Hindawi Publishing Corporation
Advances in Materials Science and Engineering
Volume 2016, Article ID 4894351, 9 pages
http://dx.doi.org/10.1155/2016/4894351

Research Article

Investigation on the Combined Effect of Fibers and Cement on the Mechanical Performance of Foamed Bitumen Mixtures Containing 100% RAP

Ehsan Ashouri Taziani, Emanuele Toraldo, Filippo Giustozzi, and Maurizio Crispino

Polytechnic University of Milan, 20133 Milan, Italy

Correspondence should be addressed to Ehsan Ashouri Taziani; ehsan.ashouri@polimi.it

Received 18 July 2016; Accepted 4 October 2016

Academic Editor: Charles C. Sorrell

Concerns about virgin aggregate sources and increasing demands for construction materials of transport infrastructures as the key parameters in development are the most important reasons, which convinced pavement engineers to develop new methods in order to use higher amount of recycled asphalt pavement (RAP). One of the common methodologies to produce mixtures containing RAP is foamed bitumen mix (FBM). In addition, according to previous research studies, incorporating various types of fibers and hydraulic binders such as cement could significantly improve the mechanical performance of mixtures. The present research study evaluated FBM containing 100% RAP and two types of fiber and Portland cement. Dynamic modulus, unconfined dynamic creep compression, and indirect tensile strength were evaluated in the laboratory at optimum moisture content, which was investigated in this research. Both types of fiber and cement proved to enhance specific properties of mixtures.

1. Introduction

Cold recycling method is a widely accepted strategy among pavement industries with regard to the lower environmental effects due to reduced emissions, decreasing amount of virgin aggregates, and economic benefits. In addition, the possibility of using high amount of recycled asphalt pavement (RAP) made this method even more interesting for pavement communities; however, some production and mechanical performance considerations still need to be cleared.

As the production temperature of cold-recycled mixes is lower than conventional methods, an agent is required to improve the workability of bitumen during mixing and compaction process. On account of that, foamed bitumen (FB) or bitumen emulsions are currently used, often in combination with Portland cement. The application of foamed bitumen was first modified and presented by Mobil Australia in 1968 and used in cold in place pavement strategy since then [1]. Foamed bitumen formation is based on interaction between 1 to 4% of water and hot bitumen (150–180°C) which results in an increment in bitumen volume and temporary changes in physical characteristics. Furthermore, the application of foaming additives in order to improve the bitumen foamability was studied in previous research; however, the rheological effect of such additives and their relationship with foaming water content (FWC) proved to be critical [2]. On the other hand, literature shows that application of cement can be used to amend the lack of bearing capacity of cold-recycled pavement layers containing high amount of RAP; however, excessive content of cement could result in extreme stiffness and lower resistance to cracking [3]. For that reason, fibers are commonly applied to control the crack propagation due to high stiffness in cement treated mixtures [4, 5].

Design and curing process of foamed bitumen mixtures can highly affect the final performance of the mixture. For that reason, optimum foamed content (OFC) and optimum moisture content (OMC) must be carefully considered through mechanical laboratory tests [6]. Dynamic modulus test and indirect tensile strength (ITS) test are often conducted by researchers to evaluate the mechanical characteristics of mixtures and obtain OFC and OMC [7–10]. Commonly used mix design such as Marshall, Hveem,

Table 1: Basic characteristics of RAP materials.

Parameter	RAP	RAP + filler
Optimum moisture content (%)[1]	6	6.5
Maximum dry density (Kg/cm^2)[1]	1960	2155
G_{mm}[2]	2.57	—
Residual bitumen content (%)	5%	—

[1]It is determined by the modified Proctor method (EN 13286-2).
[2]It is determined by the Rice method.

and Superpave design methods are reported by previous research studies [8, 11]. Furthermore, several researches showed that mixing, curing, and compaction procedures must be considered carefully due to their great influence on overall performance of mixture [12–15].

Previous studies on inclusion of fiber in hot asphalt mixtures presented several improvements in performance of mixtures such as dynamic modulus, moisture susceptibility, and permanent deformations [16–19]. Fibers in cold emulsion mixes provided lower values of Marshall Stability and dynamic modulus [19] and had limited improvement on workability, elastic stiffness, and indirect tensile strength performance of half-warm emulsion mixtures [20]; addition of fibers to foamed bitumen mixtures improved the ITS, rutting resistance, and Marshall Stability values [21]. Generally, fibers can affect the specific characteristics of mixtures such as moisture sensitivities, fatigue life, and dynamic modulus [16–19], but the application of various types of fibers beside other types of additives and fillers should be further studied. For this purpose, Portland cement ranging from 1 to 2.5% has been incorporated by previous researchers as an active filler to evaluate the mechanical performance and moisture sensitivity of mixtures [21–23].

According to the abovementioned background, this research study aimed to further investigate the mechanical performance of foamed bitumen mixtures containing 100% RAP and application of two types of polypropylene fiber and Portland cement as active filler. Laboratory tests included two parts; in the first part, optimum content of foamed bitumen (FB) on the optimum moisture content (OMC) was determined while the second part, based on the obtained results, studied the effect of two types of fibers and Portland cement on mechanical characterization of FBM.

2. Experimentation

2.1. Materials. The aggregate used in this study was RAP, which was sourced from a local asphalt plant in northern Italy. The classification of materials was based on 20 mm maximum aggregate size (MAS) and followed the foamed bitumen mixtures recommendations provided by South Africa Asphalt Academy (TG2) [24]. RAP material was further sieved into four gradations (20–10 mm, 10–6.3 mm, 6.3–2 mm, and <2 mm). As RAP material had almost no filler, 7.5% of calcareous filler was incorporated into the mixtures. The final gradation is presented in Figure 1. The basic physical characterization of RAP is shown in Table 1.

The virgin bitumen used to produce the foamed bitumen was classified 70–100 dmm penetration grade [25]. Physical

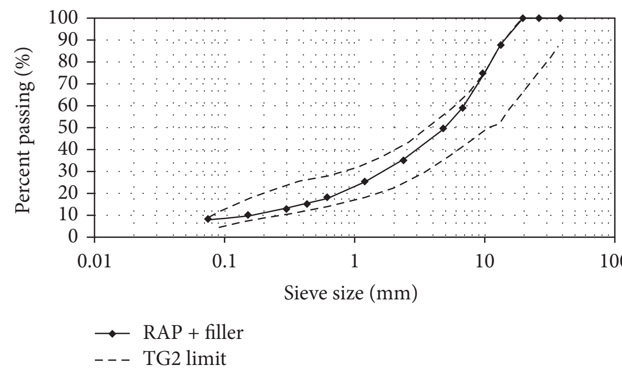


Figure 1: RAP gradation.

properties of virgin bitumen and characteristics of foamed bitumen are presented in Table 2.

Two types of polypropylene fiber were used in this study, namely, F1 and F2 (Figure 2). Fiber content varied from 0.075% to 0.30% with respect to the weight of the aggregate (includes RAP and filler). The properties of fibers are reported in Table 3.

2.2. Experimental Program. The experimentation was divided into two main parts as mentioned before.

The first part is dedicated to find the optimum FB content of mixtures on 75% of OMC and also to reassess the OMC for identified FB. On one hand, OMC (FB) was assessed while the 3.0% FB was kept constant to verify the moisture content at 50%, 75%, and 100% of the OMC which was previously obtained from the Proctor test on RAP. Then, the OFB content was evaluated considering 1.5%, 3.0%, and 4.5% of foamed bitumen (by the weight of RAP) on constant value of OMC.

The second part of the experimental campaign focused on the evaluation of the effect of two types of fibers (fiber content ranged from 0.30% to 0.075% by weight of RAP) and 2.0% of Portland cement. Improvements were first analyzed separately while the combined effects of fiber (0.075% F2) and cement were studied at a later stage.

A laboratory asphalt foaming unit and a twin-shaft pug mill mixer was used to produce the cold foamed bitumen (foaming bitumen temperature of 160°C) with 3% of foaming water by mass. RAP material was put in a climatic chamber at 25°C prior to mixing. In addition, Proctor test has been used to determine the OMC for RAP optimal compaction. Based on the Proctor hammer results, dry density and OMC of mixtures with filler were, respectively, 2150 kg/cm^3 and 6.5%; however, the present research adopted 75% of OMC value

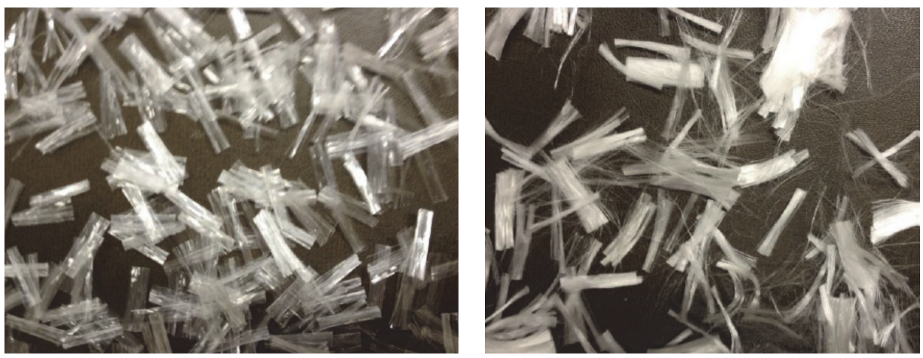
Table 2: Characteristics of bitumen.

Pen [25°C] (dmm)	R&B (°C)	PI[a]	Viscosity @ 160°C (Pa s)	Viscosity @ 135°C (Pa s)	Foaming temperature (°C)	FWC[b] (%)	ER[c]	H-L[d] (s)
75	46	−1.4	0.175	0.500	160	3	14	2

[a]PI: penetration index. [b]FWC: the ratio (by mass) of the flow rate of the water when foam bitumen is produced. [c]Expansion Ratio. [d]Half-Life.

Table 3: Properties of fibers.

Code	Type	Form	Specific gravity	Length (mm)	Decomposition temperature (°C)	Tensile strength (MPa)
F1	Polypropylene	Mesh	0.91	20	160	350
F2		Monofilament	0.91	15	160	450



F1 F2

Figure 2: Polypropylene fibers.

as the final moisture content of mixtures based on outcomes from previous studies [7, 13].

Prior to compaction, RAP and filler (and in second part of study Portland cement) were mixed together for one minute using the abovementioned mixer. When included, fibers were then added and the mixing process continues for another minute to produce a homogeneous mixture. Prior to foaming bitumen, water was added to the RAP and mixed for one minute. Finally, foamed bitumen was sprayed in the mixer directly onto the aggregates and mixing process was continued for one minute. To prepare the Marshall samples, 75 compaction blows at 25 ± 2°C on each side have been conducted. The specimens were cured for 24 h at room temperature, then 5 days at 40°C, and finally 24 days at 25°C prior to test.

The obtained samples were identified by an ID which described the presence of filler (indicated by letter F), percentage of foamed bitumen (FB), moisture content based on OMC, type and amount of fiber (F1 or F2), and cement content. For example, the mixture ID containing filler, 3.0% of FB, 75% of OMC, 2.0% cement, and 0.075% (by the weight of the RAP) of fiber type 2 will be F3075 + 2% CEM + 0.075F2.

The entire laboratory investigation was based on volumetric and mechanical tests. Volumetric characteristics were assessed by calculating the void content [26] starting from the measurement of both bulk density of the samples [27] and Theoretical Maximum Density of the corresponding loose mixtures [28].

In order to evaluate the effects of bitumen content, moisture, types of fiber, and cement content on the mechanical performance of mixtures, laboratory tests were conducted on three replicates for each test. Dynamic modulus at 25°C [29], unconfined creep compressive test at 40°C [30], and indirect tensile strength [31] at 25°C were used to investigate the mechanical behavior of the mixtures.

3. Results and Discussion

3.1. Moisture and Foamed Bitumen Content Effect. Moisture and foamed bitumen content affect mixtures as depicted in Figures 3 and 4, respectively. In case of evaluation of the OMC (FB), graphs in Figure 3 show that the minimum voids content was achieved at 75% of OMC. Moreover, this mixture (F3075) presented the best mechanical performance in terms of stiffness, creep resistance, and ITS. On account of that, 75% of OMC was selected for the remaining part of the experimentation. Regarding the OFB, the results in Figure 4 show that the optimum content of foamed bitumen is 3.0%. Specifically, this binder content allowed controlling the volumetric characteristics of the mixtures (voids similar to F1575 and lower than F4575), and the mixture F3075 showed good resistance to rutting (creep tests) and satisfactory ITS

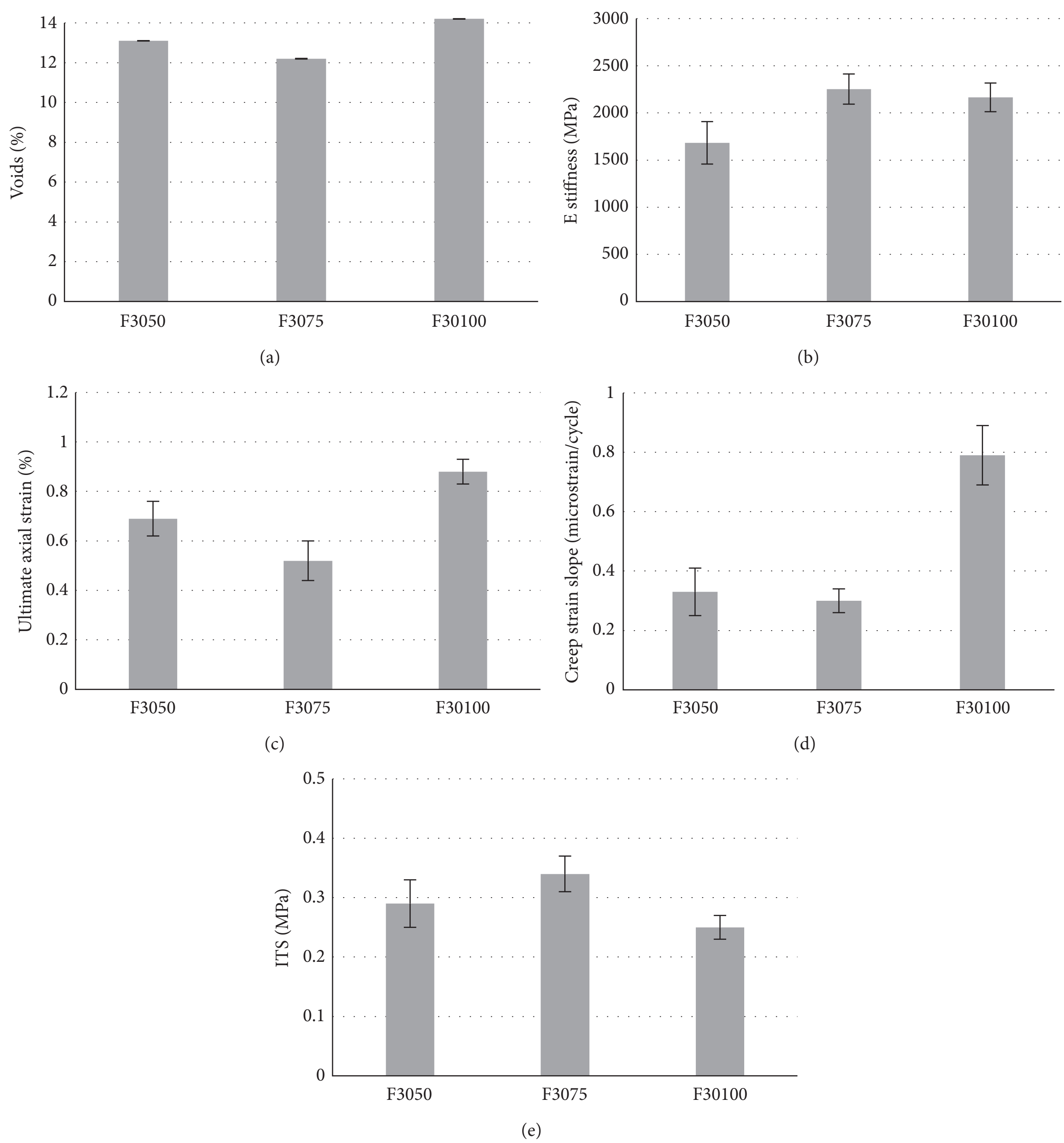


Figure 3: Effect of OMC content on mixtures: (a) voids, (b) stiffness, (c) UAS, (d) CSS, and (e) ITS. E: Stiffness Modulus.

(15% lower than F4575, which showed the best performance). Finally, all the mixtures exhibited similar stiffness. Based on the first part of the research, optimum content of both moisture (OMS (FB) which was 75%) and foamed bitumen (OFB which was 3.0%) was selected as a control mixture for the next part of the investigation.

It is important to note that foamed bitumen mixes exhibited very high voids and normally encompasses void values between 9 and 16%. In fact, the higher void contents were observed to FBM without any quantity of filler and generally the higher the FBC the higher the void content [7].

On the other hand, it should be noticed that differences in void content values on mixes are lesser than one percentage point. For example, varied results may be influenced by the high void content of specimens and the standard method for determining the bulk density which was the conventional one for HMA [26].

3.2. Effects of Fiber and Cement. The results of void content and dynamic modulus for mixtures containing three different contents (0.075%, 0.15%, and 0.30% by weight of RAP) of two types of fiber (F1 and F2) are shown in Figure 5; FB and OMC

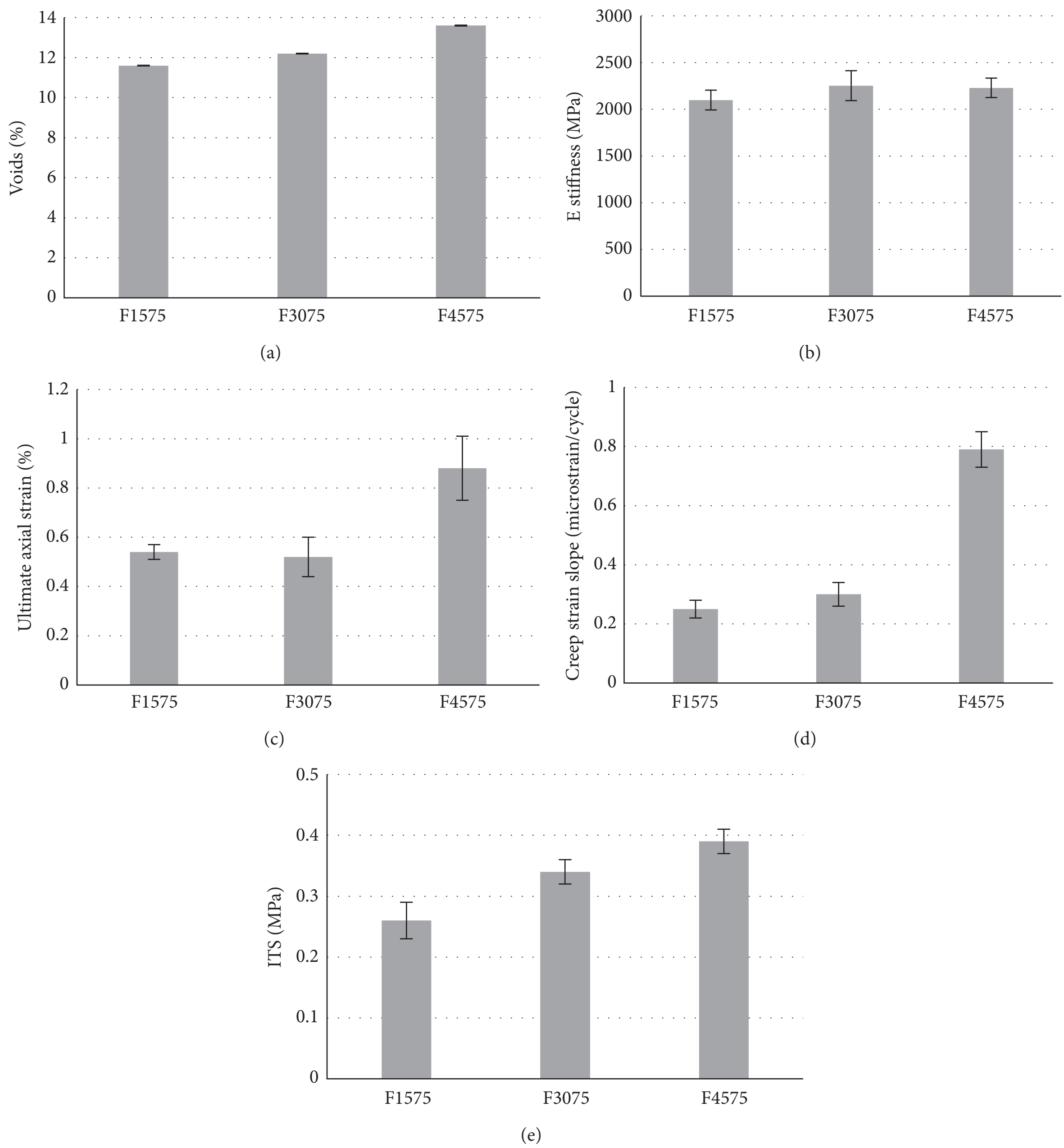


Figure 4: Effect of FB content on mixtures containing 75% OMC: (a) voids, (b) stiffness, (c) UAS, (d) CSS, and (e) ITS. E: Stiffness Modulus.

were kept constant as identified in the previous section. As it can be seen, voids contents of mixtures are similar although samples containing the greatest amount of fiber (i.e.; 0.30% F2) exhibited the highest void content. In other words, the addition of fiber reinforced ended in an increment in void content. As expected, there was a correlation between voids content and stiffness; increment in void content ended up in reduced stiffness and, except for the mix with 0.30% F2, addition of both types of fiber slightly (up to 5%) increased the dynamic modulus.

Figures 5(c) and 5(d) show the creep test results of mixtures containing both types of fibers and the control samples (F3075). Based on the charts, addition of fibers improved both ultimate axial strain (UAS) and creep strain slope (CSS) values. Again, except for 0.30% F2 samples, increasing the content of both types of fibers ended up in decreasing UAS values. In case of CSS values, results were more scattered as identified by data dispersion in the graphs; generally, F1 samples showed equal values to F3075 (except for 0.15% F1 which represented 13% lower values), while F2 samples represented up to 40% higher CSS values.

Based on ITS results of mixtures (Figure 5(e)), samples with various percentage of F1 displayed equal values to control mixtures (F3075). On the contrary, F2 samples

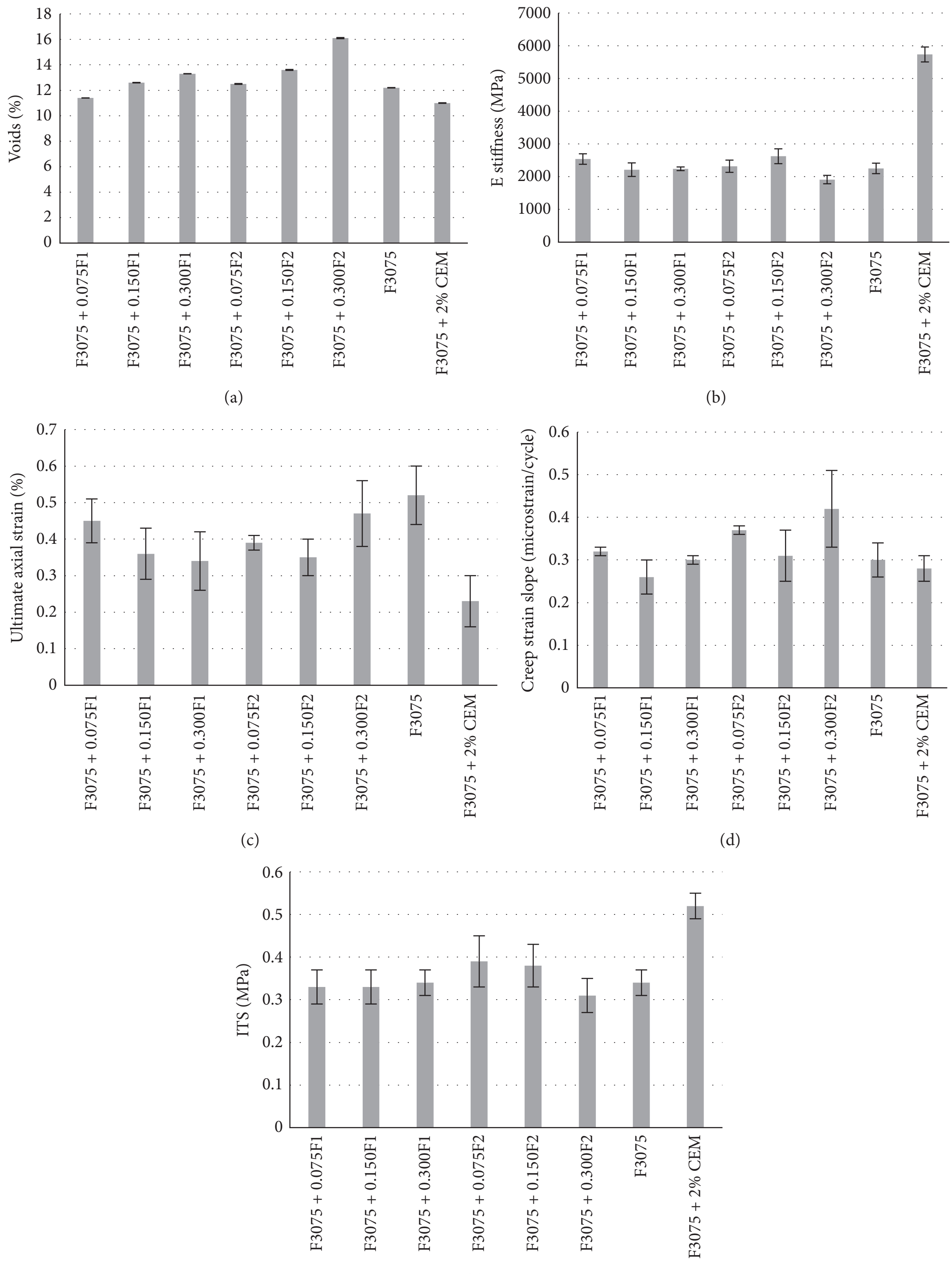


Figure 5: Effect of fiber types on (a) voids, (b) stiffness, (c) UAS, (d) CSS, and (e) ITS. E: Stiffness Modulus.

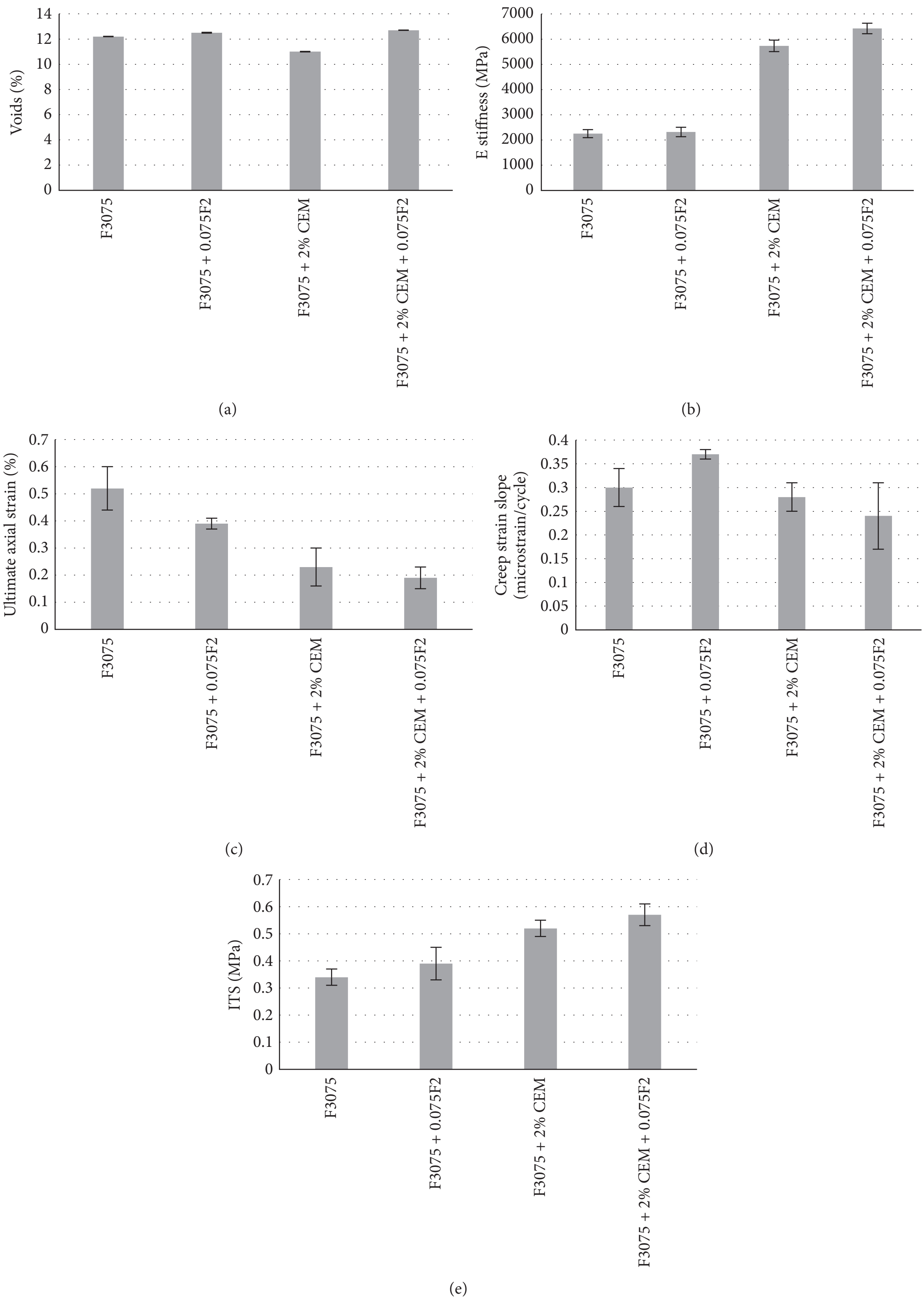


FIGURE 6: Effect of cement on (a) voids, (b) stiffness, (c) UAS, (d) CSS, and (e) ITS. E: Stiffness Modulus.

presented up to 15% higher ITS values; however, mixtures containing 0.30% F2 showed the lowest values among all mixtures (around 9% lower than F3075).

Generally, based on the overall results of previous tests, mixtures containing 3.0% of foamed bitumen, 75% of OMC, and 0.075% content of F2 (F3075 + 0.075F2) have been selected in order to evaluate the effect of Portland cement as active filler on the performance of the mixtures.

As illustrated in Figure 6, the addition of 2.0% cement (by weight of aggregates) decreased the void content of mixtures and almost doubled the stiffness whereas addition of cement and fiber, simultaneously, resulted in the greatest values of dynamic modulus.

The effect of cement on creep performance of mixtures can be seen in Figures 6(c) and 6(d). Mixtures containing cement presented the lowest values of UAS; cement indeed increased the stiffness of mixtures and made them less prone to permanent deformations. In case of CSS, addition of cement decreased the strain slope (i.e.; reduced rutting potential of the mix) and using both fiber and cement further enhanced the resistance to permanent deformations.

Figure 6(e) shows the effect of cement on ITS of mixtures. Addition of cement highly affected the strength of mixtures and mixtures containing cement presented higher ITS values in comparison with others (up to +33%). Adding fiber to mixtures containing cement could further enhance the tensile strength generating the well-known net effect within the material components.

4. Conclusions

The research was conducted to evaluate the effect of foamed bitumen content, moisture, two types of fiber, and cement as active filler on the performance of cold-recycled mixtures containing 100% of RAP. The laboratory tests included dynamic modulus, unconfined creep compression, and indirect tensile strength tests; based on the results, the following conclusions can be drawn:

(i) The preliminary laboratory tests on optimum content of foamed bitumen in mixtures with 100% RAP showed that samples containing 3.0% FB had greater stiffness with 75% OMC. It should be noticed that the aforementioned moisture content was also selected according to previous research.

(ii) Both types of polypropylene fibers increased the mechanical performance of recycled mixtures. Mixtures containing 0.075% F1 and 0.15% F2 exhibited greater stiffness (12% and 16% greater than samples without fibers), while samples containing 0.15% of both fibers displayed the greatest resistance to rutting (i.e., lowest creep strain slope). 0.30% F1 and 0.075% F2 provided greater values of ITS although F2-mixtures performed better (up to 15% greater than control mixture).

(iii) Based on the results, addition of 2.0% of cement could significantly increase the mechanical properties of mixtures such as dynamic modulus (up to 150%), tensile strength (up to 53%), and improved permanent deformation (7% lower creep strain slope and 56% lower ultimate axial strain). In case of adding polypropylene fiber to samples containing cement, the values were greater where tensile strength increased up to 68% and stiffness increased up to 180%.

Finally, the laboratory investigation showed that inclusion of polypropylene fibers and cement in foamed bitumen recycled mixtures containing 100% RAP can significantly increase specific properties of mixtures although further investigation should be conducted to evaluate the interaction of fibers and active fillers in mixtures.

Competing Interests

The authors declare no competing interests regarding the publication of this article.

References

[1] *Wirtgen Cold Recycling Technology Manual*, Wirtgen, Windhagen, Germany, 1st edition, 2012.

[2] G. Martinez-Arguelles, F. Giustozzi, M. Crispino, and G. W. Flintsch, "Investigating physical and rheological properties of foamed bitumen," *Construction and Building Materials*, vol. 72, pp. 423–433, 2014.

[3] E. Toraldo, E. Mariani, and M. Crispino, "Laboratory investigation into the effects of fibres and bituminous emulsion on cement-treated recycled materials for road pavements," *European Journal of Environmental and Civil Engineering*, vol. 20, no. 7, pp. 725–736, 2016.

[4] G. Da Rios, E. Toraldo, and E. Mariani, "Increasing durability of recycled cement bound materials: laboratory investigation on the effects of bituminous emulsions," in *Proceedings of the 1st International Symposium on Life-Cycle Civil Engineering (IALCCE '08)*, pp. 137–142, Varenna, Italy, June 2008.

[5] A. Hamidi and M. Hooresfand, "Effect of fiber reinforcement on triaxial shear behavior of cement treated sand," *Geotextiles and Geomembranes*, vol. 36, pp. 1–9, 2013.

[6] G. Martinez-Arguelles, F. Giustozzi, M. Crispino, and G. W. Flintsch, "Laboratory investigation on mechanical performance of cold foamed bitumen mixes: bitumen source, foaming additive, fiber-reinforcement and cement effect," *Construction and Building Materials*, vol. 93, pp. 241–248, 2015.

[7] K. Muthen, *Foamed Asphalt Mixes-Mix Design Procedure*, SABITA Ltd & CSIR Transportek, 1998.

[8] Y. Kim and H. D. Lee, "Development of mix design procedure for cold in-place recycling with foamed asphalt," *Journal of Materials in Civil Engineering*, vol. 18, no. 1, pp. 116–124, 2006.

[9] L. N. Mohammad, M. Y. Abu-Farsakh, Z. Wu, and C. Abadie, "Louisiana experience with foamed recycled asphalt pavement base materials," *Transportation Research Record*, vol. 1832, pp. 17–24, 2003.

[10] Y. Kim, H. D. Lee, and M. Heitzman, "Dynamic modulus and repeated load tests of cold in-place recycling mixtures using foamed asphalt," *Journal of Materials in Civil Engineering*, vol. 21, no. 6, pp. 279–285, 2009.

[11] K. Kuna, G. Airey, and N. Thorn, "Laboratory mix design procedure for foamed bitumen mixtures," *Transportation Research Record*, vol. 2444, pp. 1–10, 2014.

[12] B. Diefenderfer and A. Apeagyei, "Time-dependent structural response of full-depth reclamation," *Transportation Research Record*, vol. 2253, pp. 3–9, 2011.

[13] P. Fu, D. Jones, J. T. Harvey, and F. A. Halles, "Investigation of the curing mechanism of foamed asphalt mixes based on micromechanics principles," *Journal of Materials in Civil Engineering*, vol. 22, no. 1, Article ID 012001QMT, pp. 29–38, 2010.

[14] Y. Kim, S. Im, and H. D. Lee, "Impacts of curing time and moisture content on engineering properties of cold in-place recycling mixtures using foamed or emulsified asphalt," *Journal of Materials in Civil Engineering*, vol. 23, no. 5, pp. 542–553, 2011.

[15] M. Iwański and A. Chomicz-Kowalska, "Evaluation of the pavement performance," *Bulletin of the Polish Academy of Sciences: Technical Sciences*, vol. 63, no. 1, pp. 97–105, 2015.

[16] S. M. Abtahi, M. Sheikhzadeh, and S. M. Hejazi, "Fiber-reinforced asphalt-concrete—a review," *Construction and Building Materials*, vol. 24, no. 6, pp. 871–877, 2010.

[17] C. Bonica, E. Toraldo, L. Andena, C. Marano, and E. Mariani, "The effects of fibers on the performance of bituminous mastics for road pavements," *Composites Part B: Engineering*, vol. 95, pp. 76–81, 2016.

[18] E. Toraldo, E. Mariani, and S. Malvicini, "Laboratory investigation into the effects of fibers on bituminous mixtures," *Journal of Civil Engineering and Management*, vol. 21, no. 1, pp. 45–53, 2015.

[19] B. D. S. Bueno, W. R. da Silva, D. C. de Lima, and E. Minete, "Engineering properties of fiber reinforced cold asphalt mixes," *Journal of Environmental Engineering*, vol. 129, no. 10, pp. 952–955, 2003.

[20] E. Toraldo, G. Martinez-Arguelles, and E. Mariani, "Effect of reinforced fibers on stiffness of recycled asphalt half-warm emulsion mixes," in *Sustainability, Eco-Efficiency, and Conservation in Transportation Infrastructure Asset Management*, pp. 53–59, CRC Press, 2014.

[21] Y. Kim and T.-S. Park, "Reinforcement of recycled foamed asphalt using short polypropylene fibers," *Advances in Materials Science and Engineering*, vol. 2013, Article ID 903236, 9 pages, 2013.

[22] F. A. Halles and G. Z. Thenoux, "Degree of influence of active fillers on properties of recycled mixes with foamed asphalt," *Transportation Research Record*, vol. 2095, pp. 127–135, 2009.

[23] A. Chomicz-Kowalska and K. Maciejewski, "Multivariate optimization of recycled road base cold mixtures with foamed bitumen," *Procedia Engineering*, vol. 108, pp. 436–444, 2015.

[24] *Review of Foamed Bitumen Stabilisation Mix Design Methods*, Austroads, 2011.

[25] EN, "Bitumen and bituminous binders—determination of needle penetration," EN 1426, Brussels, Belgium, European Committee for Standardization, 2007.

[26] EN, "Bituminous mixtures—test methods for hot mix asphalt—part 8: determination of void characteristics of bituminous specimens," EN 12697-8, European Committee for Standardization, Brussels, Belgium, 2007.

[27] EN, "Bituminous mixtures—test methods for hot mix asphalt—part 6: determination of bulk density of bituminous specimens," EN 12697-6, 2007, European Committee for Standardization, Brussels, Belgium, 2007.

[28] EN, "Bituminous mixtures—test methods for hot mix asphalt—Part 5: determination of the maximum density," EN 12697-5, Brussels, Belgium, European Committee for Standardization, 2007.

[29] EN, "Bituminous mixtures—test methods for hot mix asphalt—part 26: stiffness," EN 12697-26, European Committee for Standardization, Brussels, Belgium, 2007.

[30] EN, "Bituminous mixtures—Test methods for hot mix asphalt—part 24: resistance to fatigue," EN 12697-24, Brussels, Belgium, European Committee for Standardization, 2007.

[31] EN, "Bituminous mixtures—test methods for hot mix asphalt—part 23: determination of the indirect tensile strength of bituminous specimens," EN 12697-23, European Committee for Standardization, Brussels, Belgium, 2007.