilizers are shown in Table 7. These results show that the samples with the jute and acrylic fibers have a higher dry compressive strength followed by the viscose and polyester fibers respectively.

Both immersed compressive strength and CSR results show that the synthetic fibers, especially acrylic fibers, can improve resistance to moisture damage of SMA mixtures. This implies that introducing the acrylic fibers to the SMA mixtures reduces moisture susceptibility as this type of stabilizer is an effective agent, yielding a better micro reinforcement/micro mesh for SMA mixtures.

The statistical analysis revealed that there is a significant difference between acrylic and that of control fiber specimens at 5% significance level.

### 4.2.4 Cohesion and Internal Friction Angle

Consistent with the previous study conducted by Christensen and Bonaquist [Christensen and Bonaquist 2002; Wu et al. 2006], a simplified method for determining mixture cohesion and internal friction angle was suggested based on Mohr-Coulomb theory. This method chiefly includes two main sets of testing data; indirect tensile strength σi and unconfined compressive strength σc which can be used to calculate the cohesion strength C and the angle of internal friction φ using the following equations:

$$\varphi = \sin^{-1}\left(\frac{\sigma_c - 4\sigma_i}{\sigma_c - 2\sigma_i}\right) \quad (7)$$

$$c = \frac{(2 - \sin(\varphi)\ \times \sigma_i}{\cos(\varphi)} \quad (8)$$

Also, the ratios of average cohesion strength for each group of specimens were determined using the formula as follows:

$$COSR = \frac{COSR_{con}}{COSR_{uncon}} \times 100 \quad (9)$$

where COSR: cohesion strength ratio, $COSR_{uncon}$: Average cohesion strength for unconditioned/dry specimens (kN) and $COSR_{con}$: Average cohesion strength for conditioned/immersed specimens (kN).

Table 8 shows the results of C, φ and COSR by the recommended equations above. The results indicate that the unconditioned mix with cellulose fibers, especially viscose, has the highest cohesion strength, whereas the mix containing synthetic fibers, especially polyester, has the lowest one. The reason for higher cohesion of the unconditioned mixture with cellulose fibers may be that the use of these fibers more thickens the binder film on the aggregates due to excellent absorption of these fibers. The conditioned mixtures show different results. The highest cohesion strength and COSR resulted from the mixtures containing acrylic fibers. The second highest were the mixtures with polyester fibers; the viscose-containing mixtures came third and finally the fourth were mixtures containing viscose fibers. It is clearly evident that the retained cohesion ratio increases with the addition of synthetic fibers more than those of cellulose, that is, acrylic, polyester, jute and viscose, respec-

Table 7. Summary of the effects of stabilizers on mixture properties for compressive strength test

| Mixture type | Dry compressive strength (kPa) | Immersed compressive strength (kPa) | CSR (%) |
|---|---|---|---|
| SMA with acrylic | 5813 | 5249 | 90.3 |
| SMA with polyester | 5389 | 4550 | 84.4 |
| SMA with viscose | 5665 | 4548 | 80.3 |
| SMA with jute | 5970 | 4875 | 81.7 |

tively. Hence, in terms of moisture damage sensitivity, the use of synthetic, especially the acrylic fibers, yield better micro-reinforcement of the mixtures and manage better crack propagation within the mixtures while being loaded and exposed to the moisture; these could be the underlying reasons for the synthetic fibers's higher capability to improve the resistance of moisture damage more than the cellulose fibers. Also, all the mixes show very close friction angles, which may result from the same gradation and type of aggregate used in SMA mixtures. Thence, their resistance to moisture damage, to some extent, results from their cohesion characteristics.

## 5. Conclusion

From the types of fibers stabilizers used and within the limitation of tests in this study, the following results can be achieved:

1- The cellulose fibers outperform those of synthetic in stabilizing the binder content of the SMA mixtures.

2- The acrylic, polyester (synthetic type) and viscose (cellulose type) fibers, obtained from waste streams, were effective in preventing the excessive draindown of the SMA mixtures.

3- Moisture susceptibility, as indicated by tensile strength ratio of all the mixes, is higher than the prescribed values. Therefore, all mixes are reasonably expected to perform satisfactorily in field.

4- SMA mixtures containing the synthetic fibers, particularly those of acrylic, show better resistance to moisture damage than control mixtures and vice versa for the viscose fibers. This is attributed to the better micro-reinforcement of binder by the synthetic fibers and their better preventing of cracks propagation occurring within the mixture..

5- The results of Marshall, indirect tensile strength and cohesion and internal friction angle test show that the addition of synthetic fibers increases those parameters. This increase is much pronounced for the samples with the cellulose fibers, especially viscose type.

6- MSR, TSR, PTL, CRSR and CSR results show that the waste synthetic fibers can improve resistance to moisture damage of SMA mixtures. This implies that introducing these stabilizers to the SMA mixture reduces moisture susceptibility. The use of acrylic fibers results in a significantly higher amount of those parameters with all the other fibers.

7- Unlike the addition of viscose fibers, adding synthetic fibers increases toughness of the SMA mixtures when comparing with the mixes containing control fibers.

8- The mixtures containing waste synthetic fibers (polyester and acrylic, respectively) had lower optimum asphalt contents than the mix containing cellulose fibers (jute and viscose, respectively). By reducing the amount of the most expensive constituent of an asphalt mixture (asphalt binder), the result could be more cost effective pavements.

These findings lead to the conclusion that waste fibers can be viable options for use as stabilizing additives in SMA mixtures. Also, according to results of this study, addition of waste synthetic fibers, especially acrylic fibers, provide a positive contribution to the performance of asphalt pavements.

Due to a higher amount of asphalt content in the SMA, there is a tendency for the occurrence of driping of the binder. Therefore, fibers are added in order to inhibit this issue. Among various kinds of fiber (cellulose, minerals, etc.), cellulose have been used frequently and have shown favorable results, although they suffer from the drawback of a high cost.

Table 8. Summary of results of cohesion and internal friction angle

| Mixture type | Unconditioned specimens | | Conditioned specimens | | |
|---|---|---|---|---|---|
| | Cohesion (C, kPa) | Internal friction angle (φ, °) | Cohesion (C, kPa) | Internal friction angle (φ, °) | COSR (%) |
| SMA with acrylic | 946.3 | 54 | 852.9 | 54 | 90.1 |
| SMA with polyester | 939.2 | 51.6 | 811.1 | 50.8 | 86.4 |
| SMA with viscose | 982.5 | 51.8 | 787.3 | 51.8 | 80.1 |
| SMA with jute | 969.4 | 54.0 | 804.8 | 53.5 | 83.0 |

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