FIBRA -Fostering the implementation of fibre reinforced asphalt mixtures by ensuring its safe, optimized and cost-efficient use. Preliminary results

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FIBRA - Fostering the implementation of fibre reinforced asphalt mixtures by ensuring its safe, optimized and cost-efficient use. Preliminary results.

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Abstract

The use of fibers has been presented in the last years as an innovative ideal solution to enhance the mechanical properties of hot mix asphalt (HMA). Several types of fibers found in the literature have shown promising characteristics to be used as fiber reinforced asphalt mixtures (FRAM). However, the majority of the research is focus at the laboratory scale and the economic and environmental aspects have not been taken into account. To fill this gap, the FIBRA project, funded by the European Commission Department of Roads (CEDR) under the contract number N. 867481, aims to overcome the technical barriers for the safe and cost-efficient implementation of fiber-reinforced asphalt mixtures (FRAM). The article presents the main and specific objectives of the project as well as the first results obtained so far.

Keywords: Fibers, hot mix asphalt, Multi-criteria decision making, Life cycle assessment.

1. Introduction

The constant growth of the traffic loads and the continues changes in the climate conditions have led to the development of new asphalt mixtures with enhanced characteristics that guarantee a proper functionality and mechanical performance of the asphalt pavements. The two main components of asphalt mixtures are bitumen and aggregate. The first one acts as a glue of the mixture, whereas the latter represents the mineral skeleton of the mix. However, in order to extend the service life of the pavement, innovative solutions, such as the use of fibers, have been proposed in the last years.
The use of fibers has been quite popular in Portland cement concrete (Stempihar *et al.* 2012a). However, in recent years, previous researches have reported that the use of fibers in hot asphalt mixtures significantly improves their mechanical properties (Abtahi *et al.* 2010, Slebi-acevedo *et al.* 2019). These properties mainly include low temperature thermal cracking, moisture damage, fatigue cracking and rutting (Luo *et al.* 2019). Fiber reinforced asphalt mixture (FRAM) as it is termed, intends to increase the tensile strength and brings more ductility increasing the strain energy, especially when deformation in the pavement structure occurs (Abtahi *et al.* 2010). In addition, fibers act as a reinforcement in the bituminous mixture preventing the formation and propagation of cracks (Maurer and Malasheskie 1989, Maurer DA 2003). Generally, fibers are placed between the aggregates strengthening the interlocking among aggregates. In other type of mixtures such as stone matrix asphalt and porous asphalt (PA) mixtures, fibers are used to stabilize the asphalt content and hence prevent the binder drainage (Hassan *et al.* 2005, Andrés-Valeri *et al.* 2018a). With regards to the bituminous binder, a proper type and quantity of fibers have been

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found to change the mechanical properties, reducing the penetration and increasing the softening point (Chen and Xu 2010). Besides, fibers can also modified the viscosity of the asphalt (Mohammed *et al.* 2018).

Despite the promising results of adding fibers in hot asphalt mixtures founded in the scientific literature (Hejazi *et al.* 2008, Abtahi *et al.* 2010, Kaloush *et al.* 2010, Xu *et al.* 2010, Park *et al.* 2015, Zhang *et al.* 2017, Andrés-Valeri *et al.* 2018b, Klinsky *et al.* 2018, Morea and Zerbino 2018, Slebi-acevedo *et al.* 2019), the application of FRAM is not as fully understood as it could be expected. This is mainly due to the presence of gaps in the state of knowledge that makes National Road Administrations be reluctant to their incorporation.

The FIBRA project aims to overcome the technical barriers for the safe and cost-efficient implementation of FRAM by National Road Authorities (NRAs). The GITECO research group from the University of Cantabria (Spain) coordinates this project and carry out the research together with EMPA, Material Science and Technology (Switzerland), the Institute für Straßenwesen (ISBS) from the Technische Universität Braunschweig (Germany), BAM Infra bv (The Netherlands), SINTEF AS (Norway) and Veidekke Industri AS (Norway). The project consists of improving the understanding of the applicability of FRAM by means of studying aspects such as the microstructural properties, rheological behavior and mechanical properties of asphalt mixtures characterized according to EU and US standard normative. The project contemplates the evaluation of the recyclability potential of FRAM and the potential positive effect of fibers on asphalt mixtures containing high Reclaimed Asphalt Pavement (RAP) content. In addition, in this project, numerical simulations with an advanced pavement analysis tool and a model scaled accelerated pavement test will be carry out. Once the behavior of the asphalt mixtures is better understood at the laboratory scale, two different pilot roads are planned, one in the Netherlands and the other one in Norway in order to monitor the mechanical performance of the pavement structure fostering in this way a wider adoption of FRAM. Finally, in terms of sustainability, a Life Cycle Assessment and Life Cycle Cost Analysis will be performed to the solution with the intention of validating the technology from an economic and environmental point of view.

The main purpose of this paper is to describe the general and specific objectives of the project, as well as presenting the preliminary results of the project. This first part of the project consisted on a review of the state of knowledge concerning the use of fibers for the reinforcement of asphalt mixtures and the selection of the most promising fiber from the technical, economic and environmental point of view. After the literature review of existing research on FRAM from the mechanical point of view, a multi-criteria decision making analysis was performed to select the most promising fiber based on the technical aspects derived from the scientific review. For the fiber selection, in addition to the technical aspects, a cradle to gate LCA assessment and a preliminary cost-benefit analysis were carried out. Finally, due to the lack of information concerning the impact of reinforcing fibers in porous asphalt mixtures, an experimental testing plan on fiber reinforced PA mixtures was carried out to strengthen the final selection of the fiber.

2. Objectives of the project

The overall objective of the project is to overcome the technical barriers for the safe and cost-efficient implementation of fiber-reinforced asphalt mixes by NRAs.

The specific scientific and individual objectives that will contribute to the development of the project are presented as follows:

- Review the state of knowledge concerning the use of fibers for the reinforcement of asphalt mixes.
- Understand the functional mechanisms of fibers using advanced characterization techniques.
- Optimize the operating parameters influencing the interaction of fibers with asphalt mixture components.
- Define the most cost-beneficial use of Fiber-Reinforced Asphalt Mixtures (FRAM) for NRAs.
- Evaluate the recyclability potential of the designed FRAM.
- Upscaling-up and short-term assessment.
- Quantify the economic and environmental benefits of the proposed solution.

3. Methodology and results

In this section, the methodology and results of the preliminary works are presented. Firstly, a brief background of the use of fibers is mentioned. Then the multi-criteria decision-making methodology carried out for fiber selection is described. Finally, the last part of this section includes the life cycle assessment, a cost analysis and some experimental results concerning the use of fibers in PA mixtures.

3.1 Background of the use of fibers in hot mix asphalt.

Several type of fibers have been used in hot mix asphalt (Lee *et al.* 2005, MAHREZ *et al.* 2005, Fazaeli *et al.* 2016, Tanzadeh and Shahrezagamasaei 2017, Kim *et al.* 2018, Klinsky *et al.* 2018). Morea and Zerbino (Morea and Zerbino 2018), studied the effect of adding glass fibers in asphalt concrete (AC) mixtures and evaluated their performance regarding to fracture response at low temperatures and rutting at high temperatures. According to the results, rutting behavior of the asphalt concrete was significantly improved by the addition of fibers. Similarly, adding 0.4% of glass fibers (by weight of mixture) enhanced the fracture response of the asphalt concrete. However, authors suggested that the behavior of the mixture could be improved by optimizing the binder content in the mixture design, since the optimum binder content in asphalt mixtures also depends on some fiber's properties such as their absorption and surface area (Button and Lytton 1987). On another research, Klinsky et al. (Klinsky *et al.* 2018) assessed the benefits of adding polypropylene and aramid fibers in hot mix asphalt. The experimental tested plan included resilient modulus, dynamic modulus, flow number test, fatigue and fracture energy (Klinsky *et al.* 2018). Based on the results, these fibers in the mix increased the resilient and dynamic modulus at high temperatures. Therefore, a better performance in terms of permanent deformation can be achieved. Similarly, improvements regarding the fatigue cracking and the fracture response were obtained. According to the authors, the hot mix asphalt modified with aramid/polypropylene fibers presented a higher capacity to absorb more strain energy in comparison with mixtures without fibers. Accordingly, the modified mixtures showed higher reflective cracking resistance as suggested by the authors. In this sense, aramid is characterized for having a higher thermal stability and mechanical properties than other fibers whereas maintaining similar weights as glass or steel fiber (Apostolidis *et al.* 2019). On the other hand, polypropylene (PP) fibers possess relevant properties such as high abrasion resistance and tensile properties, resistance to mineral acids and alkali, low specific gravity and do not present water absorption (Apostolidis *et al.* 2019). Tapkin (Tapkın 2008) employed PP fibers in asphalt concrete as a three dimensional secondary reinforcement. Based on the test results, the author reported that FRAM with 1% of polypropylene fibers prolonged the fatigue life by 27%. In some states of The United States, PP fibers have been used as modifier in asphalt concrete. In this sense, the Ohio State of transportation (ODOT) provided specific instructions related to the production, laying out and compaction of fiber reinforced asphalt concrete with PP fibers (ITEM400HS 1998).

Other types of polymer fibers have been extensively used in HMA. Xu et al. (Xu *et al.* 2010) studied the reinforcing effect of polyester (PS) and polyacrylonitrile (PAN) fibers in asphalt concrete mixtures. Results indicated that these fibers improved properties such as rutting resistance, fatigue life and toughness in AC mixtures. Similarly, based on the results, the authors indicated that synthetic fibers had greater effects on the aforementioned properties than organic and mineral fibers such as lignin and asbestos. An optimum fiber content of 0.35% by mass of AC was recommended to achieve optimum outputs of rutting resistance and split indirect tensile strength. Table 1 details basic physical properties of different type of fibers used in AC mixtures.

The use of fibers have not only been applied to AC mixtures. For example, Mahrez et al. (Mahrez *et al.* 2005) studied the characteristics of a glass fiber reinforced Stone Mastic Asphalt (SMA) and reported that an optimum fiber content of 0.3% by mass of the total mixture resulted in the best performance in terms rutting resistance, fatigue life and stiffness in comparison to the mixture without fibers. It is worth mentioning that when the fiber content exceeded a certain threshold, a slight degradation in the mechanical properties were observed. In this sense, an excess of fibers in the mix could generate clusters and do not get to scatter properly. Besides, the authors observed an increase of air void content in mixtures with fibers as compared to reference mixture.

Less research has been conducted on open graded mixtures using fibers as a reinforcement material. However, other uses are already well known. Due to the lack of fines in the granular skeleton of the porous asphalt, less quantity of binder can be incorporated into the mix and hence the durability of the mixture can be affected. Some fibers, such as cellulose, are usually employed as stabilizer agents to design open graded mixtures with higher binder contents. In this sense, Lyons and Putman (Lyons and Putman 2013) compared the performance of different stabilizing additives including cellulose fibers, styrene butadiene styrene and crumb rubber modifier in a PA mixture. Results indicated that crumb rubber and cellulose fiber were the most effective additive to reduce draindown. However, the combination of styrene-butadiene-styrene SBS modified binder and cellulose fibers in the mixture exhibited the major increment in loss particle resistance. According to the results, the authors concluded that cellulose fibers did not have any influence on the indirect tensile strength of the PA mixture.

Table 1. Basic physical properties of fibers used in AC mixtures.

Reference	(Tapkın 2008)	(Fazaeli *et al.* 2016)	(Fazaeli *et al.* 2016)	(Morea and Zerbino 2018)	(Morea and Zerbino 2018)	(Chen and Xu 2010)
Fiber	Polypropylene	Polyolefin	Aramid	Glass	Polyester	Polyacrylonitrile
Color	Transparent	Black	Yellow	White	White	White/Grey
Length (mm)	3 - 50	19	19	12	25	4 - 6
softening Temperature (°C)	160	100	427	860	250	> 240
Specific Gravity (g/cm^3)	0.91	0.91	1.44	2.68	1.34	1.14 - 1.16
Tensile Strength (MPa)	31 - 37	483	2758	1700	300 - 500	> 910

In terms of sustainability, some researchers suggest that the use of fibers reduces the maintenance cost of the asphalt pavement but the cost-benefit of the solution is influenced by the price of the fiber (Mahrez 2003). In order to be more competitive, the use of recycled fibers coming from industrial waste is being explored (Stempihar *et al.* 2012b, Slebi-acevedo *et al.* 2019). Thus, some researches (Yin and Wu 2018a) suggested the use of waste nylon wires coming from the production of brush wire products, such as toothbrush, hairbrush paintbrush among others could be used as fiber reinforcement in hot mix asphalt. Yin and Wu (Yin and Wu 2018b) assessed the feasibility of incorporating waste nylon fiber in SMA mixtures. In their study, the following mechanical tests were conducted: Marshall Stability test, rutting test, three point flexural test and moisture sensitivity test. The authors concluded that waste nylon wire acted like a bridge retarding the crack propagation. However, an excess of these fibers could interrupt the interlocking phenomenon produced by the aggregates. The author reported an optimal waste nylon wire content between 1% and 1.5%.

3.2 Multi – criteria decision making (MCDM) for fiber selection.

In order to select the proper fiber for the project, a multi-criteria decision making (MCDM) analysis was carried out in terms of mechanical performance. The use of decision support systems like MCDM methodologies have been extensively used in several fields related with construction, manufacturing, material selection and so on. In order to choose the best solution, MCDM methods assess multiple alternatives based on a set of criteria (Rashidi and Cullinane 2019). In the literature, many MCDM techniques can be found, such as the analytical network process (ANP), the analytic hierarchy process (AHP), the weighted aggregated sum product assessment (WASPAS), the technique for order of preference by similarity to ideal solution (TOPSIS), the data envelopment analysis (DEA), the VIsekriterijumsko KOmpromisno Rangiranje (VIKOR) and the complex proportional assessment (COPRAS), among others (Chaharsooghi *et al.* 2012, Egle and Jurgita 2013, Alam *et al.* 2018, Gul *et al.* 2018). The structured framework of the methodology is displayed in Fig 1. In the present research, a hybrid MCDM technique was selected since firstly it was necessary to determine the criteria weightage and then ranking the fibers based on quantitative data.

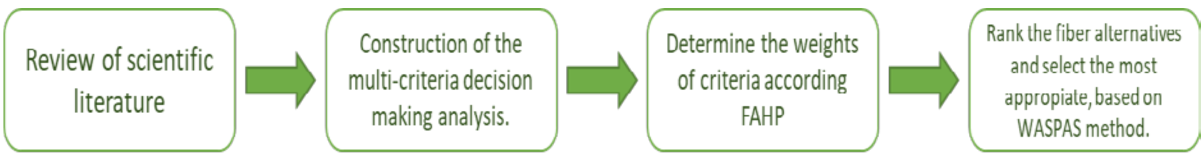


Fig 1. Structured framework of the methodology applied.

The criteria weightage was determined employing the AHP method, one of the most common used in criteria elicitation (Jato-Espino *et al.* 2014). Qualitative information from experts was obtained through a set of questionnaires related to the typical distresses that HMA could present by the action of the traffic loads and weather conditions. Based on scientific literature, toughness, indirect tensile strength (ITS), rutting and fatigue life were considered the main criteria to establish the decision making matrix. It is worth mentioning that members of private

industries, academic sector and many partners of the FIBRA project participated actively answering the surveys. A total of 25 questionnaires were received and included in the analysis. The Fuzzy set theory was incorporated to handle the uncertainty and ambiguity that the decision of the experts could present. In other words Fuzzy – AHP, also termed FAHP, was applied in the research to take into account the linguistic vagueness in the mind of decision makers (Choudhary and Shankar 2012).
WASPAS method was adopted as a precise technique to rank and select the most appropriate alternatives since this method integrates the weighted sum model (WSM) and weighted product model (WPM). Based on the literature data available, the alternatives to be ranked were Polyacrylonitrile fibers (PAN), steel fiber, polyester fibers (PET), polypropylene fibers (PP) and a blend of synthetic fibers that includes aramid and polyolefin (ARAM/POL). The main steps of the methodology are presented as follows. More details of the procedure can be observed in (Slebi-Acevedo *et al.* 2019)

- Establish the decision matrix $\left[c_{ij}\right]_{m\,X\,n}$ where *m* are the criteria and *n* represents the alternatives.
- Normalize the decision making matrix as appropriate taking into account if the criteria are beneficial (Larger the better) or non-beneficial (smaller the better).
- Construct the weighted normalize decision matrix according WSM and WPM.
- Apply a joint generalized criterion of weighted aggregation of additive and multiplicative methods.

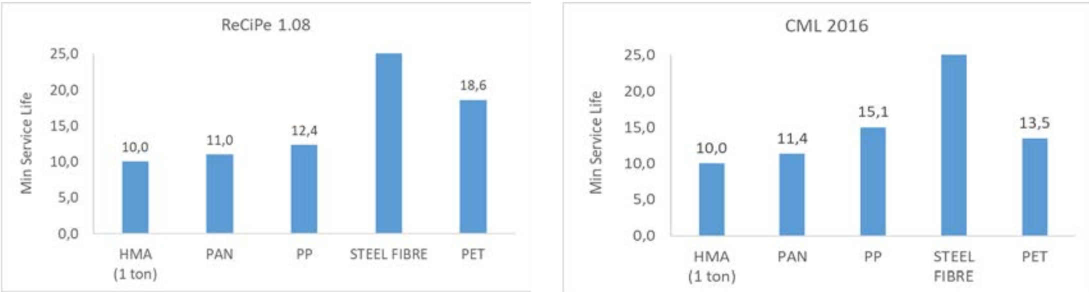
Based on the results attained from the MCDM analysis, the fibers selected in the project were two types of synthetic fibers. The first one comprises a blend of polyolefin + aramid fibers (ARAM/POL). The second fiber selected was a Polyacrylonitrile fiber (PAN). Fig 2. Shows an illustration of the both fibers selected.

Fig 2. Fibers selected to be used in FIBRA project. Polyolefin + aramid fibers (left); Polyacrylonitrile fibers (right).

3.3 Life cycle assessment and cost analysis.

Considering that the effect of the different fibers on the asphalt mixture's life expectancy is not well stablished by the literature, for the environmental assessment of the alternatives, a cradle-to-gate Life Cycle Analysis (LCA) was carried out. The life cycle inventory of the pre-selected fibers mentioned before, except for the aramid, were obtained from the Gabi 2017 database. In the case of the aramid, only the carbon footprint of the aramid production process was available (Teijin Aramid). The percentage of each fiber to be added to the asphalt mixture was selected based on the literature. With these data, the cradle to gate LCA of 1 ton of HMA with and without fibers was performed. In order to evaluate the sensitivity of the results depending on the impact assessment model selected, two different impact assessment methods were used: CML 2016 which is a method commissioned by the Dutch ministries that is recommended for carrying out Environmental Product Declarations. CML calculates 11 midpoint impacts, so if a single score is required to represent the environmental impact of a product, normalization and weighting steps are needed. The other method is ReCiPe 1.08 (mid-point) which enables the transformation of the emissions into 18 midpoint impacts, which are then transformed into endpoint impacts. In this way, the effect of the product life is calculated in three protection areas: damage to human health (HH), damage to ecosystem diversity (ED), and damage to resource availability (RA).

After normalizing the results (both for CML and ReCiPe), those category impacts with a contribution to the total sum of less than 2% were discarded. For the rest of the category impacts and assuming 10 years of service life for a conventional HMA, the minimum life expectancy that each FRAM layer should achieved in order to equal the environmental impact of said conventional HMA was estimated. In figure 3, the comparative results corresponding to each fibre is shown. In figure 4, the comparative results (including the aramid/polyolefin fiber) only considering the category impact “global warming potential” (GWP) is presented. It is well known that GWP is a measure of how much heat can be trapped by a certain amount of GHG, as compared to the heat trapped by a reference gas, normally carbon dioxide. According to the results, the model selected to perform the LCA affects the results of the study, since the ranking of the fibers change depending on the assessment methods. However, similar trends are found with both methods since PAN and STEEL fibers are both in the first and last position respectively. If only the carbon footprint is considered, similar results are obtained. The PAN and STEEL fiber are at the top and the bottom of the ranking respectively although in this case the differences are less significant. PP and PET present similar results and the blend of ARAM/POL is near the top of the ranking with the PAN fiber.



(a) (b)

Fig 3. Minimum service life extension for each FRAM to equal the impact of a conventional HMA. (a) Recipe 1.08. (b) CML 2016

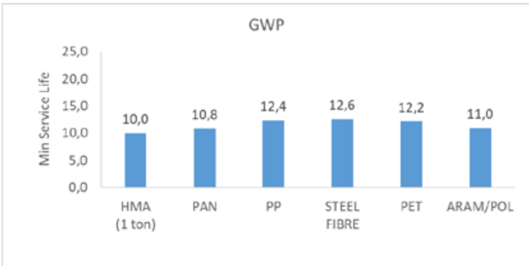


Fig 4. Minimum service life extension for each FRAM to equal the impact of a conventional HMA

In addition to the Life Cycle Assessment, a preliminary cost-benefit assessment was carried out. The aim of the analysis was to compare the production process of 1 km of a FRAM layer that incorporates different type of fibers. To calculate these costs, the cost of producing and laying a conventional HMA was assumed in 65 €/ton. Fiber costs are estimates found on the internet, on the literature or given by the provider. As the increase of durability because of the addition of each fiber is not well stablished, the minimum service life that each FRAM layer needs to achieve in order to equal the costs of a conventional HMA layer was determined. According to the results (Figure 5), a service life increase of 1 or 2 years is needed, depending on the type of fiber, to equal the costs of a conventional HMA layer. PET and PAN are the fibers that increase less the cost of the total HMA.

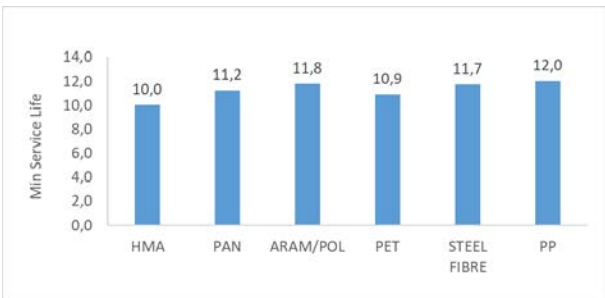


Fig 5. Minimum service life extension for each FRAM to equal the impact of a conventional HMA

3.4 Mechanical performance of fibers in porous asphalt mixtures.

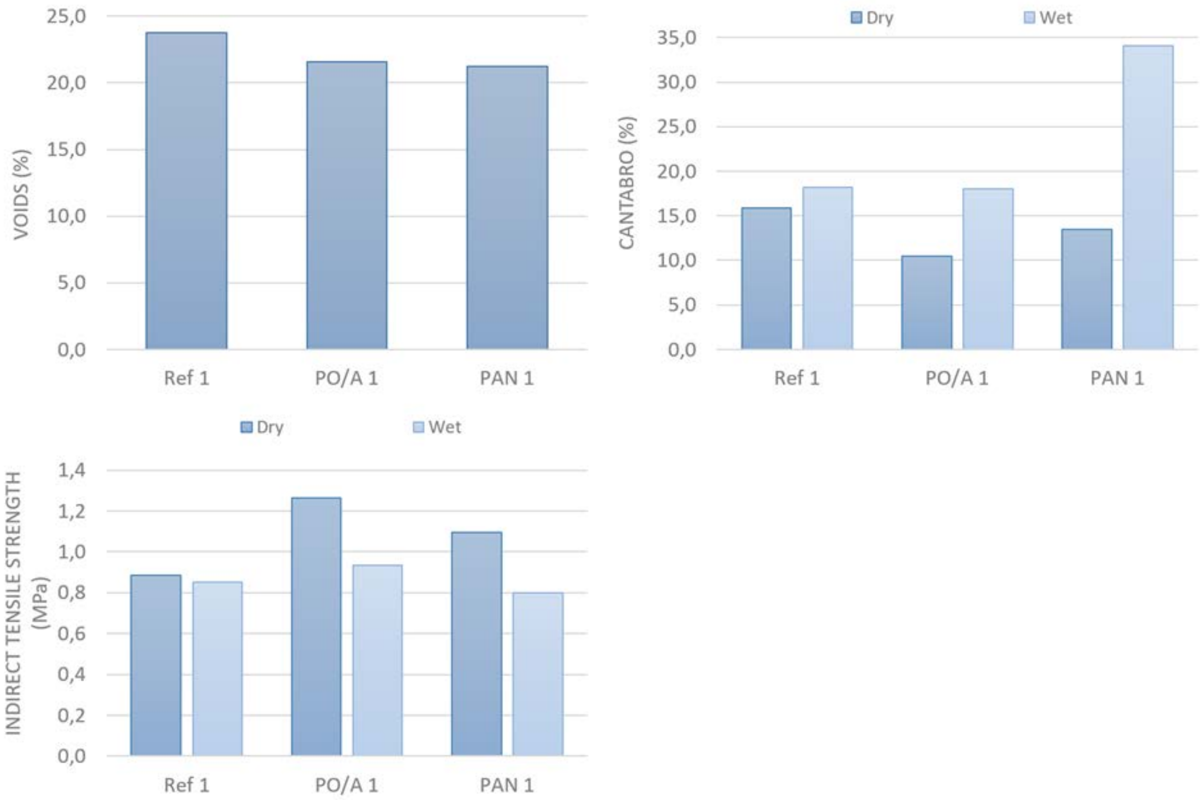
Since there is not too much literature about the use of fibers as a reinforcement in PA mixtures, a mechanical performance evaluation of the use of fibers in this type of mixture was carried out. As previously explained in the section 3.1, in the case of the porous asphalt, the use of fibers has been addressed to increase the amount of useful bitumen in the mixture, being the mechanical improvement achieved by the incorporation of the fibers mainly studied in terms of asphalt stabilization and binder drainage prevention. The use of fibers in PA mixtures with reinforcement purposes has hardly been studied. Because of this, several laboratory tests were performed. In this sense, a porous asphalt of reference was modified by adding the fibers previously selected. Two percentages of filler/bitumen ratio were used, both in the range of the quantities traditionally employed. The aim was to evaluate the variations in the mechanical behavior without the influence of the binder quantity increment. This point was analyzed with the experimental work plan presented in Table 2.

Table 2. Experimental work plan of PA mixtures.

Parameter	Standard method	comments
Bulk density	EN 12697–6	-
Total Air voids (AV)	EN 12697–8	-
Interconnected Air voids (IAV)	ASTM D7063 – 05	-
Vertical Permeability	Falling head permeameter	falling head from 30 to 10 cm
Particle loss	EN 12697-17	Dry condition
Particle loss	NLT 362/92	Wet condition
Indirect Tensile Strength (ITS)	EN 12697-23	Dry and wet conditions
Moisture Sensitivity	EN 12697-12	-

The results showed that the fibers improved the mechanical performance of the porous asphalt in dry conditions while not notable improvements were noted in in wet conditions (Fig. 6). This is due to the decision of not increasing the amount of bitumen. It is expected that when the PA mixture is designed with an optimum amount of bitumen, the mechanical performance will be significantly improved both in dry and wet conditions.

(a)



(b)

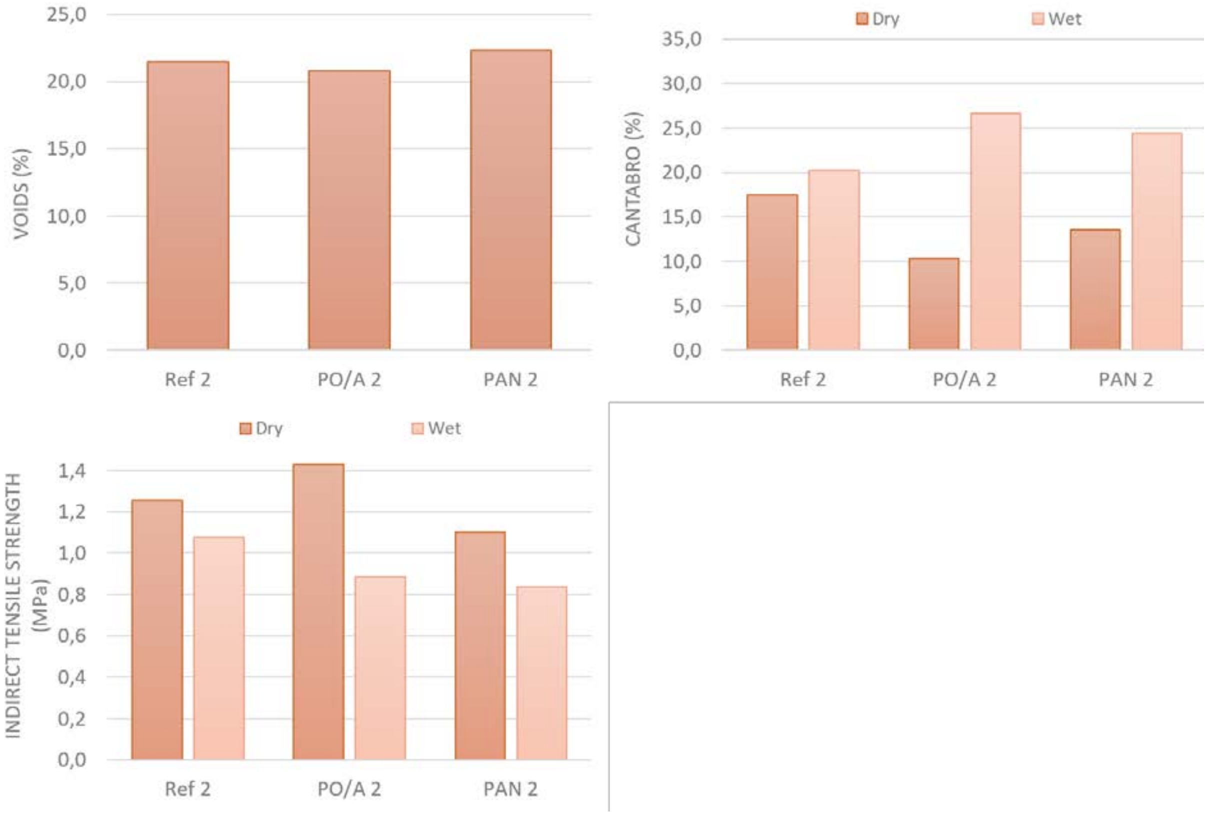


Fig 6. Mechanical behavior of PA mixtures with both quantities of filler/bitumen ratio. (a) High quantity of filler/bitumen ratio, (b) Low quantity of filler/bitumen ratio.

4. Conclusions.

This article presents the FIBRA project includying the general and specific objectives of the project as well as the preliminary results of the research developed until the moment. A literature review, a multi-criteria decision making analysis, a life cycle assessment and the mechanical characterization of fiber reinforced PA mixtures were carried out in the first stage of the project. According to the literature review, it was found that fibers in the mix contribute to support the tensile loads caused by the traffic. Besides fibers generate an interlocked effect with the aggregates preventing the formation and propagation of cracks. In porous asphalt mixtures fibers are mainly used to prevent the binder drainage in the mixture. Concerning to MCDM analysis, the most promising fibers were polyeolefin + aramid fibers and polyacrylonitrile fibers. Based on the LCA results, PAN fiber is considered the best alternative in terms of environmental impact. Similarly ARAM/POL fibers are identified as another promising alternative to be used in HMA since the impact in terms of carbon footprint is low. In PA mixture, the fibers previously selected in MCDM analysis gave significantly improvements in loss Cantabro particle test and indirect tensile strength without affecting the voids in the mixture.

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References

Abtahi, S.M., Sheikhzadeh, M., and Hejazi, S.M., 2010. Fiber-reinforced asphalt-concrete - A review. *Construction and Building Materials*, 24 (6), 871–877.

Alam, K.A., Ahmed, R., Butt, F.S., Kim, S.G., and Ko, K.M., 2018. An Uncertainty-aware Integrated Fuzzy AHP-WASPAS Model to Evaluate Public Cloud Computing Services. *Procedia Computer Science*, 130, 504–509.

Andrés-Valeri, V.C., Rodriguez-Torres, J., Calzada-Perez, M.A., and Rodriguez-Hernandez, J., 2018a. Exploratory study of porous asphalt mixtures with additions of reclaimed tetra pak material. *Construction and Building Materials*, 160, 233–239.

Andrés-Valeri, V.C., Rodriguez-Torres, J., Calzada-Perez, M.A., and Rodriguez-Hernandez, J., 2018b. Exploratory study of porous asphalt mixtures with additions of reclaimed tetra pak material. *Construction and Building Materials*, 160, 233–239.

Apostolidis, P., Liu, X., Daniel, G.C., Erkens, S., and Scarpas, T., 2019. Effect of synthetic fibres on fracture performance of asphalt mortar. *Road Materials and Pavement Design*, 1–14.

Button, J. and Lytton, R., 1987. Evaluation of fabrics, fibers and grids in overlays. Sixth international conference on the structural design of asphalt pavements. *Ann Arbor, M*.

Chaharsooghi, S.K., Ashrafi, M., Akili, E.A., Alexander, M., Ozdagoglu, A., Ozdagoglu, G., Dobos, I., Vörösmarty, G., Molamohamadi, Z., Ismail, N., Leman, Z., Zulkifli, N., Liao, C.-N., Kao, H.-P., Function, L., Hierarchy, A., and Programming, F.G., 2012. Comparison of Ahp and Fuzzy Ahp for the Multi- Criteria Decision Making Processes With Linguistic Evaluations. *The United States Social Security Administration Baltimore*, 58 (1), 1–12.

Chen, H. and Xu, Q., 2010. Experimental study of fibers in stabilizing and reinforcing asphalt binder. *Fuel*.

Choudhary, D. and Shankar, R., 2012. An STEEP-fuzzy AHP-TOPSIS framework for evaluation and selection of thermal power plant location: A case study from India. *Energy*, 42 (1), 510–521.

Egle, Š. and Jurgita, A., 2013. Solving the problems of daylighting and tradition continuity in a reconstructed vernacular building. *Journal of civil engineering and management*, 19 (6), 873–882.

Fazaeli, H., Samin, Y., Pirnoun, A., and Dabiri, A.S., 2016. Laboratory and field evaluation of the warm fiber reinforced high performance asphalt mixtures (case study Karaj – Chaloos Road). *Construction and Building Materials*, 122, 273–283.

Gul, M., Guven, B., and Guneri, A.F., 2018. A new Fine-Kinney-based risk assessment framework using FAHP-FVIKOR incorporation. *Journal of Loss Prevention in the Process Industries*, 53, 3–16.

Hassan, H.F., Al-oraimi, S., and Taha, R., 2005. Evaluation of Open-Graded Friction Course Mixtures Containing Cellulose Fibers and Styrene Butadiene Rubber Polymer, 17 (August), 416–422.

Hejazi, S.M., Abtahi, M., Sheikhzadeh, M., and Semnani, D., 2008. Using artificial neural network for the investigation of some fiber parameter performances in reinforced asphalt concrete (FRAC). *asphalt technology and pavement engineering*,.

ITEM400HS, 1998. Standard specification for asphalt concrete-high stress using polypropylene fibers. *Ohio Department of Transportation, Construction and Materials Specifications*.

Jato-Espino, D., Castillo-Lopez, E., Rodriguez-Hernandez, J., and Canteras-Jordana, J.C., 2014. A review of application of multi-criteria decision making methods in construction. *Automation in Construction*, 45, 151–162.

Kaloush, K.E., Biligiri, K.P., Zeiada, W.A., Rodezno, C., and Reed, R.X., 2010. Evaluation of Fiber-Reinforced Asphalt Mixtures Using Advanced Material Characterization Tests. *Journal of Testing and Evaluation*, 38 (480), 400–411.

Kim, M.J., Kim, S., Yoo, D.Y., and Shin, H.O., 2018. Enhancing mechanical properties of asphalt concrete using synthetic fibers. *Construction and Building Materials*, 178, 233–243.

Klinsky, L.M.G., Kaloush, K.E., Faria, V.C., and Bardini, V.S.S., 2018. Performance characteristics of fiber modified hot mix asphalt. *Construction and Building Materials*, 176, 747–752.

Lee, S.J., Rust, J.P., Hamouda, H., Kim, R., and Borden, R.H., 2005. Fatigue Cracking Resistance of Fiber-Reinforced Asphalt Concrete. *Textile Research Journal*, 75 (2), 123–128.

Luo, D., Khater, A., Yue, Y., Abdelsalam, M., Zhang, Z., Li, Y., Li, J., and Iseley, D.T., 2019. The performance of asphalt mixtures modified with lignin fiber and glass fiber: A review. *Construction and Building Materials*, 209, 377–387.

Lyons, K.R. and Putman, B.J., 2013. Laboratory evaluation of stabilizing methods for porous asphalt mixtures. *Construction and Building Materials*, 49, 772–780.

Mahrez, A., 2003. Prospect of Using Glass Fiber Reinforced Bituminous. *Journal of Eastren Asia Society for*

Transportation studies, 5 (October), 794–807.

Mahrez, A., Karim, M., and Katman, H., 2005. Fatigue and Deformation Properties of Glass Reinforced Bituminous Mixtures. *Eastern Asia Society for transportation studies*, 6, 997–1007.

MAHREZ, A., KARIM, M.R., and KATMAN, H.Y., 2005. Fatigue and Deformation Properties of Glass Fiber Reinforced Bituminous Mixes. *Journal of the Eastern Asia Society for Transportation Studies*, 6 (November 2015), 997–1007.

Maurer, D.A. and Malasheskie, G.J., 1989. Field performance of fabrics and fibers to retard reflective cracking. *Transportation research record*, 1248, 13–23.

Maurer DA, G.M., 2003. Field performance of fabrics engineering properties of fibre reinforced cold asphalt mixes. *J Environ Eng ASCE*, 129 (10), Tech notes.

Mohammed, M., Parry, T., and Grenfell, J. (J R.A.)., 2018. Influence of fibres on rheological properties and toughness of bituminous binder. *Construction and Building Materials*, 163, 901–911.

Morea, F. and Zerbino, R., 2018. Improvement of asphalt mixture performance with glass macro-fibers. *Construction and Building Materials*, 164, 113–120.

Park, P., El-Tawil, S., Park, S.Y., and Naaman, A.E., 2015. Cracking resistance of fiber reinforced asphalt concrete at -20 °c. *Construction and Building Materials*, 81, 47–57.

Rashidi, K. and Cullinane, K., 2019. A comparison of fuzzy DEA and fuzzy TOPSIS in sustainable supplier selection : Implications for sourcing strategy. *Expert Systems With Applications*, 121, 266–281.

Slebi-acevedo, C.J., Lastra-gonzález, P., Pascual-muñoz, P., and Castro-fresno, D., 2019. Mechanical performance of fibers in hot mix asphalt : A review. *Construction and Building Materials*, 200, 756–769.

Slebi-Acevedo, C.J., Pascual-Muñoz, P., Lastra-González, P., and Castro-Fresno, D., 2019. A multi-criteria decision-making analysis for the selection of fibres aimed at reinforcing asphalt concrete mixtures. *International Journal of Pavement Engineering*, 0 (0), 1–17.

Stempihar, J., Souliman, M., and Kaloush, K., 2012a. Fiber-Reinforced Asphalt Concrete as Sustainable Paving Material for Airfields. *Transportation Research Record: Journal of the Transportation Research Board*, 2266 (December 2012), 60–68.

Stempihar, J., Souliman, M., and Kaloush, K., 2012b. Fiber-Reinforced Asphalt Concrete as Sustainable Paving Material for Airfields. *Transportation Research Record: Journal of the Transportation Research Board*, 2266 (December 2012), 60–68.

Tanzadeh, J. and Shahrezagamasaei, R., 2017. Laboratory Assessment of Hybrid Fiber and Nano-silica on Reinforced Porous Asphalt Mixtures. *Construction and Building Materials*, 144, 260–270.

Tapkın, S., 2008. The effect of polypropylene fibers on asphalt performance. *Building and Environment*, 43 (6), 1065–1071.

Xu, Q., Chen, H., and Prozzi, J.A., 2010. Performance of fiber reinforced asphalt concrete under environmental temperature and water effects. *Construction and Building Materials*, 24 (10), 2003–2010.

Yin, J.M. and Wu, W., 2018a. Utilization of waste nylon wire in stone matrix asphalt mixtures. *Waste Management*, 78, 948–954.

Yin, J.M. and Wu, W., 2018b. Utilization of waste nylon wire in stone matrix asphalt mixtures. *Waste Management*, 78, 948–954.

Zhang, X., Gu, X., Lv, J., Zhu, Z., and Zou, X., 2017. Numerical analysis of the rheological behaviors of basalt fiber reinforced asphalt mortar using ABAQUS. *Construction and Building Materials*, 157, 392–401.