Laboratory Investigation on Mechanical Performance of Cold Foamed Bitumen Mixes: Bitumen Source, Foaming Additive, Fiber-reinforcement and Cement effect

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INTRODUCTION

In-place recycling of pavement has become a practical, cost-effective and environmental friendly maintenance strategy for highways agencies in several continents. Less environmental impacts, faster rehabilitation times, reduced cost and shorter traffic delays are some of the advantages acknowledged to in-place recycling through cold recycling mixes (CRM).

Foamed bitumen and emulsions are commonly used as stabilizing agent, often upgraded with the addition of active fillers (Portland cement, cement kiln dust, hydrated lime, etc.). Foamed bitumen is produced when cold water in a specific quantity (water content between 1-4%) is injected into hot bitumen, usually at temperature higher than 140°C. The process has been widely used following the modified process by Mobil Australia 1968, which employs an expansion chamber for blending water, air pressurized and hot bitumen to yield an expanded bitumen (foamed) with physical properties temporally altered (*1*). Although CRM is not a recent paving technique, literature still exhibits some major gaps such as the lack of a universally accepted mix design method, agreement on the proper method for preparing laboratory specimens, and more in-depth understanding of factor affecting stiffness (*2,3*) and the evolution of the properties of the mixes with time and stress-state (*4,5*). Furthermore, the contribution to mechanical performance of the constituents of the complex system, aggregates/RAP, filler, active filler and foamed bitumen spot-weld is still not fully understood.

OBJECTIVE

The paper present a laboratory experiment that investigated the effect of bitumen source, foaming additive, fiber-reinforced, and cement on the mechanical properties of foamed bituminous mixes (FBM). The research work had the following objectives:

- To study the effect of different bitumen source, foamed bitumen content (FBC), addition of FA on dynamic modulus |E*| and indirect tensile strength of FBM.
- To evaluate the effect of Portland cement, two types of fiber reinforced (FR) and different fiber contents on the mechanical properties of FBM.

BACKGROUND

Bitumen Influence

When designing FBM, several particular considerations must be analyzed. First, the foaming capacity of the bitumen must be assessed, defining foaming capacity or "*foamability*", as the ability to obtain the foam by room-temperature water injection into a given bitumen (*6, 7, 8*). Foamability plays an important role on FBM when fundamental and mechanical properties are considered (*8-11*). Bitumen foamability is assessed according to two parameters: the expansion ratio (ER) which measures the increase of bitumen in volume after being sprayed, and the half-life (H-L) that evaluates the durability and the stability of the foamed-state before collapsing (*1,2*). Expansion ratio is defined as the maximum increase in volume due to the foam respect to the original volume of bitumen. Half-life is the time elapsed (in seconds) for the foam to collapse to half of its maximum volume. ER is considered to be correlated to foam bitumen viscosity and H-L is a measure of the stability of the foam and provides an indication of the collapse rate of foam (*1*). Both parameters have direct influence on bitumen distribution around the aggregates and aggregates coating. Maximum ER and longer H-L allows aggregates to be mixed at optimal conditions in terms of low foam viscosity that disperse well into the mix, while long H-L offer more time for the mixing process (*1, 7, 11-13*).

Bitumen effect on foamability and its relative impact on mix behavior has been widely studied (*7, 11, 14*). Several authors have found that softer (low-viscosity) bitumens produced higher expansion ratios and longer half-lives than harder (high-viscosity) bitumens. The use of high viscosity bitumen is usually assumed to result in better coating of the aggregates (*15, 16*). Active fillers, in particular Portland cement, have shown important enhancement on moisture sensitivity and mechanical properties; cement contents between 1.5% to 2% (of aggregates weight) have been widely used (*13,17-19*). Fu et al. (*8*) demonstrated that foamed bitumen with higher ER's and longer H-L's tend to disperse better into granular material and improve bonding. The researchers found that dispersion of the foamed bitumen into the RAP material and the resulting strength of the mix are dependent on the characteristic of the RAP. Saleh (*7*) analyzed nine bitumens from different sources and concluded that bitumen temperature-susceptibility does not have a direct effect on foaming properties and that mixes prepared with bitumen offering poor foamability could perform well and exhibit comparable mechanical performance to bitumen with good foamability. Therefore, the literature show contrasting findings regarding the impact of foamability characteristics on mix strength.

Mix Design

Concerning mix design and optimum foamed bitumen content (OFC), there is agreement in the fact that OFC must be analyzed considering moisture sensitivity, and indirect tensile strength (ITS) is considered one of the most standard test for determine OFC. Several authors have recommended evaluating ITS on dry and soaked conditions, and resilient modulus (*10, 18, 20*). However, for more critical projects, it is often recommended to conduct more complex material characterization tests, such as dynamic modulus test, resilient modulus test and dynamic creep test (*12*). A number of mix design procedures have been reported in the literature; these methods comprise slight variations of the Marshall or Hveem mix-design methods, and volumetric mix-design based on the Superpave gyratory compactor (*12, 21-24*). The curing process plays a primary role on the short and long-term material properties. It has been well documented that the amount of moisture and curing time significantly affect the properties of FBM (*5, 25-27*).

Foaming Additives

Foaming additives (FA) allow bitumen to foam more and achieve the required foam characteristics. They have been available for decades, in particular in bitumen with presence of silicone defoamants (*13, 25*). Maccarrone (*28*), suggested the use of "*special surface active additives*" which would produce ER higher than 14 and H-L longer than 60 sec; he also recommended the use of 0.1% of water to wet aggregates as beneficial for coating aggregates (for improve coating). Other authors have suggested quantities varying from 0.1% to 0.45% percent of mass of bitumen (*13*); for example Jenkins (*11*) used 0.1% of FA for improving ER's and H-L's in a pronounced way. However, when he considered the effect of the FA on very limited mechanical properties on mixes with and without FA, the author found notables differences in tensile strength only in the case of lower aggregate temperatures (<17°C) and added that at temperatures above 17°C the FA benefits are negated and can be counter-productive. Cazacliu et al. (*29*) used 0.03% of FA in a Bitumen 70-100 penetration grade obtaining significant differences in foaming temperature; which was almost 30°C higher with the FA. No information was reported concerning the effect of the FA on foamed mixes performance. Crispino et al. (*30*) investigated the effect of a FA on physical and rheological properties of one bitumen and found that the bitumen viscosity is reduced after FA addition and the bitumen temperature susceptibility is altered. The effect of the FA on the mixes' performance was not addressed.

Fiber-Reinforced in CRM

Fiber-reinforced is recognized for enhancing certain properties on hot mix asphalt (HMA); in particular, the addition of fibers influence the viscoelasticity of the mix and enhance dynamic modulus, moisture susceptibility and rutting and fatigue resistance (*31-33*). Limited research is available about fiber-reinforced cold mixtures. Bueno et al. (*34*) added synthetic fiber to cold emulsion mixes (CEM) in a laboratory investigation resulting in reduced Marshall Stability and resilient moduli when comparing to plain CEM. Kim and Park. (*17*) tested short polypropylene fibers on foamed recycled bitumen and found that fiber inclusion provided higher Marshall Stability, higher indirect tensile strength and rutting resistance than conventional foamed mixes. Toraldo et al. (*35*), studied the effect of cellulose and polymeric fiber on half-warm emulsion mixes and found limited enhancements on selected mixes. Successful experiences in including fibers on HMA suggest large potential benefits of the application of fibers into CFM. However, very limited research has been done in this field.

EXPERIMENTAL PROGRAM

Materials for Foamed Bitumen Mixes

Reclaimed Asphalt Pavement Properties

Reclaimed asphalt pavement (RAP) was collected from an Italian hot-mix asphalt Plant. Material was classified as 20mm maximum aggregate size (MAS). Two gradations were constituted from the original material by sieving the RAP into four fractions (20-10mm, 10-6.3mm, 6.3-2mm and <2mm) and recombining them. Because RAP material exhibited practically no filler (0.5% <0.075mm), a second gradation was constituted with the addition of 7.5% of inert filler conforming RAP+filler gradation (100:7.5, in mass). Gradations were designed having a MAS of 20mm, and following South African Asphalt Academy recommendations for foamed bitumen mixes (*2*), details of the RAP gradations are shown in figure 1.

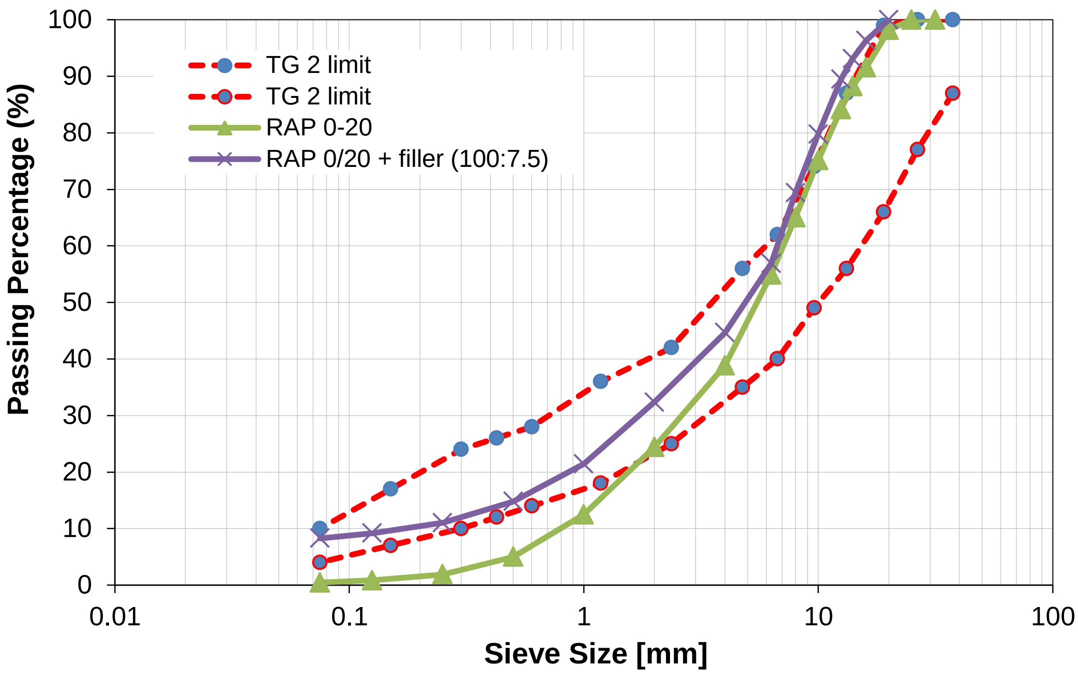

FIGURE 1 Gradations plot of RAP and mixes studied.

Foamed Bitumens and Foaming Process

Three types of bitumen were obtained from three different refineries in the northern part of Italy. For the paper they were named Bitumen A (Bit A), Bitumen B (Bit B), and Bitumen C (Bit C). Although coming from different refineries they were all classified with the same penetration grade, 70-100 dmm. One of the bitumens (Bit B) was treated with additive and was also tested without it and denominated Bitumen B without additive (Bit B NA). Bitumen foaming tests were conducted using the Wirtgen Laboratory-Scale foamed bitumen machine WLB10S to determine the optimum foaming water content (OFWC) and optimal foaming temperature considering four foaming temperatures(150°C, 160°C, 170°C, 180°C) and four foaming water content (FWC) (1%,2%,3%,4%) as recommended by Wirtgen (*1*).

FA was added to Bit B with the aim of improving its foaming properties and analyzing the effect of the additive on the mixes. Density of the FA was 0.9 gr/cm^3 and the flash point 170°C; its chemical composition was based on oleic acid diethanolamine. The dosage recommended by the supplier ranged between 0.4-0.6% by weight of bitumen; in particular, the latter content was used in the present investigation.

The bitumen basic standard properties and foaming characteristics are displayed in Table 1. Bit B was identified as a bitumen with scarce foaming capacity (acceptable ER and very short H-L) as can be observed in Table 1. More in-depth information concerning bitumens' foaming capacity can be found elsewhere (*37*).

TABLE 1 Expansion Ratio and half-life of foamed bitumens at 160°C and 3% foaming water content

Bitumens	Pen_25°C, 100g, 5s [dmm]	R&B (°C)	PI*	viscosity @160°C (Pa.s)	viscosity @135°C (Pa.s)	Foaming Temperature (°C)	FWC* (%)	ER	H-L (sec)
Bit A	133	40	-1.9	0.110	0.292	160	3	23	10
Bit B_NA	75	46	-1.4	0.175	0.500	160	3	14	2
Bit B+Add	103	45	-0.7	0.126	0.445	160	3	25	95
Bit C	86	47	-0.6	0.094	0.263	160	3	25	57

*PI: Penetration Index

*FWC: is the ratio(by mass) of the flow rate of the foamant water when FB is produced

As can be noticed from Table 1, types of bitumen with foamability categorized from scarce to exceptional were included in the study. It was expected that bitumen with higher ER and H-L would perform better than bitumen with limited or unacceptable foaming parameters. Wirtgen (*1*) recommends a minimum ER and H-L of 8 and 6, respectively. Clearly Bit B does not meet this requirement; however, the FA addition (Bit B+Add) doubled its ER and dramatically increased its H-L (almost 48 times). From Table 1, it is also possible perceives that Bit B presented the highest viscosity, lowest penetration and the second higher PI. FA in Bit B resulted a clear reduction in consistence, as evidenced in a higher penetration and viscosity reduction.

Based on foaming characteristics Bit B was selected as best candidate to investigate FA effect on mechanical properties of FM. Fiber reinforced and Portland cement impact were also investigated on selected foamed mixes with Bit B+Add.

Mixing Preparation, Compaction and Curing

Cold foamed mixes were prepared using a WLB-10S laboratory at 160°C, with 3% of foaming water by mass, and a WLM30 twin-shaft pug mill mixer. RAP was conditioned before mixing at temperatures between 23 and 25°C. The optimum moisture content (OMC) of the mixes with filler and no filler were determined after several proctor tests. For mixes with filler, the OMC was 6.5% and the dry density 2150 Kg/cm^3; in the case the mix without filler, the OMC was 6% with a dry density of 1950Kg/cm^3. Mixes were them preconditioned at 75% OMC following the experience and recommendation found in the literature (*21, 10, 25*). RAP and filler/cement were first mixed for 1 min in the twin-shaft pug mill mixer, then fiber were spread uniformly over the entire aggregates surface in the mixer, and then mixed for another minute. It was verified that this methodology produced a well-distributed and homogeneous mix. Water was added and mixed for 1 min before bitumen was foamed. RAP material inside the WLM30 was sprayed by foamed bitumen while being blended at 80% of the maximum velocity for another 1 min. Marshall specimens were prepared and compacted at 75 blows per face at room temperature, which was 25±2°C. Specimens were extruded from the mold after a period of 24h at room temperature and then cured in a forced-air oven at 40° for 5 days. With this curing period samples achieved a uniform dry state so the specimens could be tested at similar moisture content (close to 0.5%).

Experimental Program

An experimental program was designed to assess the influence of bitumen content, dynamic response at three temperatures, effect of a foaming additive, fiber reinforced and cement addition. The effect of bitumen source is studied at 3% FBC using the same gradation. The experimental program is summarized in Table 2.

TABLE 2 Experimental Program

Variable	No. of levels	Description
RAP sources	1	Maximun aggregate size 20 mm
Gradations	2	no filler (RAP100%), filler: 7.5%(RAP100%:filler7.5%)
Bitumens type	4	Bit A, Bit B, Bit C
Foaming Properties	1	160°C, 3% FBC
Foaming additives	1	Only for Bit B
Fomed bitumen content	3	1.5%, 3%, 4.5% for Bit B, other Bitumens only 3%
Cement content	1	2%(RAP mass) for selected Foamed mixes
Fibers reinforced types	2	type 1(polipropilene), type 2(polyacrylonitrile)
Fiber reinforced contents	3	0.3%, 0.15%, 0.075% on BitB+Add (% RAP weight)
Compaction effort	1	75 blows per face, marshall compactor
Curing conditions	1	5 days at 40°C
Soaked conditions	1	24h water bath at 25°C
	Mechanical test	
Dynamic modulus from indirect tension mode*	3	3 temperatures (0, 25 and 40°C), 1 frequency(2Hz)
Indirect tensile strength*	2	Dry and wet at 25°C

*3 replicates for each test

RESULTS AND ANALYSIS

Effect of Filler, Foaming Additive, and Bitumen Content

Figure 2, shows Dynamic Modulus results according to EN 12697-26 using the Indirect Tensile mode at 2Hz for three temperatures. Figure 2(a) compares the |E*| for Bit B with 0.6% of FA at three FBC; 1.5%, 3% and 4.5% for mixes with no filler (NF). Figure 2(b) presents |E*| for the same three FBC but with filler. Figure 2(c) shows same three FBC with no additive (NA). Figure 2(d) shows a comparison of three mixes at the same FBC (3%). On the basis of results displayed in Figure 2a to 2d, the following observations are made:

- The effect of the filler inclusion can be assessed by comparing Figures 2(a) and 2(b). The inclusion of 7.5% in FM showed a noticeable increasing in |E*| at 0° and 25°C for all FBC. At 40°C some varied results are observed in the case of B1.5, possibly because of the addition of filler to this low FBC does not create enough mastic in mix. This does not happen for higher FBC (B3 and B4.5). A comparison of this two mixes show that no optimal FBC can be noted at all temperatures tested. At 0°C stiffness seems to be dominated by the combined effect of residual bitumen in the RAP and FB contribution; this fact suggest that from a conservative standpoint, it may be appropriate to determine optimal FBCs at higher temperatures, at which the mixes would exhibited poor resistance to rutting. For this specific case the OFBC was 3%FBC.
- Figure 2(c) show that all |E*| values are in the same order of magnitude when comparing the same mixes produced with the FA (mixes B_, Figure 2(b)). This is important because a FA is used for improving foaming characteristics in terms of having greater ER and longer H-L providing a better dispersion of the foamed bitumen and in consequence better mechanical performance (*9-11*). Even at 25°C, mixes with NA presented higher stiffness than mixes with FA. In general, FM with and without the FA seems to show similar range of stiffness, suggesting that foamability is not the main characteristic governing foamed mixes strength. A secondary effect noted in Table 1, is that the additive reduced Bit B viscosity and increased its penetration value, clear signs that bitumen suffered a softening that in turn could also affects the bitumen aggregate coating into the mix. The FA showed a positive benefits

for mix B3 at 40°C, where this mix exhibited the higher dynamic modulus with respect to others FBC, but also considering mixes without the additive.

- Figure 2(d) seems to show a trend for low to intermediate temperature (0°C to 25°C) where viscosity of Bit B_NA impacts the strength. For higher temperatures (40°C) bitumen dispersion would be more important. To confirm this postulate, bitumen dispersion inside each mix specimens should be analyzed, but this analysis is not addressed in this paper.

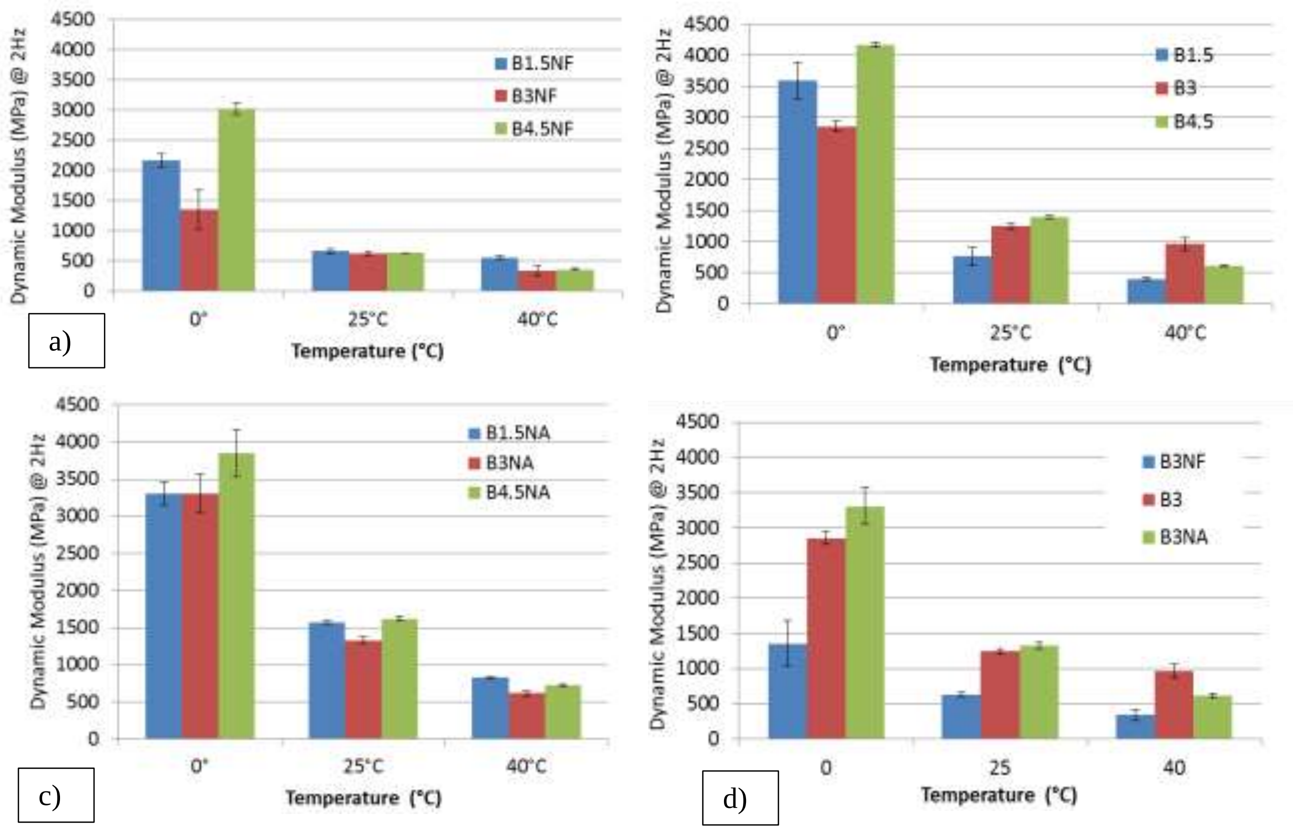

FIGURE 2 Dynamic modulus |E*| for Bit B at three temperatures and three FBC, (a) No filler and FA, (b)filler and FA, (c)filler and NA, (d) Comparison of mixes with same FBC with FA and without FA.

Figure 3 show the ITS (wet and dry) and ITS retained (ITSR) of mixes with NF, FA and NA. ITS has been reported as a good test to identify the Optimum Foamed Bitumen Content (OFCB) (*12, 18*). All FM suffered a significant reduction on ITS wet with respect to ITS dry (From 40% for lower FBC to 25% for higher FBC). The greater reductions were perceived on mixes with the FA; in contrast, NA foaming mixes exhibited higher ITSR for 3% and 4.5%FBC. Overall ITSR confirmed a direct relationship with FBC content, the higher the FBC the higher the ITSR.

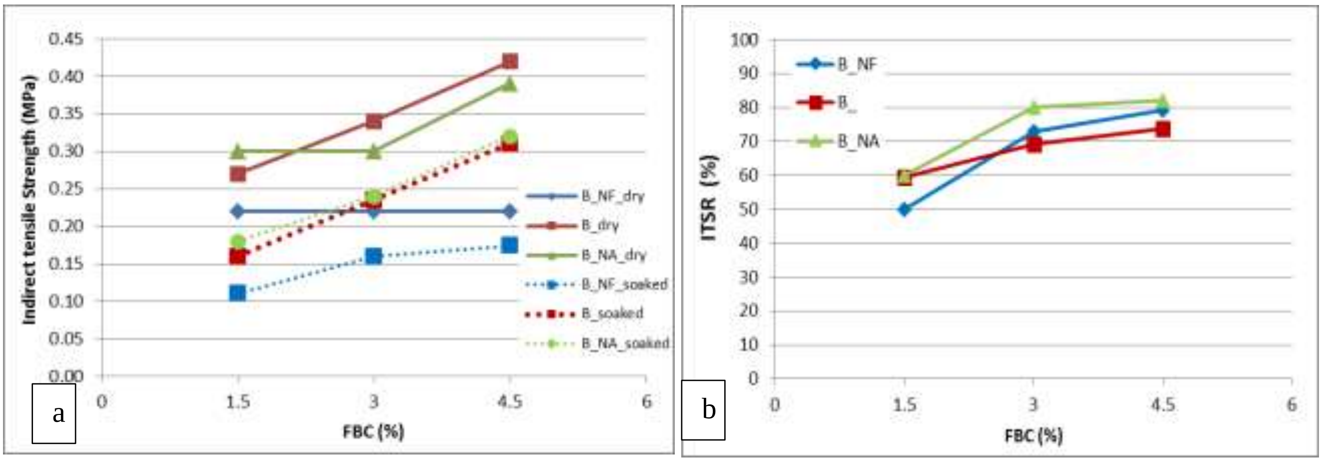

FIGURE 3 Indirect Tensile Strength for Bit B at three FBC; no filler, with FA and without FA mixes; (a) ITS_dry and soaked, (b) Indirect Tensile Strength Retained.

Fiber Reinforced Effect

Figure 4 displays results of |E*| for FM with two types of fiber reinforced, F1-polypropylene mesh form (a) and F2-polypropylene monofilament form (b). Three fiber contents were assessed in order to find an optimum fiber-reinforced content. Figure 4(c) and 4(d) show mixes appearance after mixing. It can be seen from Figure 4(a) that F1 increased the Dynamic modulus especially at 0°C (34% higher). Optimum fiber content was identified for mixes with B3F1_0.075% where higher dynamic moduli were also exhibited at 25°C (24%). For F2, greater improvements were perceived for all fiber contents at all temperatures studied. Optimum fiber content is noted at B3F2_0.15%, showing increments on dynamic moduli at 0°C and 25°C of 27% and 28% respectively. F2 effects at 40°C decreased |E*|, it could explained because of the viscoelasticity of bitumen which at higher temperature, bitumen become softer and aggregates interlock domain the mechanical behavior in the mix. In consequence the three dimensional mastic network created by FB, filler and fibers may become softer losing effectivity in the dynamic response of the foamed mix. It should be distinguished that all fiber-reinforced mixes were produced with the foaming additives, as a result, fiber effects was detrimental for higher temperatures as well. This detrimental effect at high temperatures should be verified on proper high-temperature performance tests to assess the direct influence in the mixes for instance, rutting resistance, where fiber effect could provide its tensile strength during a plastic deformation state.

For both fiber types, |E*| exceeded from lightly to a significant way the dynamic response of mixes without the FA (B3NA).

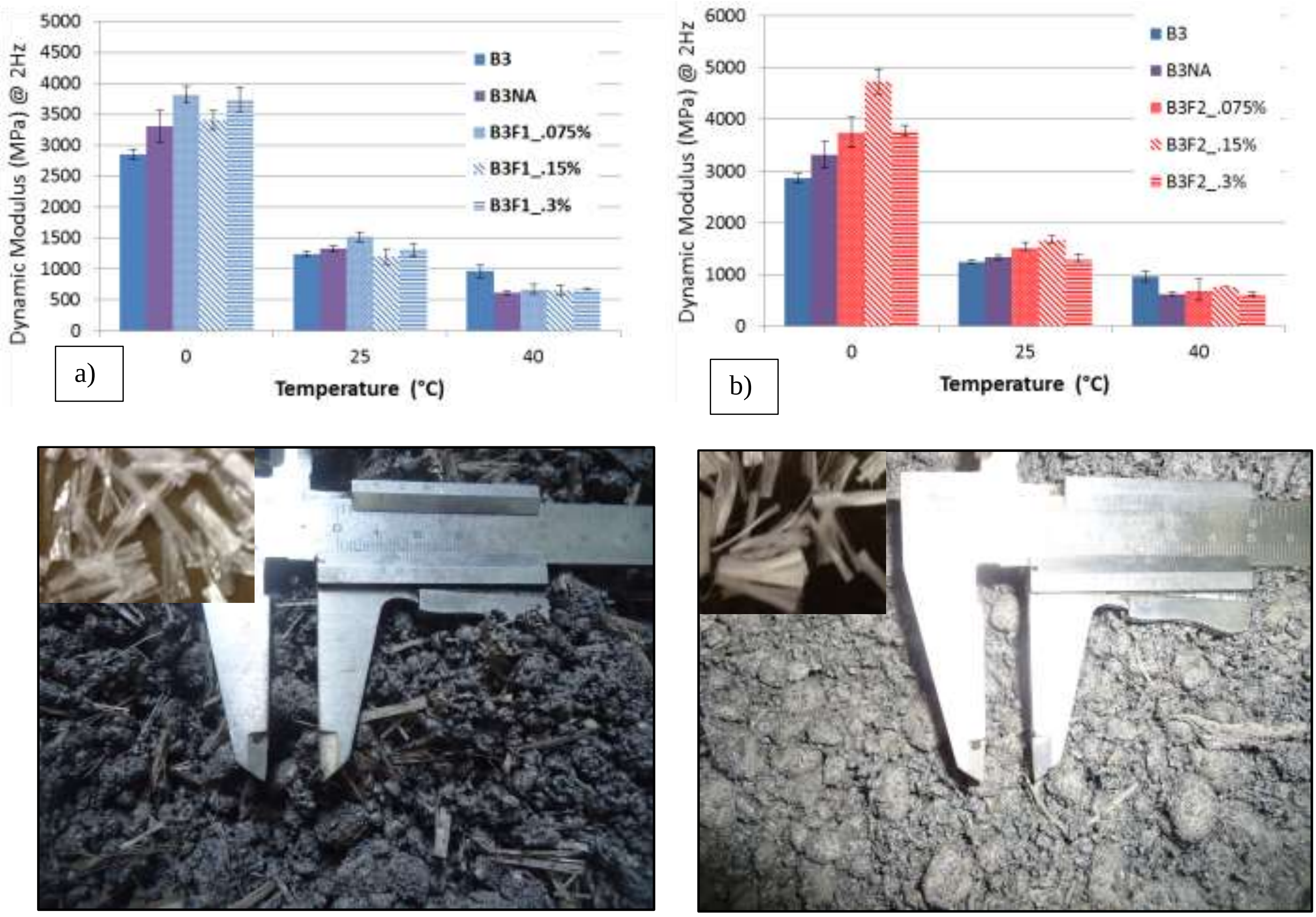

FIGURE 4 Fiber reinforced effect on FBM B3 (Bit B+Add); (a) polypropylene mesh form F1, (b) polypropylene monofilament form F2, (c) a close-up F1 before compaction, (d) F2 before compaction.

Table 2 shows the moisture effect on |E*| and ITS for FBM reinforced with fibers. Although both fibers showed significant increase in |E*|dry for specific fiber contents, no significant improvements were observed at wet condition with respect to B3 mix. Fiber reinforced improved moisture resistance of B3 mixes, in particular when F2 was applied. ITS value for the control mix increased from 0.23 MPa to a maxima of 0.30 in the case of B3F2_0.075%. ITSR for all fiber types and contents were at the same level in the case of F1, while for F2 provided higher retained strength than the control mix.

TABLE 2 Moisture effect on |E*| and ITS at 25°C

Foamed Bitumen	|E*|dry @ 25°C (MPa)	|E*|wet @25°C (MPa)	Ratio Ewet/Edry_25°C (%)	ITS @25°C (MPa)	ITSwet@25°C (MPa)	TSR_25°C (%)
B3	1247	979	79	0.34	0.23	69
B3NA	1331	722	54	0.30	0.24	80
B3F1_.075%	1525	972	64	0.33	0.23	70
B3F1_.15%	1201	697	58	0.33	0.23	70
B3F1_.3%	1304	843	65	0.34	0.25	74
B3F2_.075%	1529	901	59	0.39	0.30	77
B3F2_.15%	1674	872	52	0.38	0.28	74
B3F2_.3%	1306	619	47	0.31	0.24	77

Effect of Bitumen Source and Cement Addition

Figure 5(a) presents dynamic modulus at three temperatures for two Bitumens. Mixes presented contains all a FBC of 3%, and were foamed at 160°C with 3% FWC. As was mentioned before only FM B3 was prepared with the FA. Comparing this four FM, several observations can be drawn considering that each bitumen provided very different foaming properties and physical properties (Table 1):

- The literature in general has reported that bitumens with higher ER and longer H-L provide better foamed bitumen dispersion into the mix, in consequence better mechanical properties (strength). Jones et al (37) suggested choosing the bitumen with the best foamability; i.e., to compute the product of the ER and H-L and to select the one with the highest product (Table1). In decreasing order we have; Bit B (BitB+Add) provided a product between ER and H-L of 2375 times-sec, Bit C=1425 times-sec, Bit A=230 times-sec and Bit B_NA=28 times-sec. Dynamic response by means of the dynamic modulus showed a different trend with respect to the foamability ranking expressed by the product of ER and H-L. FBM prepared with Bit A(ER=23, H-L=10) and Bit C(ER=25, H-L=57) revealed higher moduli at 0°C and 25°C. Thus, bitumen viscosity effect seems to be independent of the foamed mixes mechanical performance. Bitumen with lower viscosity exhibited superior dynamic moduli at least at two of the temperature tested. The addition of the FA to Bit B, does not exhibited greater improvement on dynamic modulus even with respect of the same bitumen but without the additive.
- Figure 5(b) shows the effect of the addition of Portland cement as active filler for FBM with a 3%FBC and 2% Portland cement, including mix B3C2 which was prepared with the FA. In general, substantial increases are noted for all FBMs at all temperatures. For all FBM´s the cement effect at least doubled the dynamic modulus for the same mixes without cement.
- Figure 6(a) and 6(b) show the impact of the Portland cement on |E*|wet and ITS wet respectively. These results confirm the important benefits of the Portland cement on moisture resistance. Retained resistance in |E*| wet and ITS wet provided dry/wet ratio of at least 88% for both dynamic modulus and Indirect tensile strength. It should be highlighted that moisture sensitivity seems to be more critical when conditioned dynamic modulus are analyzed. For FBM without cement (Figure 6(a), the ratio |E*|wet/dry showed more sensitivity with respect to that of the ITSR. For instance in mixes C3 and A3, ITSR values exhibited 71% and 90%, whereas for the ratio |E*|wet/dry 59% and 63% for the same mixes. Similar effect can be noticed in Table 2.

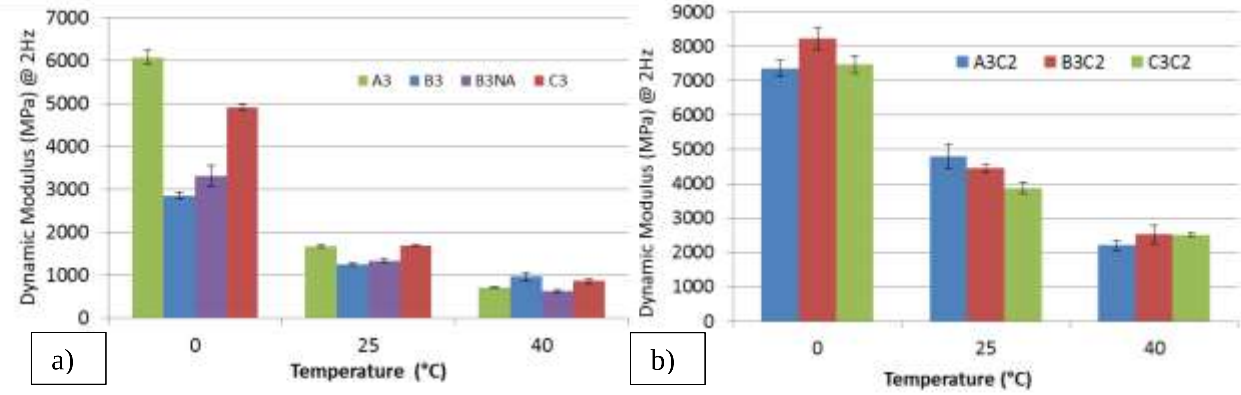

FIGURE 5 Effect of bitumen source (a) and effect of cement addition (b)

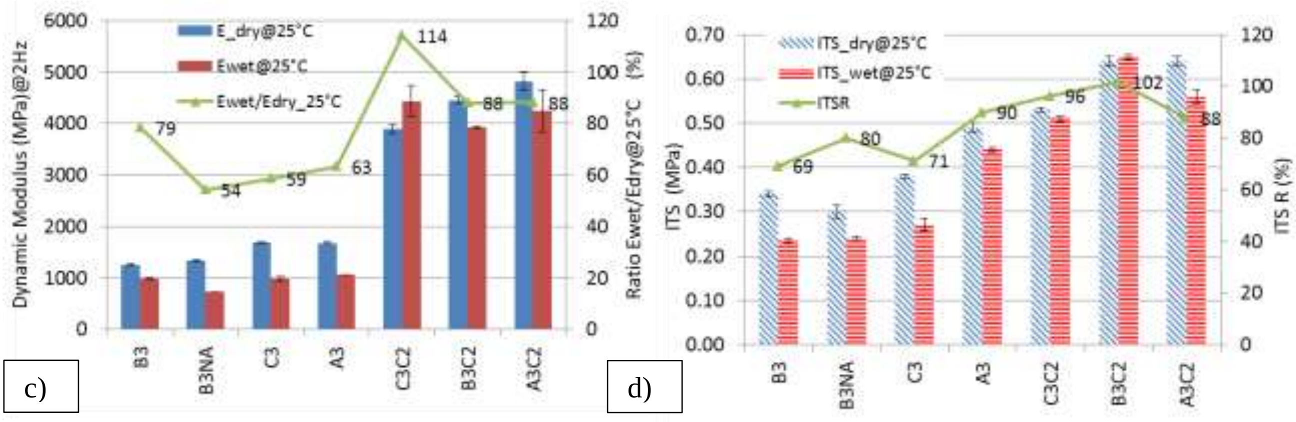

FIGURE 6 Moisture sensitivity, (a) dynamic modulus, (b) Indirect tensile strength

CONCLUSIONS

A laboratory investigation studied the impact of three type of bitumens, one addittive, Portland cement, and two types of fiber-reinforced on the mechanical properties of recycled foamed mixes. Mechanical properties were evaluated by means of the dynamic moduli at 2Hz at three temperatures, and the ITS test in both dry and wet condition. The main conclusions are summarized as follows:

- The addition of 7.5% filler to recycled foamed mixes improved the mechanical properties for all temperatures; the addition of filler contributes to create more mastic, increasing stiffness and tensile strength, and moisture sensitivity.
- The FA improved the foaming properties of the poor-perfoming bitumen; however, this improvement was not always reflected in the mechanical properties. Mixes with the same bitumen but without FA ehxibited higher dynamic modulus and better moisture sensitivity.
- Fiber-reinforced increased the mechanical properties at low and intermediate temperatures. The optimum fiber contents were 0.075%(mass aggregates) for F1 and 0.15% for F2. The contribution of F2 was evident at 0°C, temperature at which the dynamic modulus increased of 75% with respecto B3. Moisture sensitivity with F2 fiber was improved as well.
- The comparison of bitumens from different sources showed that bitumens with relative low but still apppropiate foamibility provided better mechanical performance than the bitumen with the best foamibility.
- The study also confirmed the significangt contribution of the additon of Portland cement to increase strength and reduce moisture sensitivity.

Another interesting finding is that the retained dynamic modulus (Ewet/Wdry) resulted to be more conservative than ITSR, moisture damage seems to be more evident under dynamic response.

In summary, the experiment show that fiber-reinforced and foaming additives can help improve specific performance characteristics of foamed mixes. However, more complex tests (e.g., fatigue, rutting and cyclic triaxial tests) should be considered to fully understand the effect fiber-reinforced and foaming additives on FM performance and its evolution.
Finally, it is recomended that when using foaming additives, the designers should test their effect on the foamed mixes and the mixes thermal susceptibility and instead of basing it solely on the foaming characteristics.

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