INTRODUCING AN ACTIVATED MINERAL AS INNOVATIVE BINDER-STABILIZER FOR SMA PAVING MIXTURES

Theme: Innovations in Road Planning & Design, construction and maintenance
Sub-themes: Construction Materials; infrastructure in challenging environments; tools to assess greenhouse gas emissions

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ABSTRACT

Due to problems associated with the addition of cellulose fibers to SMA mixes, a new binder stabilizer was developed to prevent excessive drainage of the bitumen during storage, hauling and placement of the mix. This stabilizer is an activated fine-ground raw silica mineral, which is the waste by-product of the mining for the Phosphate Industries. The activation was aimed for obtaining Thixotropic and Shear-Thinning properties for the bitumen, by which the mastic in the mix possesses high viscosity at rest (storage, hauling and after placing) for reducing draindown, and low viscosity at motion (mixing and placing) for maintaining the proper workability.

The objectives of this study were: 1) Practical development of a more efficient and user friendly binder-stabilizer for preventing the bitumen draindown in SMA mixes, 2) Identifying some positive added values of the role of the active bitumen-stabilizer in the compacted SMA also under service condition, and 3) Verification of these advantages by a comprehensive laboratory study, as compared to the cellulose fibers.

In extensive laboratory studies it was found that SMA mixes, combined with the new bitumen stabilizer, exhibit low acceptable bitumen draindown values which are comparable to those with the fibers. As a result of systematic mix designs, European and American SMA mixes also show comparable and better mechanical properties related to: resistance to water damage, wear resistance, indirect tensile strength, and rutting & fatigue resistance. These results were obtained with 0.5% less binder content and 10^{o}C lower mixing temperature, as compared to the fibers.

In addition to the engineering advantages, an analysis of the environmental benefits was performed. Generally, the comparison of the environmental indicators analyzed, clearly demonstrates a quantitative decline in the greenhouse gas emissions and in the negative environmental economic cost per ton SMA mix, when using the new activated-mineral binder-stabilizer as compared to the cellulose fibers.

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1. Introduction

1.1 Background

Stone Mastic (or Matrix) Asphalt – SMA is a hot mix surface course which was developed in Germany in the 1970's to resist rutting and wear from studded tires. Because of its superior performance for longer service life, SMA has been widely adopted in Europe, Australia, USA, Canada, China, and many other countries worldwide, as a surface course for heavily trafficked roads. SMA has a high coarse aggregate content that interlocks to form a stone skeleton that resist permanent deformation due to the stone-to-stone contacts. The voids between the aggregates skeleton are filled with mastic of bitumen and filler to which fibers are added to prevent the drainage of the binder during transport and placement. The stone-to-stone contact provides a strong skeleton, and the mastic enhances the durability of the SMA. It should be noted that not all surfacing called "SMA" are identical in their composition or their performance. SMA is a generic term that refers to a broad range of paving mixes with the same general characteristics.

Due to its many functional and structural advantages (such as: durable for longer life, rut resistant, textured and skid resistant, noise reducer, etc.) SMA mixes are considered as the best engineering choice for surface courses of heavily trafficked pavements. However, because of its unique composition and materials, the production, hauling and placing of SMA mixes are also associated with some major disadvantages (1 through 4):

- Draindown of the asphalt binder ("Bitumen" or "Asphalt Cement") during production and hauling, and flushing occurrences due to the higher binder content and VMA;
- The necessity to add cellulose fibers to the mix in order to rigidify the bitumen for preventing the binder draindown;
- The addition of the fibers to the mix requires special equipment. Also its sensitive handling often creates operational problems.
- Further increase of binder content mainly due to higher filler content and cellulose fibers added. It is assumed that part of the bitumen is absorbed and "lost" in the fibers;
- Increase of mixing time and reduction of productivity associated with lower workability due to the higher binder and mastic consistency caused by the fibers;
- Increase of mixing temperature due to the high consistency of the binder (usually a modified bitumen) and to the fibers in the mastic.
- All of the above contribute to a substantial increase of SMA mixes cost, together with environmental hazards, as compared to conventional HMA (dense-graded mixes, Superpave mixes, etc.).

In general it was found that "SMA requires more attention to details when mixing and being produced, transported and placed in the field". It is often considered "an art" to produce and lay a quality SMA mix, or as stated: "SMA is an unforgiving mix and requires changes and modifications to the mix design to enhance the characteristics of its performance (3).

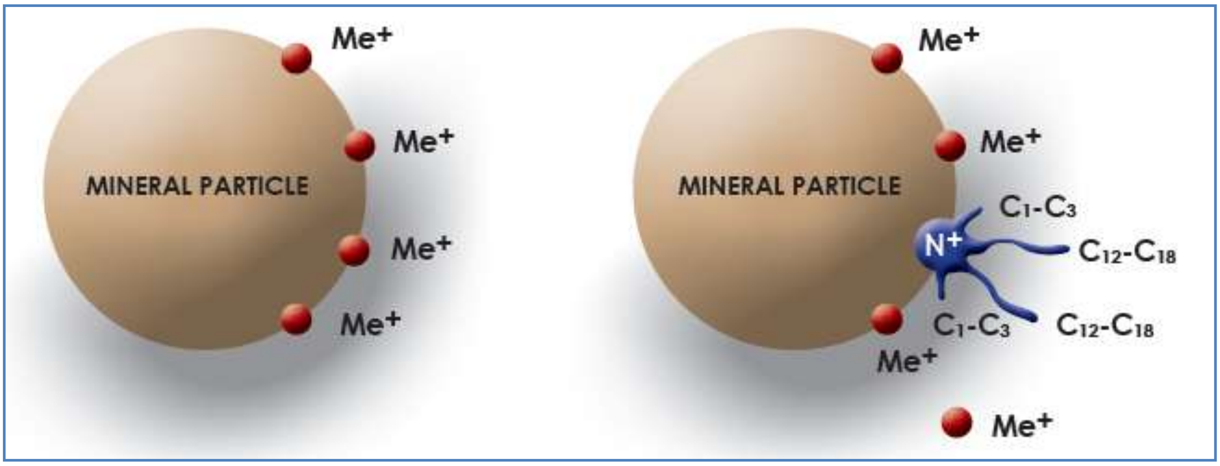
One of the main reasons for the above disadvantages is the "functional" addition of the cellulose fibers to the SMA, only for preventing the binder draindown during production and hauling. The high fibers cost and its negative side effects, mainly with respect to the very hot mixing and placing temperatures, sometime create objections for choosing SMA mixes despite the many advantages. Also, as recently stated (4): "Fibers serve no real purpose after the mix is compacted in place"

1.2 Objectives

Consequently, the objectives of the study summarized in this paper were three fold: 1) to develop a more efficient and user & environmental friendly binder-stabilizer for preventing the bitumen draindown in SMA mixes; 2) to look for some positive added values of the role of the active bitumen-stabilizer in the compacted SMA also under service condition; and 3) to verify these advantages by a comprehensive laboratory study, as compared to the cellulose fibers.

2. The New Activated Mineral Binder Stabilizer (AMBS)

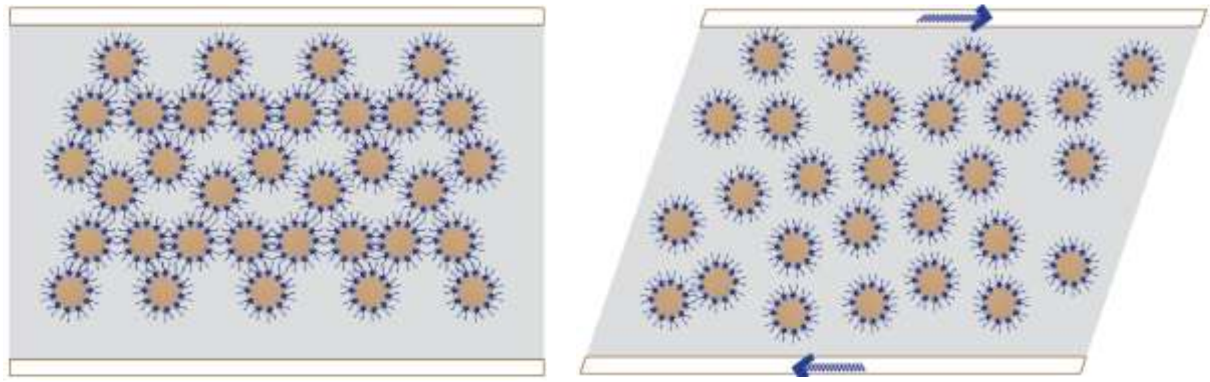
This stabilizer is a surface activated fine-ground raw silica mineral, which is the waste by-product of the mining for the Phosphate Industries near the Dead Sea, Israel. The activation was done by Quaternary Ammonium with long chains. The physico-chemical mechanism of this surface activation can be illustrated in Figure 1. It describes the exchange of the mineral particles surface metal cations (Me) by organic cations with long chains. Activated by organic compound, mineral particles have the ability to swell in organic liquids like bitumens.



<u>Figure 1:</u> Activation reaction on a silica particle surface by cations exchange

This surface activation is widely used in industry for alteration of the rheological properties of many organic compounds, for obtaining Thixotropic and Pseudo-plastic (Shear-Thinning) properties. **Thixotropy** is the property of certain gels or fluids that are thick (viscous) under normal conditions, but flow (become thin, less viscous) over time when shaken, agitated, or otherwise stressed. In more technical language: some non-Newtonian pseudo-plastic fluids show a time-dependent change in viscosity. **Shear thinning** is an effect where **viscosity** decreases with increasing shear rate. Materials that exhibit shear thinning are called **pseudo-plastic**. This property is found in certain complex solutions, and it is also a common property of polymer.

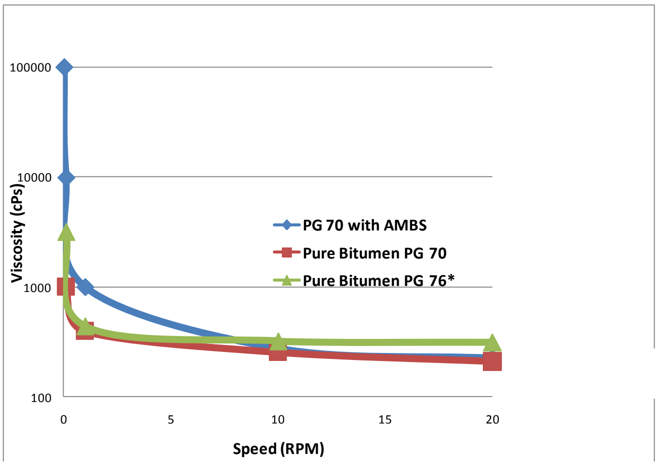
Both these phenomena (Thixotropy and Pseudo-plasticity) permit the rheological system to function as follows in bituminous mixtures: When the asphalt mix is at rest condition, a "Card House" structure of stabilizer activated particles is being formed inside the bitumen medium. This highly increases the viscosity of the bitumen. When the mix is under moving condition (mixing, laying) the card house structure is collapse, and the viscosity of the bitumen reduced close to its original value. When the system returns to its rest position, the card house is built again in the bitumen medium, and its viscosity increases to prevent excessive bitumen drainage (Draindown). This rheological mechanism is schematically described in Figure 2.



Stabilizer Net at Rest ("Card House") Stabilizer Particles in Movement

Figure 2: Rheological mechanism of bitumen stabilization by the shear thinning effect

The shear thinning (Pseudo-plasticity) mechanism can be actually demonstrated by simple viscosity testing at different shear rates. Figure 3 shows the results of viscosity measurement at 160°C using the Brookfield Viscometer on PG 76-22 & PG 70-22 plain (pure) bitumens and a bitumen treated by the new developed Activated Mineral Binder Stabilizer (AMBS) at 5% by weight. The rheological shear thinning effect of the binder stabilizer is quite significant as compared with the pure unsterilized bitumen.



	Speed (RPM)				
	0.01	0.1	1	10	20
	Viscosity (cPs)				
PG70+AMBS	100000	10000	1000	275	225
Plain PG 70	*	1000	400	256	210
Plain PG 76	*	3200	440	324	316

* Below sensitivity

Figure 3: Shear-Thinning mechanism of stabilized binder as reflected by viscosity testing

3. Experimental Program

3.1 Objective and Scope

The objective of the investigation was to compare the long-term behavior of two typical SMA mixtures containing the two different bitumen stabilizers: one with the activated mineral (AMBS) and another with a commercial brand of Cellulose Fibers. The initial major emphasis was to determine the proper range of **mixing temperature** and the **optimum bitumen content** of these two stabilizers for obtaining optimal and acceptable SMA mixes as per European and American Standards. To carry out this comparison, formulation studies were made based on the

European Norm EN 13108-05 (6) and the United States South Carolina SMA Specifications as per mix design procedure (7). The experimental work was performed in CONSULPAV Laboratory, Portugal.

3.2 Type of SMA Mixes and Specifications

The SMA mixtures tested were composed of polymer modified bitumen, crushed siliceous aggregate, and the two Stabilizers. The aggregate met the 11 mm and 12.5 mm gradation limits according to the European Standard EN13108-5 and the South Carolina Department of Transportation's (SC DOT) Specification. AMBS or Fibers were included at 0.3% by weight of the mixture to act mainly as a bitumen stabilizer for preventing draindown of the asphalt binder. The typical specification limits of the EN and SC gradations are shown in Figure 4.

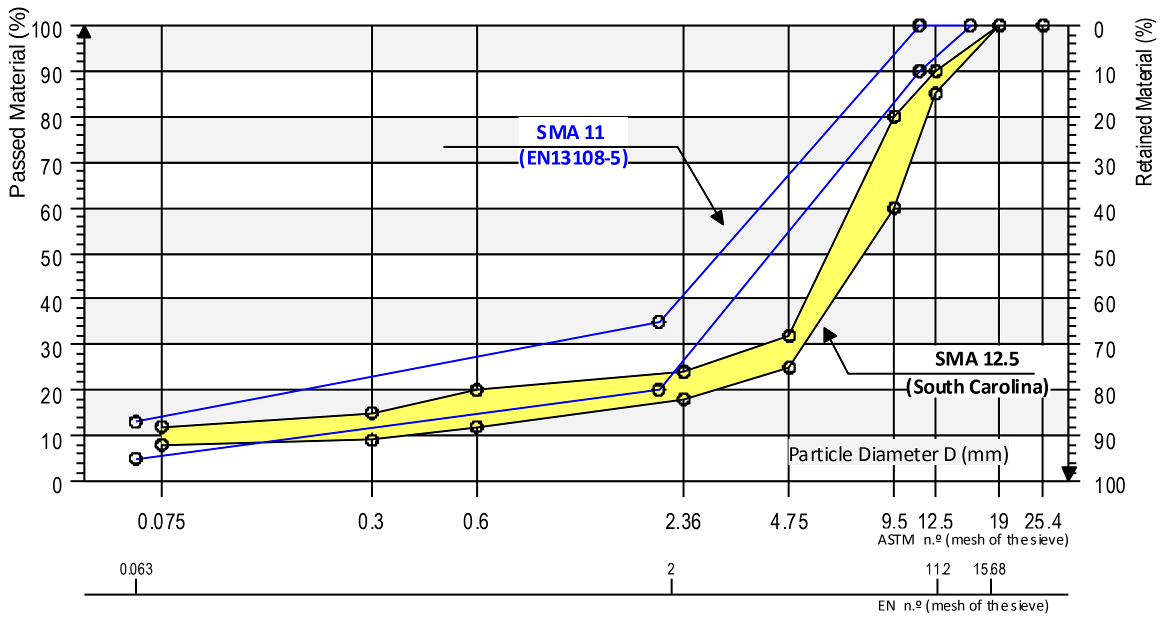


Figure 4: European (EN) and South Carolina (SC) aggregate gradation limits for the SMA mixes tested

3.3 Materials

The aggregates used in this study were Granodiorites that contain about 53% Silica Oxide (SiO_2). Hydrated lime was included, at 1.0% by weight of the dry aggregate, as an anti-strip additive in all mixtures.

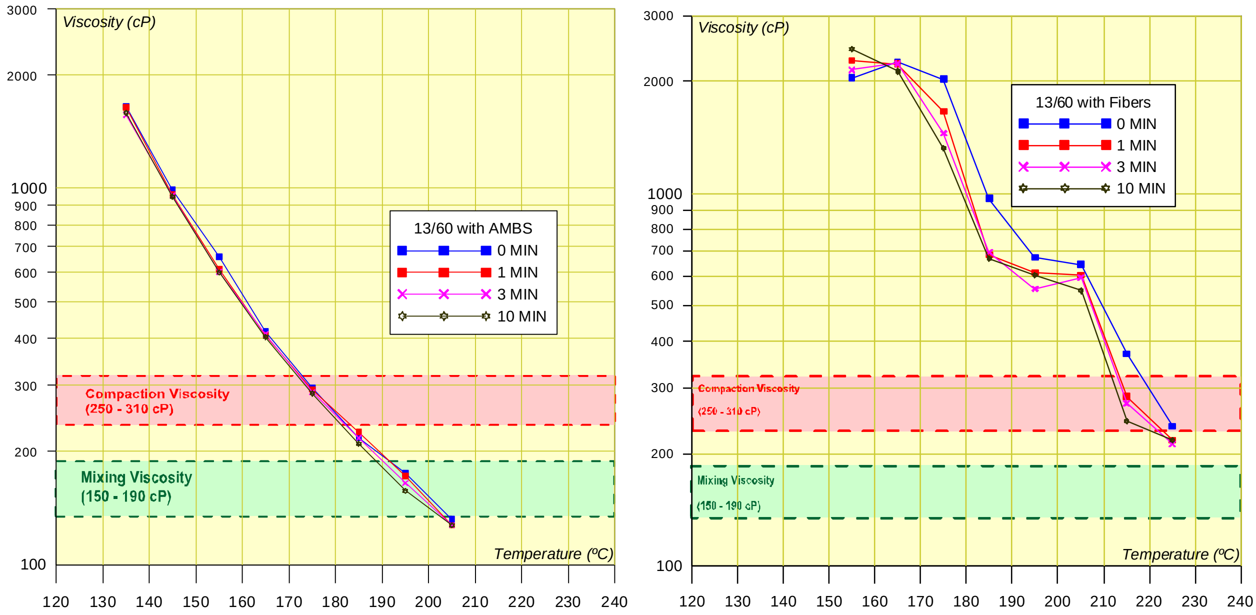
The Polymer Modified Bitumen (PMB) for the SMA mixes was graded as a Styrelf 13/60. It was tested by the DSR and evaluated as PG76-28. Viscosity and some other tests were also performed on Pen 35/50 (PG 70-22) non-modified bitumen.

Two bitumen stabilizers were included to prevent draindown in the SMA mixes. As described earlier, the new Activated Mineral Binder Stabilizer (AMBS) is a fine silica mineral (ground down to 40 microns and finer), activated by a quaternary ammonium compound. The AMBS was tested and compared to a commercially available Cellulose Fibers.

3.4 Type of Tests Performed and Results

3.4.1 Viscosity vs. Temperature Tests

In order to determine the **effect of temperature on the consistency** of bitumen-stabilizer mastics, viscosity tests were performed at the practical temperature range. These tests were also aimed to determine the mixing and compaction temperatures of the SMA mixes for the two stabilizers. The tests were done using the Brookfield Thermosel apparatus, according to AASHTO TP 48. Typical test results are shown in Figure 5.



<u>Figure 5:</u> Viscosity vs. Temperature of Bitumen 13/60 (PG 76-28) with AMBS and Fibers

The test results showed the following trends:

a) The viscosity variation with temperature of both the plain bitumen PG 76-28 (without stabilizer) and the same bitumen stabilized with 5% AMBS is actually identical. It means that the addition of AMBS does not affect much the viscosity of the plain binder at this temperatures range.

b) Fibers do cause a <u>very</u> significant effect on increasing of binder viscosity. For example, it can be seen that a viscosity of 300 cP is reached at 173^{o}C for the bitumen-AMBS mastic, while with the fibers, a temperature of 218^{o}C is needed to reach the same viscosity (a difference of 45^{o}C). Also, the viscosity-temperature relationship is very irregular.

c) These results practically mean that by replacing the fibers with the new AMBS stabilizer, it is possible to decrease the bitumen temperature by more than 40^{o}C (72^{o}F) for obtaining comparable workability (viscosity). The practical temperature difference of the actual SMA mix is smaller, thus a difference of 10^{o}C was set between the mixing temperatures of SMA mixes combined with the two stabilizers.

3.4.2 Mix Design and Optimum Bitumen Contents (OBC) Determination

Four SMA mixes were investigated – a combination of two gradations (EN and SC – see Figure 4) and two binder stabilizers (AMBS and Fibers). Volumetric and mechanical properties of the mixes, at a wide range of bitumen contents, were determined by the SC DOT Marshall mix design procedure. Mixing Temperature of 160ºC was chosen for the AMBS mixes, and 170ºC for the Fiber mixes. The compaction was carried out by 50 blows, where a temperature of 150ºC was selected for all mixes. The analyses of the test results lead to the following determination of the OBC's for each of the four mixes, as shown in Table 1:

	Property	Mix Design Criterion	Bitumen content for each property AMBS (%)	Bitumen content for each property Fibers (%)	Remarks
EN	%Air Voids	2.0-4.5	5.3	5.1	
	% VMA	Min. 17	6.5	7.1	
	%VFB	65-85	5.0	5.0	
	Bulk Sp. Grav.	Max.	7.0	7.0	
	Marshall Stab. (N)	Max.	5.0	7.0	At elevated high value
	Average % OBC		**5.76**	**6.24**	**0.48% difference**
	Recommended % OBC		**6.0**	**6.5**	
SC	%Air Voids	3.5±0.5	4.4	5.5	
	% VMA	Min. 17	6.6	6.3	
	%VFB	65-85	4.5	5.1	
	Bulk Sp. Grav.	Max.	5.0	6.0	
	Marshall Stab. (N)	Max.	6.0	6.0	
	Average % OBC		**5.30**	**5.78**	**0.48% difference**
	Recommended % OBC		**5.5**	**6.0**	

Table 1: – Determination of Optimum Bitumen Contents (OBC) for the EN and SC Mixes

It can be observed that for both gradations the AMBS mix designs yielded an OBC about 0.5% lower than those with the Fibers. This is quite expected, as fibers contribute to the absorption of the non-effective binder, thus requiring increase in OBC. The values of the properties of all four mixes at OBC are summarized fully complied with the SC and EN requirements. Also, it was found that there is no significant unique trend for any of the two stabilizers and the results are generally comparable.

3.4.3 Draindown Tests at Optimum Bitumen Contents

Systematic draindown tests were also performed for all mix combinations at OBC, using the suitable method for each gradation (either EN or SC). As shown in Table 2, all results comply with both American and European Specifications.

Gradation	European Norm - EN		South Carolina - SC	
Stabilizer	AMBS OBC=6.0%	Fibers OBC=6.5%	AMBS OBC=5.5%	Fibers OBC=6.0%
EN 12697 – 18 (Beaker	0.1	0.1	-	-
EN 12697 – 18 (Basket)	0.0	0.0	-	-
ASTM D6390-5 (Basket)	-	-	0.3	0.3

Table 2: Draindown Tests for all mixes at Optimum Bitumen Contents

3.4.4 Mechanical Tests at Optimum Bitumen Contents

A series of mechanical tests were performed on all four SMA mix combinations at Optimum Bitumen Contents, for comparison between the AMBS and the Fibers. The following tests were carried out:

1. Immersion Compression Test for measuring the water damage resistance.
2. Wheel Tracking Test for measuring the resistance to permanent deformation (Rutting).
3. Cantabro Wear Test for measuring the resistance to aggregate disintegration and wear of the compacted mix.
4. Indirect Tensile Strength (ITS) for measuring the tensile strength of diametrical specimen in dry state, and also after warm water conditioning for obtaining the Tensile Strength Ratio (TSR).
5. Four Points Bending Beam Test for measuring the fatigue life of compacted beams, as recommended by SHRP A-003A.

Results of all mechanical tests performed at OBC's are summarized in Table 3:

Gradation	European Norm - EN		South Carolina - SC	
Stabilizer	AMBS OBC=6.0%	Fibers OBC=6.5%	AMBS OBC=5.5%	Fibers OBC=6.0%
Water Damage Resistance (% Compression Strength)	115.1	96.2	132.9	115.1
Wheel – Tracking (mm Rutting)	3.54	3.52	2.30	2.87
Cantabro (% Wear)	4.0	1.8	3.8	3.1
Indirect Tensile Strength, Dry (Kpa)	683	655	707	583
Tensile Strength Ratio, TSR (%)	91.7	99.5	80.7	88.3

Table 3: Results of Mechanical Tests for all Mixes at Optimum Bitumen Contents

Generally it can be observed that AMBS specimens tested for water resistance, wheel tracking and indirect tensile on dry conditions, performed identical or better than those stabilized with Fibers. In the Cantabro test all mixes exhibits very low wear, as compared to the 20% maximum requirement. The TSR values of the fiber mixes are higher than those of the AMBS, while both stabilizers exhibit high resistance to water and temperature.

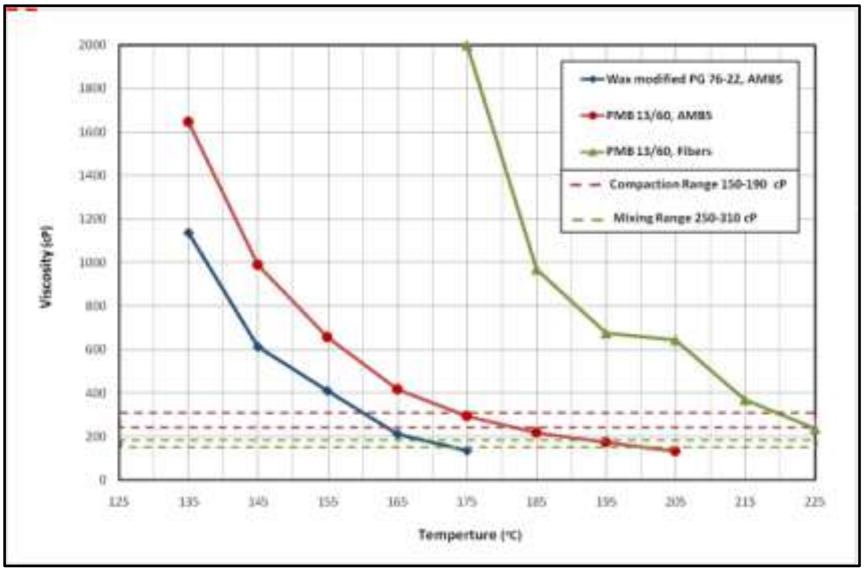
As for the fatigue results, it appears that AMBS mixes do indeed yield an equal or better fatigue life then Fiber SMA mixes, even though they contain less binder than Fiber SMA mixes. Actually, the ratio of actual fatigue life from beams in laboratory and that obtained from Asphalt Institute fatigue model (using actual beam properties) indicates that AMBS mixes have about 38% better longevity than the SMA Fiber mixes they attempt to replace (based on the binder type used in this research). Using the SHELL Model, the results also indicate that the Fiber SMA mixes have a fatigue life similar to mixes with about less 0.6% binder content. The AMBS SMA mixes appear to behave in the SHELL fatigue model as if they actually have about 1% more binder content then they actually have.

4. Reduction of Working Temperatures

SMA is a very hot mix, since it produced at 170-190^{o} C, mainly due to the addition of the fibers. Therefore, for environmental protection, a mixing temperature decrease is very desirable. As shown in Figure 5, by replacing the fibers with the new AMBS stabilizer, it was possible to decrease the bitumen temperature by more than 40^{o}C (72^{o}F) for obtaining comparable workability (viscosity). The practical temperature difference in the mix is smaller, and a difference of 10^{o}C was set in the laboratory between the mixing temperatures of SMA mixes combined with the two stabilizers. Practically, in trial asphalt plant mixing, it was found that the temperature difference for obtaining comparable mixing workability, enable a decrease of 15-25^{o}C when the AMBS is used instead of the fibers.

In order to follow the current trend towards Warm Mix Ashalt (WMA), further reduction of mixing and compaction temperatures is needed. This was achieved by using bitumen binder modified with temperature-reducer additives. Practically, a PG 76-22 modified by a wax flow- improver (Sasobit or equivalent [8]) was used. Actual mix production and road test paving were performed with the use of SMA mixes stabilized with the AMBS. Generally, the wax modified PG 76-22 exhibit workable mixing and compaction viscosities at substantially lower temperatures, while maintaining the proper high viscosities at critical service temperatures.

The effect of the wax modification on reducing viscosities at the mixing and compaction ranges, as compared to the conventional European Polymer Modified Bitumen (PMB 13/60), is illustrated in Figure 6. It represents Viscosity-Temperature relationship of modified bitumens stabilized with 5.0% Fibers or AMBS, as measured by the Brookfield Viscometer. The curves representing the conventional PMB's, with Fibers and AMBS, were taken from Figure 5 at standard conditions. The third curve represents a PG 76-22 wax modified binder. This figure clearly illustrates the two stages of working temperatures reduction. The first stage, for the conventional PMB, represents a reduction of 25-45^{o}C in working temperatures due to the replacement of the Fibers with AMBS. The second stage, for the wax modified PG 76-22, represents an additional reduction of 15-30^{o}C in working temperatures, due to the use wax flow- improver additive to the bitumen, together with the AMBS.



<u>Figure 6:</u> Viscosity-Temperature relationship of different modified bitumens stabilized with 5.0% Fibers or AMBS, as measured by the Brookfield Viscometer

For practical verification, two carefully controlled road tests were recently performed in northern and southern Israel with the use of SMA mixes stabilized with AMBS and a PG 76-22 bitumen modified with a wax flow-improver. The northern project was an SMA overlay of an access road to an operational heavy- duty quarry near the city of Beit Shean, using Basalt aggregates. In the south, the main arterial street of the city of Beer Sheva was milled and overlaid with similar SMA mix using local Dolomite aggregates (night job).

Based on preliminary testing of viscosity-temperature relationships, the mixing and compaction working temperatures of the Bitumen-AMBS binder were determined. They ranges between 140-150^{o}C for mixing, and 110-120 for compaction. Under that mixing temperature range, optimal aggregate coating was achieved without any need to elongate the mixing cycle time in the batch asphalt plant. Also, at that compaction temperature range, acceptable high densities were obtained for the plant mixes in the QC laboratory samples, and in the compacted layer in the field. Under these conditions and with a difference of about 30-40^{o}C in mixing temperatures (as compared to the very hot conventional SMA mixes with fibers), the SMA mixes with the AMBS binder stabilizer, together with a wax modified bitumen, can be considered as Warm SMA mixes – WSMA.

Some highlights of the two road tests are presented in Pictures 1 through 4:


<u>Pictures 1, 2:</u> SMA overlaying job near Beit Shean with AMBS, wax modified PG 76-22 and Basalt aggregates (August 2010)


<u>Pictures 3, 4:</u> Milling and SMA overlaying night job in the city of Beer Sheva with AMBS, wax modified PG 76-22 and Dolomite aggregates (April 2011)

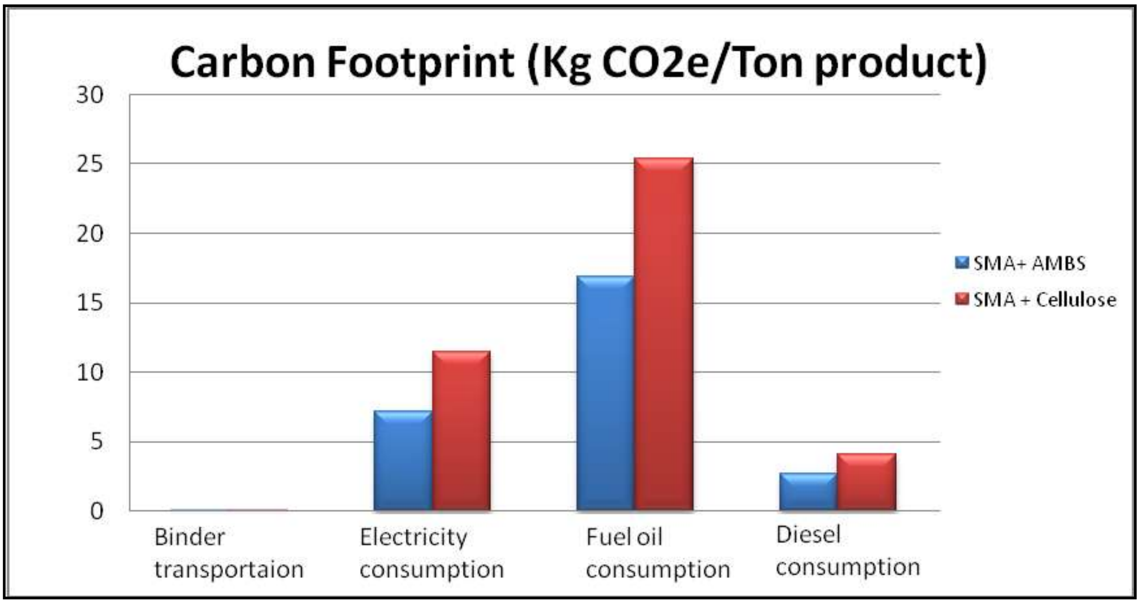
5. Environmental Analysis and Benefits

The incorporation of the AMBS and the temperature reduction possesses also pronounced environmental benefits. A comparison of several environmental indicators was specially conducted (9). Based on the fact the asphalt production is an energy intensive industry, this analysis focused on the most important air pollutants associated with fuel use and the emission of greenhouse gases. The indicators that were chosen are: Carbon Dioxide (CO_2), Nitrogen Oxides (NOx), Sulfur Oxides (SOx), Particulate Matter (PM) and Carbon Monoxide (CO).

Those indicators were converted to reflect their value in terms of external cost, based on academic research on the issue (ExternE [10]) as well as on European Union guidelines. Creating a currency for all of the air pollutants, which is based entirely on the cost of the pollution to society, enabled to quantify the cumulative environmental effect of the above mentioned air pollution emissions into a uniform environmental benefit indicator.

An example of the comparison between the AMBS and Fibers with respect to the Carbon Footprint Index is illustrated in Figure 7. Generally, the comparison of the environmental indicators analyzed, clearly demonstrates a 33% decline in the negative environmental economic cost per ton product when using the AMBS binder as compared to the cellulose fibers, 34% decline in greenhouse gas emissions for every ton product of SMA with AMBS binder and 33% decline in energy consumption for every ton product of SMA with AMBS binder. Overall, using AMBS could generate about 44 **Eurocents** of environmental benefit for every ton of SMA by lowering the external costs associated with asphalt production.

It should be stressed that this analysis was based on the effect of the AMBS vs. Fibers only. The additional effect of the wax modified bitumen cause further reduction of the working temperatures of the SMA mix. Consequently, this will intensify the total environmental benefits.



<u>Figure 7:</u> Comparison between the AMBS and Fibers SNA mixes with respect to the Carbon Footprint Index

6. Conclusions

Based on the above, the following major conclusions can be summarized and presented:

- Using unique physico-chemical processes, activated fine-ground raw silica mineral can serve as an efficient binder stabilizer to prevent bitumen draindown in SMA paving mixes.

- When replacing the cellulose fibers by the activated mineral powder, SMA mixes can be mixed and compacted at the same conditions as regular HMA with respect to the shorter mixing duration, and substantially lower mixing & compaction temperatures. Also, mixes can be designed at lower binder content.

- In addition to the immediate operational advantages, SMA mixes, combined with the new binder stabilizer, also exhibit some added values in properties and behavior. At optimum designs, European and American SMA mixes also show comparable and better mechanical properties related to: resistance to water damage, wear resistance, indirect tensile strength, dynamic flexural stiffness modulus, rutting and fatigue resistance. These results were obtained in the laboratory at 0.5% less binder content and 10^{o}C lower mixing temperature, as compared to the fibers.

- The incorporation of the AMBS possesses also pronounced environmental benefits mainly due to the reduction in mix working temperatures: Generally, the comparison of the environmental indicators analyzed, clearly demonstrates a 33% decline in the negative environmental economic cost per ton product when using the AMBS binder as compared to the cellulose fibers, 34% decline in greenhouse gas emissions for every ton product of SMA with AMBS binder and 33% decline in energy consumption for every ton product of SMA with AMBS binder.

- By replacing the conventional PMB with wax modified bitumens additional reduction in mixing and compaction temperature was possible in practical conditions. Under these conditions, and with a total difference of about 30-40^{o}C in mixing temperatures (as compared to the very hot conventional SMA mixes with fibers), the SMA mixes with the AMBS binder stabilizer, together with a wax modified bitumen, can be considered as Warm SMA mixes – WSMA.

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