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PhD Thesis/ Tesis Doctoral

**EXPERIMENTAL EVALUATION OF FIBER-REINFORCED POROUS ASPHALT MIXTURES THROUGH THE DESIGN OF EXPERIMENTS INTEGRATED WITH MULTI-CRITERIA DECISION-MAKING ANALYSIS**

**EVALUACIÓN EXPERIMENTAL DE MEZCLAS ASFÁLTICAS POROSAS REFORZADAS CON FIBRAS A TRAVÉS DEL DISEÑO DE EXPERIMENTOS INTEGRADO CON ANÁLISIS DE TOMA DE DECISIONES DE CRITERIOS MÚLTIPLES**


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*Research has no limits. This research probably leads to more questions than answers. Once you have solved one query, then you realize that you have created a couple more.*

***Dedication***

*To my parents for having forged me in the person that I am today. To all people who love me.*

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# ABSTRACT

Porous asphalt mixture (PA) is a type of mixture characterized by having large air voids content, with aggregates of high quality and a small number of fines, commonly used as wearing course in pavement structures due to the various benefits that this mixture provides in terms of safety and environmental care. In general, PA mixture allows the water drainage through its structure, improving the skid resistance and mitigating noise pollution. Despite the multiple functional benefits, the durability of this mixture is lower in comparison to dense-graded asphalt mixtures.

In Europe and some countries of America, the use of polymer-modified binder (PMB) is quite common to improve the durability of PA mixture. However, other additives such as synthetic fibers could be presented as an innovate alternative to increase the overall performance of PA mixture. The following study investigated the effect of adding synthetic fibers on the performance properties of PA mixtures employing an innovative methodology which combines the Design of Experiment (DOE) concept with the Multi-Criteria Decision-Making (MCDM) analysis. In the first phase of the research, a complete laboratory assessment plan was developed to evaluate the effectiveness of adding polyolefin-aramid (POA) and Polyacrylonitrile (PAN) synthetic fibers in PA mixtures in terms of functionality and mechanical performance. As the bituminous mortar plays a dominant role in the cohesive forces of the mix to keep the aggregates together, the effect of synthetic fibers at asphalt mortar scale was also analyzed. Once the most promising fiber was selected, in a second phase of the study, a novel methodology that integrates the Taguchi DOE concept with the CRITIC-TOPSIS hybrid MCDM analysis was proposed to evaluate the impact of fibers taking into account other control factors such as the binder type, the fiber content and the binder content.

Among the most relevant results found in the research is that both POA and PAN fibers increase the raveling resistance and indirect tensile strength in dry conditions. However, the higher mechanical performance was provided by the addition of POA fibers. At the asphalt mortar scale, significant improvement of strength at low temperature (-15°C) was observed when adding 0.3% of POA and PAN fibers.

Concerning the novel DOE-MCDM method proposed, the main effects plot for means obtained from the Taguchi method, allowed to determine the proper levels of the control factors for the different responses carried out. As multiple responses were obtained, the MCDM analysis allowed to transform the multi-response optimization problem into single-one response optimization problem. CRITIC was contemplated as an objective weighting approach whereas TOPSIS method contributed to identify the optimal combination of the control factors and the preference ranking among the experimental designs.

From the results obtained, POA fibers acted very well as a stabilizer agent and as reinforcement since they reduced the particle loss in dry conditions. In the same way, the modified binder increased the raveling resistance in both dry and wet conditions without affecting the functional performance of the mixture and without presenting a risk of binder drain down.

Although the first positions of the order of preference refers to experiments with mixes using polymer modified binder, admissible results can be also obtained using a conventional binder as long as the proper proportions of fibers are applied. The integration of DoE techniques and MCDM analysis can be considered a powerful tool for the evaluation of the impact of different control variables on different responses.

## RESUMEN

La mezcla asfáltica porosa (PA) es un tipo de mezcla que se caracteriza por tener un gran contenido de huecos, fabricada con agregados de alta calidad y una baja cantidad de finos, comúnmente utilizada como capa de rodadura en estructuras de pavimento debido a los diversos beneficios que proporciona esta mezcla en términos de seguridad y más amigable con el medio ambiente. En general, la mezcla PA permite el drenaje del agua a través de su estructura mejorando la resistencia al deslizamiento y mitigando la contaminación acústica. Sin embargo, a pesar de sus múltiples beneficios, la durabilidad de esta mezcla es mucho menor en comparación con las mezclas asfálticas densas.

En Europa y algunos países de América, el uso de betún modificado con polímeros (PMB) es bastante habitual para mejorar la durabilidad de la mezcla porosa. Sin embargo, otros aditivos como las fibras sintéticas suelen presentarse como una alternativa novedosa para aumentar el rendimiento global de la mezcla porosa. El siguiente estudio investigó el efecto de añadir fibras sintéticas en el comportamiento general de la mezcla PA utilizando una metodología innovadora que combina el concepto de diseño de experimentos (DOE) con el análisis de toma de decisiones de criterios múltiples (MCDM). En una primera fase de la investigación, se desarrolló un plan experimental en laboratorio para evaluar la efectividad de añadir fibras sintéticas de poliolefina-aramida (POA) y poliacrilonitrilo (PAN) en mezclas PA en términos de funcionalidad y comportamiento mecánico. Como el mortero bituminoso juega un papel determinante en las fuerzas cohesivas dentro de la mezcla para mantener los agregados juntos, también se analizó el efecto de las fibras sintéticas a la escala del mortero asfáltico. Una vez que se seleccionó la fibra más prometedora; En una segunda fase del estudio, se propuso una nueva metodología que integra la metodología Taguchi DOE con el análisis multicriterio CRITIC-TOPSIS para evaluar el impacto de las fibras teniendo en cuenta otros factores de control como el tipo de betún, el contenido de fibra y el contenido de betún.

Entre los resultados más relevantes encontrados en la investigación, se encuentra que las fibras POA y PAN, ambas aumentaron la resistencia a la pérdida de partículas y la tracción indirecta en condiciones secas. Sin embargo, el mayor rendimiento mecánico se obtuvo mediante la adición de fibras POA. A la escala del mortero asfáltico, se observó una mejora significativa de la resistencia a baja temperatura (-15°C) al agregar 0.3% de fibras de POA y PAN.

En relación con el innovador método DOE-MCDM propuesto, los gráficos principales de efectos medios obtenidos de la metodología Taguchi, permitieron determinar los valores adecuados de los factores de control para las diferentes respuestas llevadas a cabo. A medida que se obtuvo más de una respuesta, el análisis multi-criterio permitió transformar el problema de optimización de respuesta múltiple en un problema de optimización de respuesta individual. CRITIC se consideró como una aproximación de ponderación objetivo, mientras que el método TOPSIS contribuyó a identificar la combinación óptima de los factores de diseño y la clasificación de preferencias entre los diseños experimentales.

A partir de los resultados obtenidos, las fibras POA actuaron muy bien como agente estabilizador y como refuerzo, ya que redujeron la pérdida de partículas en condiciones secas. De la misma manera, el betún modificado con polímeros aumentó la resistencia a la pérdida de partículas tanto en condiciones secas como húmedas sin afectar el comportamiento funcional de la mezcla y sin presentar un riesgo de escurrimiento del betún. Aunque las primeras posiciones del orden de preferencia se refieren a experimentos con mezclas que usan betún modificado con polímeros, también es posible obtener resultados que mejoren el comportamiento de la mezcla usando un betún convencional siempre que se apliquen las proporciones adecuadas de fibras. La integración de las técnicas DOE y el análisis MCDM puede considerarse una herramienta poderosa para la evaluación del impacto de diferentes variables de control en múltiples respuestas.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| **AHP** | Analytic Hierarchy Process |
| **AS** | Appraisal Score |
| **BC** | Binder Content |
| **BD** | Binder Drain down |
| **BT** | Binder Type |
| **BWM** | Best-Worth Method |
| **CCC** | Closeness comparative coefficient |
| **CRITIC** | Criteria Importance Through Inter-Criteria Correlation |
| **DOE** | Design of Experiments |
| **EDAS** | Distance from Average Solution |
| **ELECTRE** | Elimination and Choice Expressing Reality |
| **FAHP** | Fuzzy Analytic Hierarchy Process |
| **FC** | Fiber Content |
| **FE** | Fracture Energy |
| **FL** | Fatigue Life |
| **FRAM** | Fiber-Reinforced Asphalt Mixture |
| **FRPA** | Fiber-Reinforced Porous Asphalt |
| **GRA** | Gray Relational Analysis |
| **HL** | Hydrated Lime |
| **HMA** | Hot Mix Asphalt |
| $I_{AV}$ | Interconnected Air Voids |
| **ITS** | Indirect Tensile Strength |
| **ITSR** | Indirect Tensile Strength Ratio |
| **ITT** | Indirect Tensile Test |
| **JPS** | Joint Performance Score |
| **k** | Permeability |
| **MCDM** | Multi-Criteria Decision-Making |
| **NIS** | Negative Ideal Solution |
| **OGFC** | Open Graded Friction Course |
| **PA** | Porous Asphalt |
| **PAC** | Permeable Asphalt Concrete |
| **PAN** | Polyacrylonitrile |
| **PE** | Post-Cracking Energy |
| **PET** | Polyester |
| **PFC** | Porous Friction Course |

| | |
|---|---|
| **PIS** | Positive Ideal Solution |
| **PL** | Particle Loss |
| **PMB** | Polymer Modified Binder |
| **POA** | Polyolefin-Aramid |
| **PP** | Polypropylene |
| **RAP** | Reclaimed Asphalt Pavement |
| **RR** | Rutting Resistance |
| **RSM** | Response Surface Method |
| **SAW** | Simple Additive Weighting |
| **SD** | Standard Deviation |
| **SMA** | Stone Matrix Asphalt |
| **SN** | Signal to Noise |
| **T** | Toughness |
| **$T_{AV}$** | Total Air Voids |
| **TOPSIS** | Technique for Order of Preference by Similarity to Ideal Solution |
| **WASPAS** | Weighted Aggregated Sum Product Assessment |
| **WPM** | Weighted Product Model |
| **WSM** | Weighted Sum Model |

# 1. INTRODUCTION

## 1.1 Framework of the thesis

### *1.1.1 Background*

The majority of countries employ dense-graded hot mix asphalt as a surface layer in the construction of their roads. Nevertheless, other types of mixtures such as the open-graded asphalt mixtures have become an attractive option for the development of new pavement structures. This mixture, commonly known as Porous Asphalt (PA) in Europe [1,2] Open Graded Friction Course (OGFC) or Porous Friction Course (PFC) in the United States [3,4], and Permeable Asphalt Concrete (PAC) in China [5], is deemed an innovative eco-friendly solution due to the many benefits that this type of mixture offers [3]. Among its advantages, better stormwater management due to the high porosity (i.e. usually in the range between 18-22%) highlights [6,7]. The air voids in the porous asphalt structure allow the drainage of water also preventing the splash and spray phenomenon. Similarly, PA mixtures help to reduce the noise produced by the path of the vehicles and to decrease the risk of aquaplaning and wet skidding [3]. Other profits include the mitigation of the urban heat island effect [8] and the decrease of the accident rate due to the improved visibility, especially during the rainy weather [9].

Despite the many benefits, the durability of the mixture is substantially smaller than conventional dense-graded asphalt mixtures. The raveling, which can be defined as the loss of particles from the surface of the pavement due to the abrasion generated by the traffic is one of the most common types of failure in these mixtures [10]. For the above, some government agencies from America and Europe have included in their specifications the use of polymer modified binders due to the higher elasticity especially at lower temperatures and with the idea that the aging rate of this bitumen is lower than conventional bitumen [11]. However, the high initial costs, high manufacturing temperatures, and specialized equipment are sometimes necessary making the use of PA limited to some extent.

On the other hand, Fibers appear as an innovative alternative to be implemented in PA mixtures. In many construction materials such as Portland concrete and soils, fibers are mainly used as reinforcement and added with the purpose to increase the tensile strength and to bring ductility to the composites [12]. In bituminous composites such as dense-graded asphalt mixtures, the use of different types of fibers including mineral, organic, steel and synthetic have also been studied [13]. There have been a large number of fiber-modified asphalt mixtures in which fibers have been used to deal with the main flexible pavement problems as permanent deformation, fatigue cracking, and thermal cracking [14]. Meanwhile, in PA mixtures, organic fibers such as cellulose are usually employed to reduce the binder drain down. To date, few research efforts and very little information concerning the use of fibers in PA mixtures are found in the scientific literature. Given the good improvements in the mechanical properties of other composites, analyzing the influencing effect of fibers in PA mixtures, is the challenge that this research took into consideration.

As a novel contribution of this study, the Design of Experiments (DOE) concept combined with Multi-Criteria Decision-Making (MCDM) analysis appears as a powerful statistical tool to deal with the crucial objectives in this research. On the one hand, a DOE based on Taguchi orthogonal array has been applied since it allows to analyze the interaction of different control factors with a reduced number of experiments. In the same way, DOE enables to handle various variables simultaneously and identify the most relevant factors and optimal levels that influence each one of the responses.

On the other hand, MCDM analysis is a suitable alternative for organizing and solving problems that involve multiple criteria [15]. In the present research, a MCDM analysis helped in the selection of the most suitable fibers that could reinforce the PA mixture. Additionally, since more than one response was obtained experimentally, the MCDM analysis was proposed to transform the multi-response optimization problem into a single-one response optimization problem.

### *1.1.2 Normative for the elaboration of the thesis*

This thesis has been presented as a compendium of research articles based on the specifications of the civil engineering PhD degree at the University of Cantabria (Spain) as shown below.

- Regulations of Academic Management of Doctoral studies regulated by the Royal Decree 99/2011 approved by the Governing Council of the University of Cantabria on March 4, 2015, in its title IX. "Preparation of the thesis as a compendium of articles.
- Regulations for the elaboration of the thesis as a compendium of articles within the Doctoral Program of Civil Engineering of the Doctoral School of the University of Cantabria.

The compendium of research articles that supports the present PhD thesis is as follows.

- **Article 1**. Laboratory assessment of porous asphalt mixtures reinforced with synthetic fibers. (DOI: 10.1016/j.conbuildmat.2019.117224). Accepted for publication on October 11 of 2019.
- **Article 2.** An experimental laboratory study of fiber reinforced asphalt mortars with polyolefin-aramid and polyacrylonitrile fibers. (DOI: 10.1016/j.conbuildmat.2020.118622). Accepted for publication on February 28 of 2020.
- **Article 3.** Multi-Response Optimization of Porous Asphalt Mixtures Reinforced with Aramid and Polyolefin fibers employing the CRITIC-TOPSIS Based on Taguchi Methodology. (DOI: 10.3390/ma12223789). Accepted for publication on November 8 of 2019.

### *1.1.3 Projects associated with the thesis*

The current research presents the results performed in the research line of "*Construction of new pavement structures*" developed by the Construction Technology Applied Research Group (GITECO) of the University of Cantabria. The doctoral thesis has been carried out in the framework of two European projects:

- FIBRA project: *Fostering the implementation of fiber-reinforced asphalt mixtures by ensuring its safe, optimized, and cost-efficient use*. This project has received funding from the European Commission of the Department of Roads (CEDR) under Transnational Road Research Program call 2017 under contract N. 867481. The FIBRA project aims to overcome the technical barriers for the safe and cost-efficient implementation of fiber-reinforced asphalt mixtures (FRAM) by National Road Authorities (NRADS). The GITECO research group from the University of Cantabria (Spain) coordinates this project and carries out the research together with EMPA, Material Science and Technology (Switzerland), the Institute für Straßenwesen (ISBS) from the Technishche Universität Braunschweig (Germany), BAM Infra bv (The Netherlands), SINTEF AS (Norway) and Veidekke Industri AS (Norway).

- Foresee project: *Future-proofing strategies FOr Resilient transport networks against Extreme Events.* This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 769373. The overall objective of the project is to provide cost-effective and reliable tools to improve the resilience of transport infrastructure as the ability to reduce the magnitude and/or disruptive events. The present doctoral thesis is linked to work package three whose main objective is to develop porous asphalt mixtures with improved infiltration capacities with similar durability and structural capability than conventional permeable mixtures.

## 1.2 Research objectives and Scope

The main objective of this study was to analyze the reinforcing effect of fibers on PA mixtures employing a novel methodology which combines the design of experiments concept with the Multi-Criteria Decision-Making analysis. The present research analyzed experimentally the effects of fiber addition on the functional and mechanical performance of porous asphalt and bituminous mortar. Furthermore, the reinforcing effect of fibers on PA was compared taking into account other control factors such as binder type, fiber content and binder content. To that end, a parametric study based on the concept of Taguchi DOE was developed. As more than one response was obtained from the experiments, a MCDM analysis was applied to turn the multiple response optimization problem into a single one response optimization problem. To achieve this objective the following tasks were completed:

- A consistent laboratory plan assessment of porous asphalt mixtures reinforced with synthetic fibers.
- An experimental laboratory study of fiber-reinforced asphalt mortars with synthetic fibers.
- A novel combination of DOE-MCDM analysis was proposed to analyze the reinforcing effect of fibers considering other control factors.

## 1.3 Relationship between the articles constituting the thesis

This thesis includes a total of three scientific articles indexed in the Journal Citation Report (JCR). Two of them belong to the first quartile (Q1), while the remaining one belongs to the second quartile

(Q2) according to the most favorable category of the JCR. These articles fulfill the different specific objectives that have been defined for the realization of this thesis. The published articles comprise many experimental tests carried out in the laboratory, and the use of statistical analysis as well as decision support models to analyze the reinforcing effect of adding fibers in PA mixtures.

The development of this doctoral thesis can be divided in two phases. A summary of the phases carried out as well as the articles that make up each phase are described below. It is important to clarify that the publications are not presented in chronological order of publication but based on the methodology set forth to achieve the final objective of the thesis.

The first phase which comprises the article 1. Laboratory assessment of porous asphalt mixtures reinforced with synthetic fibers. (DOI: 10.1016/j.conbuildmat.2019.117224) and the article 2. An experimental laboratory study of fiber-reinforced asphalt mortars with polyolefin-aramid and polyacrylonitrile fibers. (DOI: 10.1016/j.conbuildmat.2020.118622). In this phase, the effectiveness of adding polyolefin-aramid (POA) fibers and polyacrylonitrile (PAN) fibers in PA mixtures in terms of functional and mechanical performance was studied. In the same way, the reinforcing effect of POA and PAN fibers at the asphalt mortar scale were also evaluated. Overall, considering the obtained results, the highest mechanical and functional performance of the PA mixtures were provided by the addition of the POA fibers. Therefore, this fiber was selected to carry out the second phase of the present research.

The second phase of this study includes the article 3. Multi-Response Optimization of Porous Asphalt Mixtures Reinforced with Aramid and Polyolefin fibers employing the CRITIC-TOPSIS based on Taguchi Methodology. (DOI: 10.3390/ma12223789). In this research, a parametric study based on the concept of design of experiments was carried out through the Taguchi methodology. The effects of different control factors such as binder type, fiber content, and binder content were taken into account to evaluate both the functional and mechanical performance of PA mixtures. Different experimental tests like total and interconnected air voids, raveling resistance in dry and wet conditions, and binder drain down were performed, and the response parameters were analyzed individually. Additionally, a MCDM analysis was included to unify all the experimental responses in one unified index value. Criteria importance through inter-criteria correlation (CRITIC) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) were the methods used to transform the multi-response problem into a single-one response problem. Among the main conclusions, it was observed that POA fibers act very well as stabilizer agents and as reinforcement since they reduce the particle loss in dry conditions. With the fiber addition, total and interconnected air voids are slightly reduced, and not clear improvements in the raveling resistance in wet conditions were observed unless the bitumen content increased. The integration of DoE and MCDM techniques have proved to be a useful tool for the evaluation of the impact of different admixtures on different responses, as well as for the optimization of multiple responses simultaneously. It is recommended to apply this novel methodology to other composites of materials.

## 1.4 Structure of the thesis

This thesis is composed of seven chapters which are: Introduction, synthesis of the state of the art, methodology, published articles, discussion of results, conclusions and future research lines and the extended abstract in Spanish.

The first chapter introduces the framework of the thesis providing background information on the research topics, the academic regulations for the realization of the thesis, and the projects entailed with the thesis. Additionally, the research objectives and the scope are presented as well as the relationship between the articles that compose the thesis. The second chapter presents a summary of the state of the art emphasizing the main topics of this research which are porous asphalt mixtures, fibers in bituminous mixtures, Design of experiments, and Multi-Criteria Decision-Making analysis. The third chapter details the materials and methods employed to complete this research. In the fourth chapter, the three published articles related to this thesis are attached, as well as the information of the journals according to the Journal Citation Report. In the fifth chapter, the results of the research are analyzed and discussed. The main conclusions and the recommendations about future research lines are included in chapter six. Finally, an extended abstract in Spanish is included in chapter number seven.

# 2. SYNTHESIS OF THE STATE OF THE ART

## 2.1 Porous asphalt mixture

Porous asphalt (PA) as it is commonly known in Europe or Open-graded friction course (OGFC) as it is also termed in the United States is a special type of bituminous mixture characterized by having a large air voids content manufactured with high-quality aggregates and reduced quantity of fines [3]. In general, a minimum air voids content of 20% is recommended for this type of mixture. However, in the US a minimum value of 18% is also appropriate [6]. Given the high porosity, this mixture is highly permeable allowing the passage of water through its structure. Other effects such as hydroplaning, splash and spray effects, rolling noise, and surface reflectivity are also reduced with the incorporation of PA mixtures. An increment in the skid resistance especially in wet conditions and a better storm water management are also other advantages reported in the literature [16].

### *2.1.1 Background of PA mixtures*

In the United States, its use dates back to 1950, while in Europe, this mixture began to be used from 1970 [11,16]. In the same year, the use of OGFC gained popularity in the US to increase the skid resistance in roadways. However, due to poor durability, some states have stopped or discontinued their use. The open structure of the mix is highly exposed to the air and water conditions weaken the cohesion inside the mortar and the adhesion generated in the binder-aggregate interface [17]. Some states such as Oregon, Georgia and Texas tried to improve the mixture design employing high viscosity polymer modified binders and fibers as a stabilizer to avoid the leakage of binder or the binder drain down [14]. According to Fitts [18], the use of a modified binder allows increasing the binder film thickness around the aggregates decreasing the exposition oxidation and preventing the raveling. Concerning experiences in Europe with the use of PA mixtures, slight differences can be identified when compared to the US. Overall, a minimum air voids content of 20% is necessary to guarantee the proper functional performance of the mixture. Similarly, the use of polymer modified binders is recommended but its use is not exclusively of all European countries. The United Kingdom started the use of PA mixture in the early 1960s to increase the skid resistance in weather conditions and void the aquaplaning. A thickness layer of 50 mm with a maximum particle size of 20 mm of particle sized aggregate was used [11]. In France the use of PA mixture dates back to 1976. According to Bonnet [19], a 40 mm thick layer with a maximum particle size of 10 mm and conventional 50/70 penetration graded binder was used. On especial highways and conceded motorways the use of polymer modified binder and fiber modified bitumen is almost exclusively [19]. However, previous experience states that there is no clear evidence that the use of polymer modified binder increases the raveling resistance of the mixture when is compared to unmodified binders. In Netherlands, the use of PA mixture as wearing course began to be of interest in 1972 [20]. Despite of the shorter expectancy life of the use of PA mixture as surface layer, the advantages in terms of noise mitigation and safety properties make this mixture an attractive solution to be implemented in this country. The Dutch Department of Public Works (Rijkswaterstaat) have installed qualified porous asphalt in almost all the main highway network [20]. Due to raveling which is the main type of failure observed in the PA mixture, the service life of the pavement is about 10 – 12 years, and in narrow curves, the raveling phenomenon can be observed after three years of use [11]. Similarly to other European countries, 50 mm of thickness layer is used due to the higher water storage capacity of the layer. Unmodified bitumen, cellulose fibers, and limestone or hydrated lime as filler are the most common admixtures to increase the raveling resistance and increase the bonding forces inside the PA mixture. In Spain, the first application of porous asphalt started in 1980 in northern highways in a region of frequent rainfall [21]. According to Spanish experience, thickness layer of 40 mm with 0/10 or 0/12.5 gradings, with few amount of fines and conventional or modified bitumen results in mixtures with a voids content higher than 20% [21]. Actually, the use of polymer modified binder is preferred over conventional binder to increase the resistance to particle loss in open-graded mixtures through a greater cohesion and getting longer durability because of the low susceptibility to temperature changes and higher flexibilities at low temperatures. In the design of PA mixtures, Spain has also become an international reference. Many tests such as Cantabro and LCS permeameter have been crucial in the design of PA mixtures [22,23] with a proper durability and drainage capabilities. According to Ruiz et al. [21] PA mixture must have a minimum binder content to ensure the resistance against particle loss and a maximum binder content to avoid binder runoff and keep a good drainability.

### *2.1.2 Benefits of PA mixtures*

Based on the review presented by Alvarez et al. [6] the benefits of PA mixtures can be understood mainly in two perspectives: safety and environment

Concerning safety benefits, it is well known that the PA mixture improves the skid resistance, especially in wet conditions. Given the large porosity of the mix, the water can pass through the top layer to the subsequent layers preventing the condition of hydroplaning. Since the water is dispersed through the pores of the mixture, the contact between the tire and the pavement is notably increased. The splash and spray effects generated by the rolling of the wheels are also mitigated increasing visibility. The glare reduction has been reported as another advantage with the use of open-graded asphalt mixtures. Less water in the surface layer entitles a reduction in the reflection of the incident light improving visibility, especially in the rainy days. The frictional resistance, especially under wet weather conditions, is also improved by the use of PA. Higher skid resistance in wet conditions can be achieved at high speed in porous mixtures instead of dense-graded asphalt mixtures.

The environmental benefits have been the main reason why different countries have employed PA mixture as a surface layer. The mitigation of the noise pollution caused by the passage of the vehicles has motivated the use of PA mixture in the Netherlands. Measurements performed in the Netherlands have shown that the use of PA mixture as surface layer reduces the noise levels by approximately 3dB in comparison to dense asphalt concrete mixtures [20]. Due to the open structure of the PA, the noise is absorbed and rapidly dissipated through the pores. Besides, higher driver comfort levels can be achieved since the noise reduction can be perceived inside the vehicle.

Apart from noise reduction, other benefits can be observed such as the production of a cleaner runoff than the obtained from conventional dense-graded mixtures.  The rate at which chemicals are removed from the asphalt by leaching is higher using the PA mixture [6].

Concerning the structural capacity of the mix, the stone-on-stone contact formed by the coarse aggregates provides a suitable resistance to plastic deformations [24]. Given the coarse aggregate interlock formed in the internal structure of the PA mixture, it can be inferred that this mixture presented a superior resistance to rutting when compared to dense-graded asphalt mixtures.

### *2.1.3 Drawbacks of the PA mixture*

Despite multiple utilities that PA mixture offers in the road network, one of the main challenges to deal is the short service life expectancy of this mixture compared to dense-graded asphalt mixtures. While in a conventional asphalt concrete mixture the expectancy of life is approximately 18 years, in PA mixtures the service life is limited to 10 – 12 years approximately. Raveling, which can be defined as the loss of particles in the wearing course of the pavement caused by the repetitive abrasive loads of the traffic, is the most relevant type of failure observed in PA mixtures. This type of distress is related mainly to binding failure in the stone-contact interface. The lower binder film thickness that covers the aggregate and keeps the aggregates together is highly affected by both the excessive aging of bitumen and the damage caused by the action of water. Besides, the loss in the cohesive force through the pure mortar and the adherence in the binder-aggregate matrix can also occur, allowing the particles to come off. Once raveling occurs in the mix, it accelerates rapidly causing an increase in the rate of particle loss. The Cantabro test developed in Spain [22] has been extensively used in many countries around the world to measure the raveling resistance of porous asphalt in terms of particle loss. This test can provide reliable results in evaluating the long-term durability of the mixture in field conditions. Moreover, new and innovative tests are being developed to measure the raveling resistance of PA mixtures and also Portland cement pervious concrete[25,26]. The rotating surface abrasion test (RSAT), for example, reproduces in a more realistic way, the abrasion caused by the tire contact by applying both wrenching and shearing forces between the wheel and the asphalt specimen [27]. Another test is the loaded wheel abrasion tester, which is a variation of the loaded wheel tester commonly used to measure the rutting potential of bituminous mixtures. Nevertheless, to generate abrasion on the sample, steel studs are added to the wheel surface [25]. It is important to point out that these tests are still under development and hence out of regulations.

### *2.1.4 Typical admixtures used in PA mixtures*

Given the poor durability of the mixture, the employment of high-quality aggregates for producing PA mixtures is so typical. Concerning the type of binder, polymer modified binders, and rubber modified binders are the most commonly used. Styrene Butadiene Styrene (SBS), Styrene-Butadiene Rubber (SBR), and Ethylene Vinyl Acetate (EVA) are the most popular polymers added to the asphalt. These modified binders have higher flexibility than conventional binders, especially at low temperatures, and hence it is believed that their binders coat the aggregates more properly, increasing the resistance against the abrasion. The addition of fibers appears as an alternative to increase the durability of the mixture. The large surface area of fibers allows to retain more bitumen and therefore, higher amounts of bitumen can be added to the mix without risk of binder drain down. Cellulose fiber is the preferred option since is a type of fiber environmentally friendly, biodegradable, easy to buy, and low cost. The use of fibers as reinforcement in the bituminous mixture have also been investigated extensively (i.e. especially in Asphalt concrete). A review concerning the use of fibers in hot mix asphalt is presented in chapter 4 of this work.

Hydrated lime and anti-stripping agents are also common admixtures to enhance the affinity of the aggregates with the bitumen, improving its adherence and hence to increase the durability of the mixture, especially against the moisture damage. Hydrated lime in bituminous mixtures affects positively the stiffness, toughness, and oxidation of the mixture [28]. Overall, hydrated lime is mixed with aggregates before the addition of the binder. The general practice is to replace part of the filler with hydrated lime. Adding from 1 to 3 percent by dry weight of aggregate is the most typical amount. On the other hand, anti-stripping agents are chemical composites which contain amines. This additives act reducing the surface tension presented within the asphalt-aggregate interface increasing the bonding force. Generally, they are blended with asphalt before the addition of aggregates.

### *2.1.5 PA mixture design practices*

Each country within its regulations has different criteria for manufacturing PA mixtures. In general, an open aggregate gradation curve is the first factor to be taken into account in the design of a PA mixture to keep an adequate porosity. The porosity is normally measured based on the volumetric properties of the specimens. In other states from the US, the permeability of the mixture is another indicator of the functional performance of the mixture. Once good levels of air voids content are achieved, the durability of the mixture is measured. Cantabro test and moisture sensitivity test are the typical tests applied to PA mixtures to evaluate the raveling resistance and moisture damage. The binder drainage is the other important criterion to take into account. Due to the low amount of fines, PA mixtures are susceptible to present loss of binder. Therefore, tests such as mesh basket drain down and Schellenberg tests are the most popular to record this property.

According to Spanish standards [29] and other recommendations found in the scientific literature, the minimum requirements that a porous mixture must satisfy are:

- The air voids in the mixture must be at least 20%.
- The particle loss in the Cantabro test must be lower than 20% in dry conditions and 35% in wet conditions.
- The indirect tensile strength ratio (ITSR) must be higher than 85%.
- PA mixtures must not present binder drain down problems. A threshold of 0.3% is recommended.

Figure 1 shows the typical particle size distribution specified in the Spanish specifications for a PA16 (maximum nominal size of the aggregate equal to 16 mm).

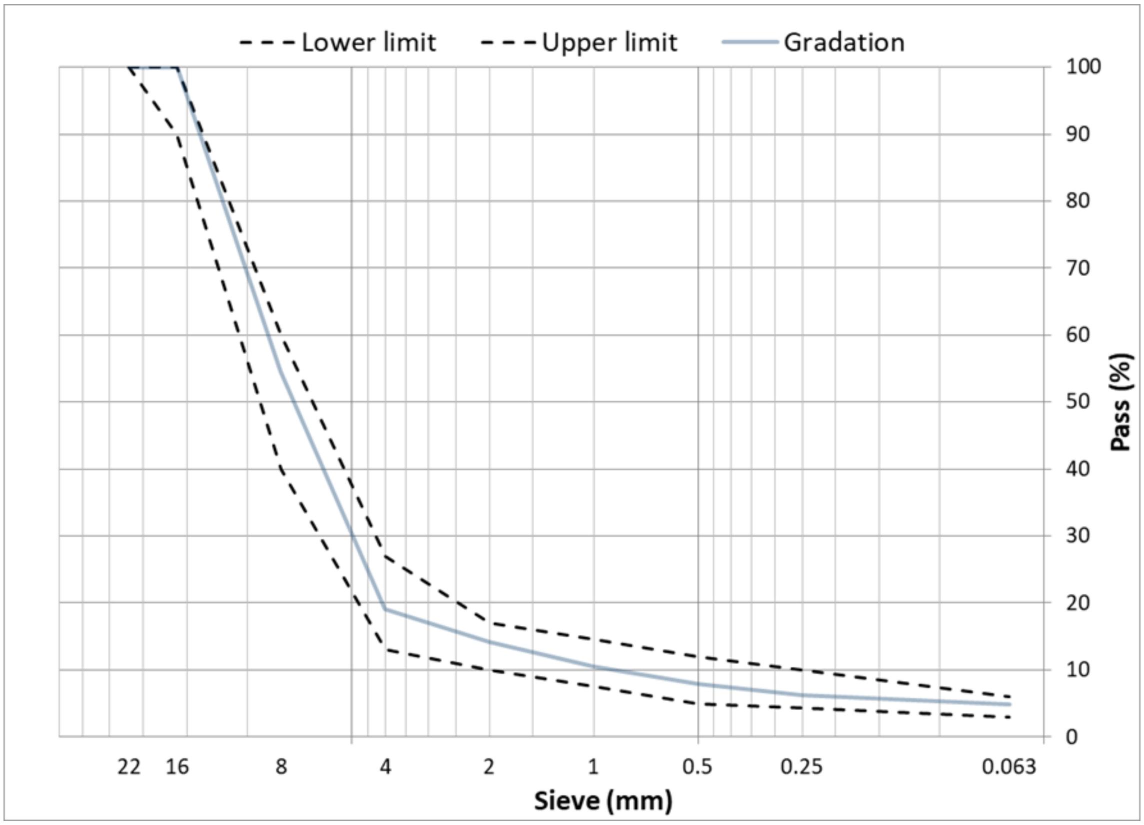



*Figure 1 Particle size distribution of the PA mixture*

## 2.2 Fibers in bituminous mixtures

Fiber-reinforced asphalt mixture (FRAM) can be defined as a mass of bituminous mixture whose discrete elements as fibers are distributed randomly, to provide an improvement in the mechanical performance of hot mix asphalt. In other words, FRAM behaves as a composite in which fibers are embedded in the asphalt matrix to increase the mechanical properties. Several types of fibers (see Figure 2) including mineral (basalt, asbestos); organic (cellulose, lignin, coir); steel, and synthetic (polyester, polyacrylonitrile, polyolefin, aramid, nylon, polypropylene) have been added to FRAM as reinforcement. Overall, the main objective of the inclusion of fibers is to bring ductility to the mixture and to provide additional tensile strength. In the same way, fibers act as a crack barrier preventing the formation and propagation of cracks. In Stone Matrix Asphalt (SMA) and PA mixtures, the inclusion of fibers with large surface area helps to prevent the binder leakage [30].


*Figure 2 Fibers used as reinforcement in hot mix asphalt*

### *2.2.1 Blending process of fibers in HMA*

Fibers can be added to hot mix asphalt by the dry or wet process. In the first process, fibers are initially mixed with aggregates before the addition of bitumen. In the wet process, fibers are firstly blended with bitumen and they are incorporated into the whole mixture. In both cases, there is a need for a homogeneous distribution of the fibers within the mixture. Generally, the dry process is preferred over the wet process due to many reasons. The main one is because by dry process fibers tend to distribute better avoiding the formation of clusters, in a phenomenon also known as "balling". Similarly, in the plant production costly and specialized equipment is necessary to blend the fibers with bitumen.

### *2.2.2 Reinforcing effect of fibers in HMA*

Many types of fibers have been used in hot mix asphalt [31–36]. Morea and Zerbino [37], investigated the effect of adding glass fibers in asphalt concrete (AC) mixtures and evaluated their performance regarding fracture response at low temperatures and rutting at high service life temperatures. According to the results, the 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 [38]. In another research, Klinsky et al. [35] assessed the benefits of adding polypropylene and aramid fibers in hot mix asphalt. The experimentally tested plan included resilient modulus, dynamic modulus, flow number test, fatigue, and fracture energy [35]. Based on the results, these fibers in the mix increased the resilient and dynamic modulus at high temperatures. Therefore, 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 by having higher thermal stability and mechanical properties than other fibers while maintaining similar weights as glass or steel fiber [39]. 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 [39]. Tapkin [40] 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 USA, 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 [41].

Other types of polymer fibers have been extensively used in HMA. Xu et al. [42] 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. The optimum fiber content of 0.35% by mass of AC was recommended to achieve optimum outputs of rutting resistance and split indirect tensile strength.

The use of fibers has not only been applied to AC mixtures, but Mahrez et al. [28] also studied the characteristics of a glass fiber reinforced Stone Mastic Asphalt (SMA). The authors reported that an optimum fiber content of 0.3% by mass of the total mixture resulted in the best performance in terms of 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 was observed. In this sense, an excess of fibers in the mix could generate clusters and does 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 (PA), 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 [30] compared the performance of different stabilizing additives including cellulose fibers, styrene-butadiene-styrene, and crumb rubber modifiers in a PA mixture. Results indicated that crumb rubber and cellulose fiber were the most effective additives to reduce drain down. However, the combination of 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.

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 [43]. To be more competitive, the use of recycled fibers coming from industrial waste is being explored [44,45]. Thus, some researches [46] suggested the use of waste nylon wires coming from the production of brush wire products, such as toothbrushes or hairbrush paintbrushes among others could be used as fiber reinforcement in hot mix asphalt. Yin and Wu [46] assessed the feasibility of incorporating waste nylon fiber in SMA mixtures. 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%. A more complete literature review about the use of fibers in HMA can be found in Slebi et al. [44].

## 2.3 Design of experiments

The design of experiment (DOE) concept was introduced by Ronald A. Fischer in the first half of the 20$^{th}$ century in the United Kingdom. This method has been extensively used in different fields of the industry, such as the machining process, materials optimization, and construction engineering [47,48]. One of the great advantages of the DOE is the possibility of investigating a wide spectrum of parameters and obtaining responses to different types of criteria. Overall, it is widely known that the majority of experimental designs are full or fractional factorial designs. In the full factorial design, all the combinations of levels for all factors are taken into account while in a fractional factorial design, the experimental points are carefully selected based on the most important information revealed by the problem under study. That said, the fractional design is considered a practical tool especially when resources are limited because the number of experiments is reduced, taking into account the most relevant information for the problem. Within the best-known methods of factorial designs, there is the response surface method (RSM) and the Taguchi method.

### *2.3.1 Response Surface method*

The Response Surface Method (*RSM*) was introduced by George E.P Box and K.B Wilson in 1951 as a response of the large number of runs using the full factorial design [49]. This approach allows to perform an experimental design that combines different input variables and uses the responses from the data to determine a set of equations that governs theoretically the values of an output. Unlike full factorial designs, the RSM is a fractional factorial design where the number of experiments can be reduced notably. The method has been applied especially in optimization processes like friction stir processing or machining processing [48]. Also, to identify the proper combination of parametric levels in a specific response the RSM is a suitable tool. In other words, the advantage of the method is that several variables can be studied simultaneously to identify the most optimal response. Three are the main steps in the implementation of RSM. The first step corresponds to design the experiments. In this step Box Henken and Central composite design are the most common types of practices to prepare the experimental plan. The difference lies in the certain number of axial points, factorial points, and central points considered to carry out the experimental runs. Some authors suggest that Box Henken is a simplified method of central composite design where the axial points are not needed and some constraints are embedded in the method such as the minimum number of control factors and the regression models that must satisfy it [49]. In the second step, statistical and regression analysis are done to model equations that represent the behavior of the response surface. Linear, linear plus interaction, and polynomial equations (i.e. second, third, or more orders depending on the number of factors) can be developed to describe the response surface modeling. Statistical analysis as analysis of variance allows assessing the goodness-of-fit of the predictive equations and the statistical significance of each input variable that governs the model. Also, estimating the error between the response values of the model and the experimental values are checked. In the third step, the optimization of variables is done through the best fit regression model. In bituminous mixtures, the use of RSM contributes to identify the proper combination of a specific group of admixtures that leads with an optimal durability response. To cite an example, Khedmati et al. [50] examined the effect of grading, binder content, zycosoil content, sasobit content, and mixing temperature on moisture susceptibility of warm stone matrix asphalt. The central composite design was selected to design the experimental runs that comprise the five factors at three levels each control factor. Polynomial models of second-order fitted very well on the moisture susceptibility response and hence in the prediction of the optimal levels of these parameters. In another research, Varanda et al. [51] optimize different bitumen blend formulations through the response surface modeling on the softening point and penetration graded response. In this study, the analysis of variance was performed to analyze the significance of the predictive models on the experimental values. In that sense, RSM demonstrated to be an essential tool for bitumen formulation that involves a large number of input components.

### *2.3.2 Taguchi method*

The Taguchi method is a type of DOE, proposed by Genichi Taguchi in Japan during the 80s, successfully applied in the Japanese industry for the optimization of various processes and materials development. In civil engineering it has been utilized in different fields such as geopolymer concrete [52], polymer blended concrete [53], previous Portland concrete pavement [54], and self-compacting mortar [55]. The main questions that can be solved employing the Taguchi approach are as follows.

- Compare various additives in a composite to select the best one in a given response.
- Compare two or more materials with respect to a specific criterion.
- Identify the most relevant control variables that influence one or more characteristics of a final product.
- Identify the main factors or operational conditions that affect a determined process.
- Support the design and redesign of novel products and processes.

Different control factors and parametric levels can be examined through the concept of orthogonal arrays proposed in the Taguchi method. The use of orthogonal arrays contributes to reducing the number of experiments facilitating the design of experiments. Besides, the signal to noise (*SN*) Ratio typical from the Taguchi method is a measure that enables the calculation of significant input parameters by assessing the minimum variance [56]. In other words, higher values of the *SN* Ratio suggest more relevance of the input parameters on the responses. In general, *SN Ratio* can be specified in three different scenarios namely the *smaller-the-better*, the *larger-the-better*, and the *nominal-the-better*. The equations used for calculating the *smaller-the-better*, the *larger-the-better* and the *nominal-the-better* scenarios are shown respectively as follows:

$$\text{SN Ratio}_{\text{smaller-the-better}} = -10\,log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

$$\text{SN Ratio}_{\text{larger-the-better}} = -10\,log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right) \tag{2}$$

$$\text{SN Ratio}_{\text{nominal-the-better}} = 10\,log\,\frac{\bar{y}}{s^2} \tag{3}$$

Where $y_i$ corresponds to the experiment result at the $i^{th}$ experiment, *n* refers to the total number of experiments, and *S* is the standard deviation of the experimental results for the given factor level combination. Figure 3 shows the typical flow chart to carry out a typical design of experiments through the Taguchi methodology.

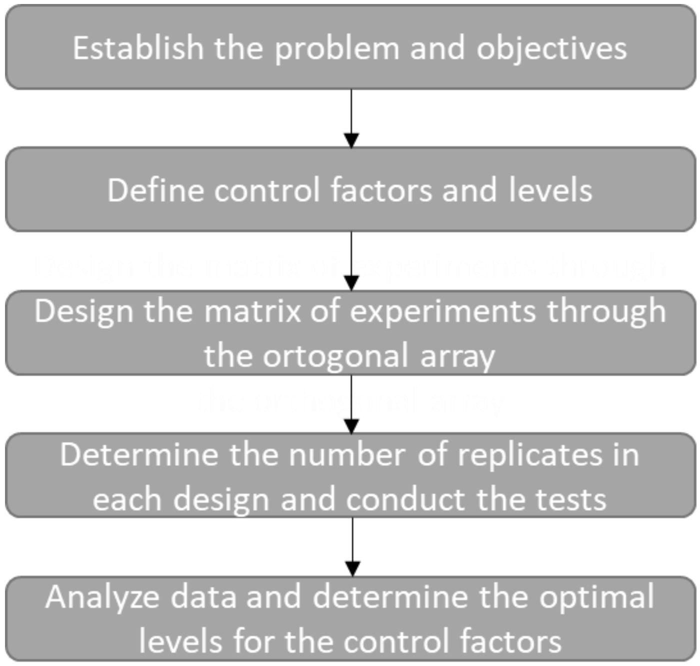



*Figure 3. Taguchi DOE flow chart*

## 2.4 Multi-Criteria decision-making analysis

### *2.4.1 Overview of MCDM analysis*

Given the great advances in the construction and implementation of new materials, products, and processes in the industry, complex decisions that involve a series of alternatives and criteria become a fairly time-consuming task. Multi-criteria decision-making (MCDM) methods enable to identify the most promising alternatives contained in a set of alternatives based on previously established attributes [57]. These methodologies contribute to facilitate the decision-making process and establish a preference ranking based on established criteria. To mention some examples, Simple Additive Weighting (SAW), Weighted Product model (WPM), ELimination and Choice Expressing REality (ELECTRE), Gray Relational Analysis (GRA), Technique of Ordering Preferences by Similarity to Ideal Solution (TOPSIS), Weighted Aggregated Sum Product Assessment (WASPAS), multi-criteria optimization and compromise solution (VIKOR), and Distance from Average Solution (EDAS) have been applied in diverse fields such as material selection, military location, service quality, construction, and manufacturing processes [58,59].

To overcome criteria elicitation drawbacks, decision-makers have also applied other MCDM approaches. The first ones include subjective weighting methods that include human participation for determining the relative weights of criteria. The most commonly known are Analytic Hierarchy Process (AHP), Analytic Hierarchy Process under fuzzy environment (FAHP), and the best-worth method (BWM). Nonetheless, since these methods depend on human decisions, objective approaches are also attractive since the weights are assigned by mining the information contained in the original data. The criteria importance through the inter-criteria correlation (CRITIC) method and Entropy approach are referred to as an objective weighting method which facilitates automated decision making [60].

The combination of MCDM methodologies allows a much more robust model in the decision-making process. On the one hand, some techniques are used to determine the weights of the attributes while the other methods focus on establishing a unified index of which may be the best alternative. In the construction industry, AHP-TOPSIS hybrid MCDM analysis highlights as one of the most preferred alternatives to carry out a decision-making process, the above, probably because it involves the participation of decision-makers and employs a straightforward structured mathematical algorithm with low computational efforts [61]. In the last few years, some authors [62] have argued that the Weighted Aggregated Sum Product Assessment (WASPAS) methodology performs more accurately than others. Zakarevicius et al. [62] suggested that WASPAS is more robust than the WSM and WPM approaches. Moreover, concepts like uncertainty and vagueness are present in the evaluation process and hence the incorporation of fuzzy sets is a valuable tool when tackling this kind of problem. The problem associated with imprecise input parameters is handled by employing Monte-Carlo (MC) stochastic simulations. This tool serves mainly to consider quantitative variables not as single numbers but as probability distributions.

### *2.4.2 Multi-subjective Weighting approach*

AHP approach is one of the most popular MCDM tools on criteria elicitation. In this method, the criteria measurement is done through pairwise comparisons and relies on the judgments of decision-makers for the allocation of weights. Apart from the identification of the relative weights, this method helps to synthesize a series of factors of a robust decision-making process in a hierarchical manner. In the first step of AHP, the main factors that affect the decision must be organized in a hierarchical structure where the goal is at the top level, followed by the criteria which are in the middle level and the alternatives in the third level. Although the AHP method can be applied as a MCDM analysis in an autonomous and isolated way to prioritize the attributed and ranking the alternatives of a decision-making problem. The most frequent practice is to identify the relative weights through human participation. To that purpose, a set of matrices is constructed to calculate the relative weights based on pairwise comparisons. Besides, this method helps to check the consistency of the data obtained by the participation of decision-makers leading with the bias and the vagueness in the decision-making process. Despite not being a strictly mandatory practice, documenting the reasons that led to such decisions is a useful technique to justify and improve the decision-making process[63]. Furthermore, to capture the ambiguity presented in the judgment of attributes, some authors recommend adding fuzzy sets to the AHP method [64]. The study cases where the AHP method has been used are related to the industry including different types such as manufacturing, electronics, oil, construction, and entertainment [64].

### *2.4.3 Multi-objective weighting approaches*

Multi-objective weighting approaches are denoted to those methods where human participation is not necessary and the allocation of weights is assigned based on the information provided by data.

The Entropy and CRITIC method is among the most popular methods for determining the relative weights of different attributes taken into account in the decision making process. On the one hand, entropy proposed by Shannon [65] is utilized in information theory to identify the amount of information presented in a determined message. In a decision-making problem when a decision matrix is established, the set of alternatives provides a certain amount of information that can be successfully identified by the entropy method. A set of alternatives in an attributed with low entropy information is generally assigned with larger weights and vice versa. Unlike the AHP method, Entropy relies on the objective data given by the alternatives. On the other hand, the CRITIC method introduced by Diakoulaki et al. [66] in 1994, is another multi-objective multi-criteria decision making to identify the relative weights of attributes. The method is based on the concept of the contrasting intensity of each criterion and conflict assessment between criteria in the decision-making problem [67,68]. Similar to Entropy, the quantity of information contained in a set of alternatives for a specific criterion is determined. The greater amount of information involved in a given criterion, the higher the relative weight of the criterion in the decision-making problem. This method has been used for criteria elicitation in many contexts as the machining process, manufacturing control, and selection problem, and so on [60].

*2.4.4. Methods for ranking alternatives*

The TOPSIS approach is considered one of the most popular mathematical models to determine the optimal solution or best-preferred alternative of a MCDM analysis. The practicality and its easy applicability with low computational cost make TOPSIS the preferred method in the construction industry together with AHP for the weighting of criteria. The algorithm of TOPSIS is structured based on the concept of the distance of the alternatives proposed to positive and negative ideal solutions [69]. In other words, a positive ideal solution (PIS) refers to an alternative that maximizes the benefit responses and minimizes the cost responses, whereas a negative ideal solution (NIS) is considered the least preferred solution as it minimizes the benefit responses and maximizes the cost responses. Therefore, the best alternative would be the one closest to the positive ideal solution and furthest from the negative ideal solution. The WASPAS method introduced by Zavadskas et al. [62] in 2012 is considered one of the new powerful multi-criteria approaches because it integrates two different multi-criteria methodologies known as the Weighted Sum Model (WSM) and Weighted Product Model (WPM).

# 3. METHODOLOGY

The structured framework of the current research is displayed in Figure 4. As can be observed, the research is divided in two main phases. In the first phase, the effectiveness of adding synthetic fibers in the PA mixture is analyzed experimentally in terms of functional and mechanical performance. A set of polyolefin-aramid (POA) fibers and polyacrylonitrile (PAN) fibers were the chosen ones to be used through to the whole investigation. It is worth to clarify that these fibers were pre-selected to be applied in this thesis based on a previous MCDM analysis carried out among the partners of the FIBRA project. The MCDM analysis was oriented to select the most suitable fibers from the mechanical point of view based on available information in the literature concerning asphalt concrete mixtures. Continuing with the explanation of the first phase, a complete experimental plan was carried out not only at porous asphalt scale but also at bituminous mortar scale since the main distresses occurs due to the loss of the cohesive forces in the bituminous mortar matrix and the loss of adherence in the mortar-coarse aggregate interface. Besides, in this phase, the most promising fiber was selected and thus advance towards the second phase of this research which consisted in study the effects of different control factors simultaneously. Binder Type (BT), Fiber Content (FC) and Binder Content (BC) were the principal control factors into consideration to be analyzed experimentally. A novel method that combines the Design of Experiments and Multi-criteria Decision-making analysis was proposed to turn the multiple response problem into single one-response problem to then select the optimal parametric levels per each control factor and the preference ranking among the alternatives.

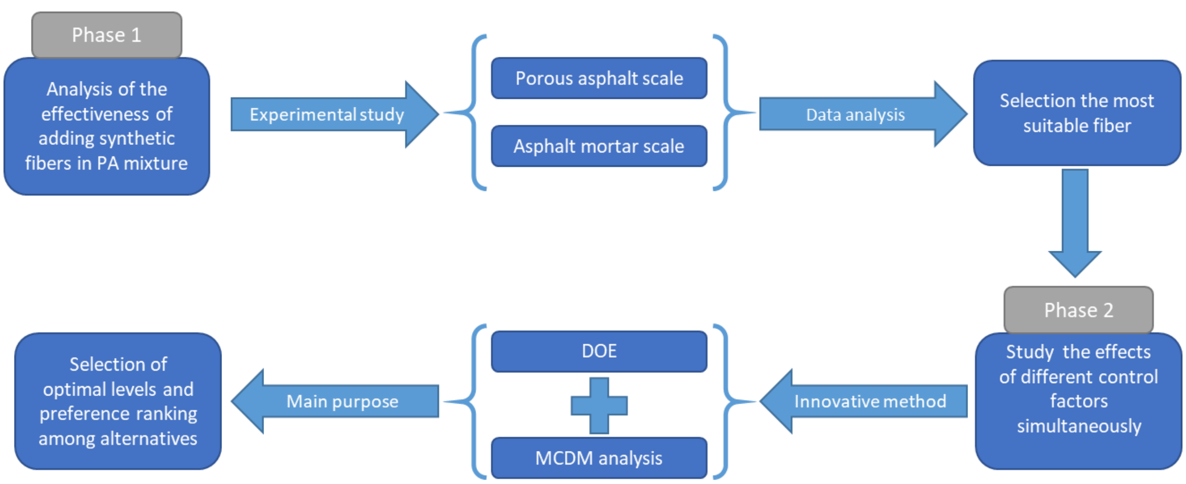



*Figure 4 Structured framework of the current research*

In this chapter, the methodology is divided into five main sections. In the first section, the preselection process carried out to select the POA and PAN fibers are briefly explained. In the second section the materials and sample preparation are described. The samples manufactured included mainly PA cylindrical samples and cylindrical mortar specimens. As the research has a significant experimental component, section three describes all the tests carried out along the study. Finally, the fourth and fifth sections present the experimental designs, procedures and statistical tools carried out in each one of the two main phases of this thesis.

## 3.1 Pre-selection process of the most suitable fibers to be used in this research

Based on a literature review done by Slebi-Acevedo et al. [44] It is well known that in asphalt concrete mixtures, many types of fibers have been used as a reinforcement to increase the mechanical performance. Meanwhile, in PA mixtures, cellulose fibers are the typical fibers employed, since they allow to retain more bitumen and hence increasing the durability of the mixture. For the above, the selection of the most suitable fibers that could reinforce the open-graded mixture was a complicated task, so the election was based on the improvements reported in the scientific literature regarding adding fibers in AC mixtures. The fiber pre-selection included three main steps. Step1: Definition of the decision-making analysis; Step 2: Weighting of criteria and Step 3: Assessment of alternatives. Figure 5 illustrates the structural framework of the pre-selection process.

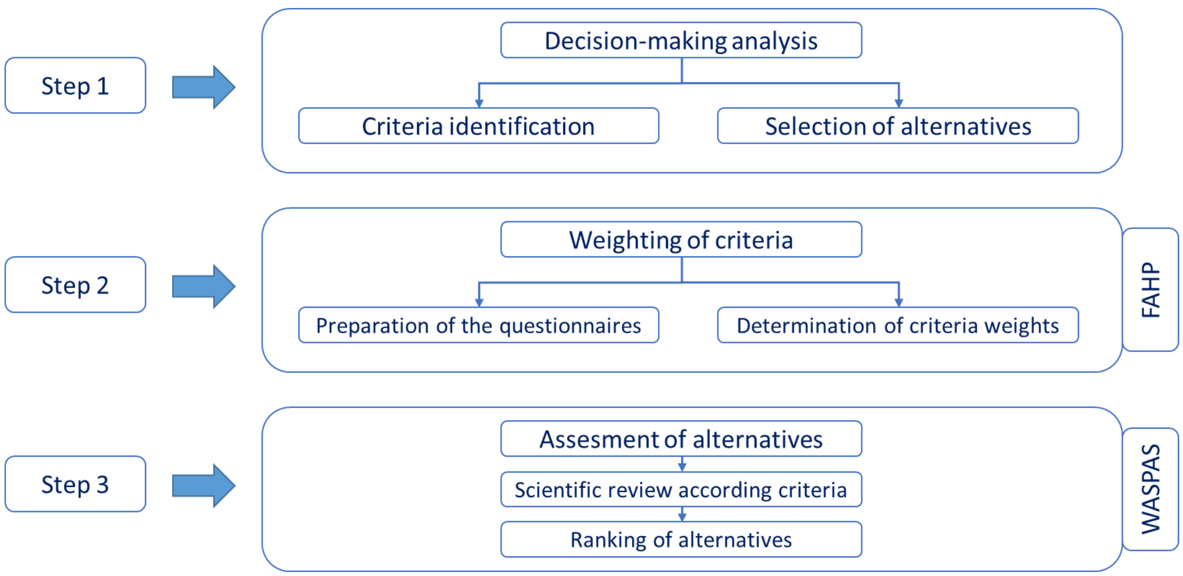



*Figure 5 Main steps performed in the fiber pre-selection process*

### *3.1.1 Definition of the decision-making analysis*

The decision-making analysis comprised two crucial tasks. The first one corresponded to criteria identification and the second one refers to the selection of the alternatives. As this analysis was done from the mechanical performance point of view, only mechanical properties were considered. Based on different research studies, the main properties found were: Rutting resistance (RR), Fatigue Life (FL), Toughness (T) and (ITS). As alternatives, the fibers selected were as follows polyester (PET), polypropylene (PP), fiber glass (FG), polyacrylonitrile (PAN) and the set of polyolefin-aramid (POA) fibers.

### *3.2.1 Criteria evaluation and assessment of alternatives*

For criteria evaluation, the Analytic Hierarchy process (AHP), one of the most widely multi-attribute decision-making techniques, was applied for determining the relative importance of the set of criteria previously established. The advantage of the approach lies in that it heavily involves human participation and judgments which in this context is appropriate. Besides, the AHP technique was combined with fuzzy sets (FAHP) to take into account the uncertainty associated with the process and deal with the unbalance scale of judgment.

To give weights to different criteria, the judgment of different experts was requested. Thus, a series of questionnaires were elaborated and sent to worldwide experts on the topic. The questionnaires were completed by 25 experts from different sectors and perspectives, including academic, industry and public authorities.

Concerning the assessment of alternatives, The FAHP method was integrated with the Weighted Aggregated Sum Product Model (WASPAS). This method which belongs to the newer generation of MCDM methods comprises two methodologies, the Weighted Sum Model (WSM) and the Weighted Product Model (WPM). In addition, this model is based on the additive utility assumption, which states the total value of an alternative. More information regarding the methodology applied for the selection of fibers aimed at reinforcing asphalt concrete mixtures can be consulted in Slebi-Acevedo et al. [70].

## 3.2 Materials and specimen preparation

### *3.2.1 Binders*

For this study two types of binders were used. A conventional 50/70 penetration grade binder (binder 50/70), and a polymer modified binder known as PMB 45/80 – 65 (Binder PMB). Their main properties according to the supplier are presented in Table 1.

*Table 1 Main properties of binders used*

| Binder ID | Binder type | Test | Standard Method | Value |
|---|---|---|---|---|
| 50/70 | 50/70 conventional penetration grade. | Penetration at 25°C (mm/10) | EN 1426 | 57.00 |
| | | Specific Gravity | EN 15326 | 1.04 |
| | | Softening point (°C) | EN 1427 | 51.60 |
| | | Fraass brittle point (°C) | EN 12593 | -13.00 |
| PMB | PMB 45/80-65 Polymer modified binder | Penetration at 25°C (mm/10) | EN 1426 | 49.50 |
| | | Specific Gravity | EN 15326 | 1.03 |
| | | Softening point (°C) | EN 1427 | 72.30 |
| | | Fraass fragility point (°C) | EN 12593 | -13.00 |
| | | Ductility force at 5 °C ($J/cm^2$) | EN 13589 | 3.11 |
| | | Elastic recovery at 25°C (%) | EN 13398 | 90.00 |

### 3.2.2 Aggregates

Ophite, which is a type of igneous rock was used as the coarse fraction while the fine and the filler fractions were completed with limestone for the preparation of PA mixtures. The physical properties determined according to Spanish standards are shown in Table 2.

*Table 2 Physical properties of aggregates used*

| Characteristic | Spanish - Standard | Value |
|---|---|---|
| Coarse Aggregate | | |
| Specific Weight (g/cm$^3$) | EN 1097 - 6 | 2.794 |
| Water absorption (%) | EN 1097 - 6 | 0.6 |
| L.A abrasion (%) | EN 1097 - 2 | 15 |
| Slab Index (%) | EN 933 - 3 | < 1% |
| Polishing Value | EN 1097 - 8 | 60 |
| Fine Aggregate | | |
| Specific Weight (g/cm$^3$) | EN 1097 - 6 | 2.724 |
| Sand Equivalent | EN 933-8 | 78 |

### 3.2.3 Fibers

Two different fiber types were studied in the present study (see Figure 6). The polyolefin-aramid (POA) fibers which consisted of a blend of synthetic fibers (aramid plus polyolefin) that has given good results in dense-graded asphalt mixtures [71]. The density of this blend according to the standard method UNE-EN 1097-6 was 0.947 g/cm$^3$. The physical properties of the POA fibers according to the manufacturers are given in Table 3. The second fiber used in this study is a homopolymer polyacrylonitrile (PAN) synthetic fiber. For this type of fiber, two different sizes, 4 mm and 12 mm, were considered. The physical properties provided by the manufacturers are presented in Table 4.

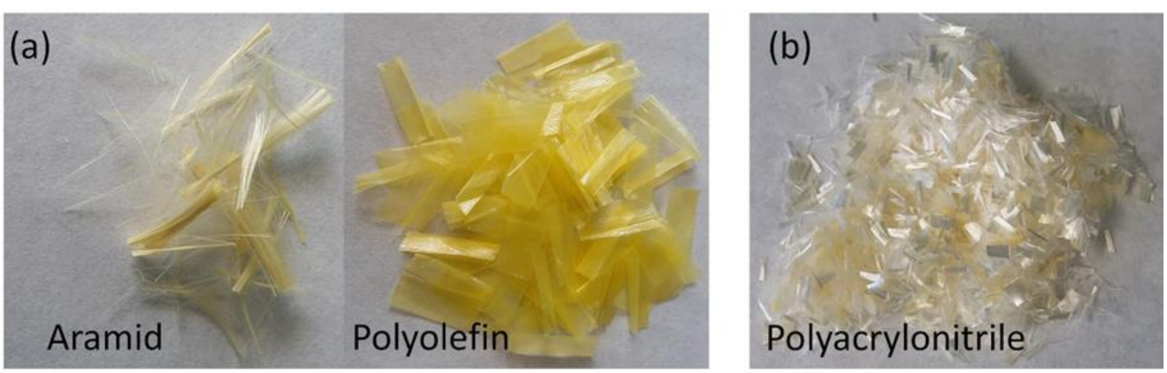



*Figure 6 Set of polyolefin-Aramid (POA) fibers (a); polyacrylonitrile (PAN) fibers (b)*

*Table 3 Physical properties of POA fibers*

| Fiber | Aramid | Polyolefin |
|---|---|---|
| Form | Monofilament | Serrated |
| Color | Yellow | Yellow |
| Density (g/cm$^3$) | 1.44 | 0.91 |
| Length (mm) | 19 | 19 |
| Tensile Strength (MPa) | 2758 | 483 |
| Decomposition temperature (°C) | 157 | > 450 |
| Acid/Alkali Resistance | Inert | Inert |

*Table 4 Physical properties of PAN fibers*

| Fiber | Polyacrylonitrile |
|---|---|
| Form | Staple fibers |
| Color | Bright straw-yellow gold |
| Density (g/cm3) | 1.18 |
| Length (mm) | 4 / 12 |
| Tenacity (MPa) | > 708 |
| Elastic modulus (MPa) | 16500 |
| Elongation at break (%) | < 13 |
| Diameter (mm) | 0.0127 |

### *3.2.4 Specimen preparation of PA cylinders*

Compacted PA mixtures were prepared according to the Spanish specification “General Technical Requirements for Works of Roads and Bridges” [29], a document approved by the Ministry of Public Works of the Government of Spain. The particle size distribution of the mixtures was kept as constant and corresponded to an open gradation curve, which falls within the upper and lower limits established in the Spanish standard [29]. For the conventional binder, the mixing temperature utilized was 150°C, while in the case of the polymer-modified binder, a mixing temperature of 170°C was employed according to the recommendations of the provider. In both cases, the aggregate temperatures were 15°C higher than the mixing temperature according to the type of bitumen. In the case of mixtures modified with fibers, the fiber addition was done by dry method; the above means that fibers were initially mixed and distributed with aggregates properly before the addition of bitumen to the mixture. The compaction of samples was done by applying 50 blows per side with the use of Marshall Hammer following the European Standard EN 12697 – 30.

### *3.2.5 Specimen preparation of asphalt mortars*

One of the main causes of raveling is the loss in the cohesive forces between the bridges inside the mortar matrix. Therefore, to analyze the reinforcing effect of fibers at the asphalt mortar scale, mortar cylindrical specimens with a diameter of 100 mm and a height of 61 mm approximately were manufactured by using the gyratory compactor machine. The mixing procedure of asphalt mortar mixes was done analogously to the PA mixture. Mineral filler and fine aggregates were heated prior to the addition of fibers followed by a mixing process of one minute. Next, the pre-heated bituminous binder was added to the fiber-fine aggregate mix and mixed for five minutes, guaranteeing a good homogeneity of the mixture. All the mortar mixes were manufactured with a target air voids content of 2.50%. The gradation curve of the mortar mixes is shown in Figure 7.

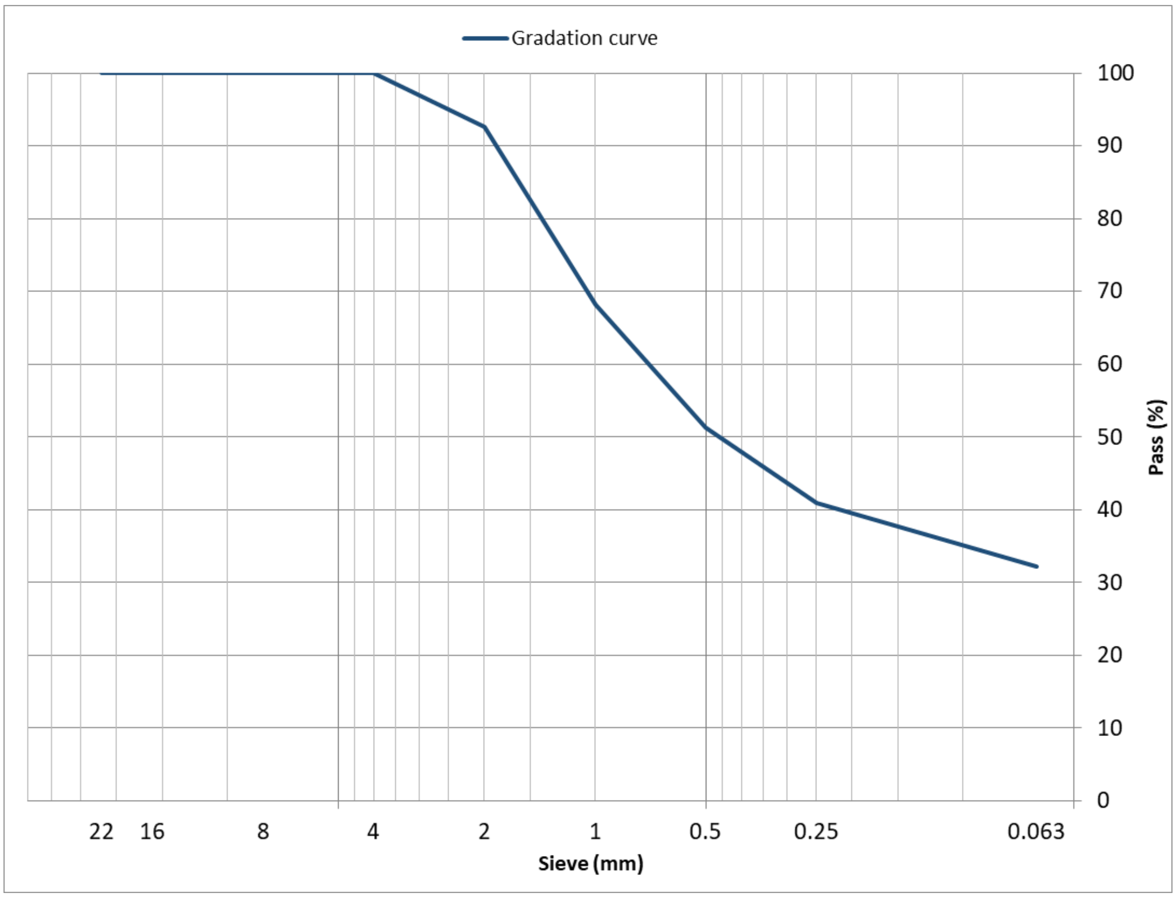



*Figure 7 Gradation curve of asphalt mortar mixes*

### 3.3 Experimental tests

#### *3.3.1 Total air voids*

The total air voids ($T_{AV}$) of PA mixtures were measured based on the volumetric determination test calculated according to European Standard EN 12697 – 8 by using the following equation.

$$\mathrm{T_{AV}}\ (\%) = \left(1 - \frac{\mathrm{m_{dry}}}{\mathrm{V \cdot G_{mm}}}\right) \times 100 \tag{4}$$

Where $m_{dry}$ corresponds to the mass of the sample weighted in dry conditions, *V* corresponds to the volume of the sample geometrically calculated, $G_{mm}$ is the maximum theoretical specific gravity of the mixture.

#### *3.3.2 Interconnected air voids*

The interconnected air voids ($I_{AV}$) were measured using the equation proposed by Lyons et al. [30]. Based on the volumetric properties of the specimen, the $I_{AV}$ was calculated as follows.

$$\mathrm{I_{AV}}\ (\%) = \left(\frac{\mathrm{V} - \dfrac{\mathrm{m_{dry}} - \mathrm{m_{satw}}}{\rho_{\mathrm{water}}}}{\mathrm{V}}\right) \times 100 \tag{5}$$

Where $m_{satw}$ is the mass of the saturated sample recorded in the water.

#### *3.3.3 Permeability*

The permeability ($k$) of the specimens was measured with the radial flow falling head permeameter. Based on Darcy's law, the permeability of the mixture was calculated by using the following equation.

$$\mathrm{k} = \frac{\mathrm{aL}}{\mathrm{At}} ln\left(\frac{\mathrm{h_1}}{\mathrm{h_2}}\right) \tag{6}$$

Where *a* and *A* are the cross-sections of the standpipe and the specimen in $mm^2$ respectively; *L* is the height of the specimen in mm and *t* is the time required for the water to fall from an initial height of 300 mm above the sample ($h_1$) to a height of 100 mm above the sample ($h_2$).

#### *3.3.4 Particle loss Cantabro test*

The particle loss was calculated in dry and wet conditions according to European EN 12697 -17 and Spanish NLT 362/92 Standards, respectively. The test consists in measuring the loss of particles when a compacted PA mixture is subjected to abrasion in the Los Angeles machine without steel spheres. The test is performed at 25°C at a rotation speed of 30-33 rpm and the mass losses after

300 revolutions are recorded. The particle loss in dry conditions ($PL_{dry}$) is then calculated by using the following formula:

$$\mathrm{PL}\ (\%) = \left(\frac{\mathrm{m_1} - \mathrm{m_2}}{\mathrm{m_1}}\right) \times 100 \tag{7}$$

Where $m_1$ and $m_2$ are the initial and final masses of the specimens. To measure the particle loss in wet conditions ($PL_{wet}$), the compacted samples were initially submerged in water at 60°C for 24 hours and then placed in air conditions at 25°C for 24 hours prior to carrying out the test.

*3.3.5 Indirect tensile strength and moisture sensitivity*

The indirect tensile strength (*ITS*) test was tested in specimens in both dry and wet conditions ($ITS_{dry}$ and $ITS_{wet}$) according to European EN 12697 - 23. The ITS was measured by loading diametrically the samples across the circular cross-section and recording the load to failure. From this test, toughness can also be determined by analyzing the area under the stress-strain curve as shown in Figure 8**.** The toughness consists of two parameters, the Fracture Energy (*FE*) and the Post-cracking Energy (*PE*). The former corresponds to the area under the stress-strain curve until the strain at the maximum stress is reached, $\varepsilon_p$ [72]. The PE is calculated as the area under the stress-strain curve from $\varepsilon_p$ to $2\varepsilon_p$ as suggested in [72]. According to said authors, *ITS* and *FE* have proven to be good indicators of the cracking resistance prior to major crack development and *PE* gives an idea of the mixture ductility and its resistance to crack propagation. In this study, the toughness, *FE,* and *PE* were determined for all the specimens, dry and wet conditioned.

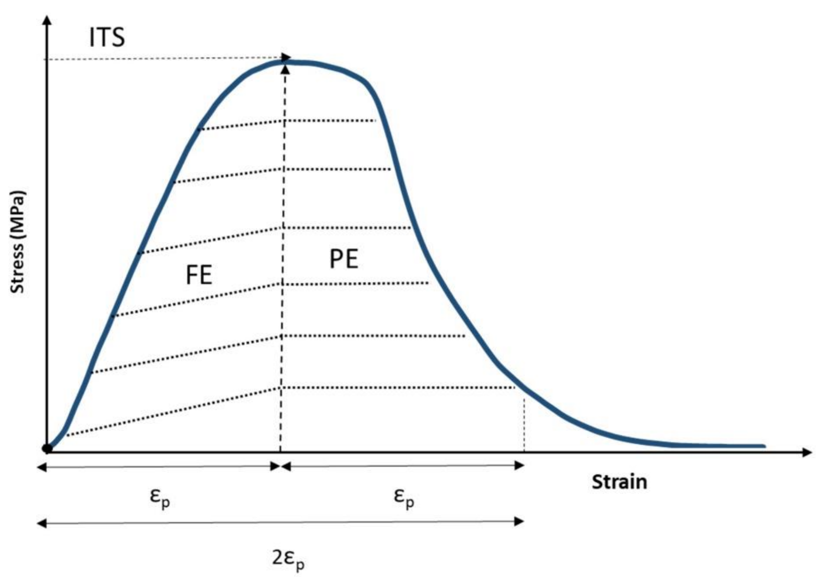



*Figure 8 Stress-strain curve recorded from ITS*

On the other hand, moisture sensitivity was evaluated based on the indirect tensile strength ratio (*ITSR*) following the European standard EN 12697 - 12. The *ITSR* is the ratio of the wet *ITS* to the dry *ITS* and is expressed in percentage as follows:

$$\mathrm{ITSR}\ (\%) = \frac{\mathrm{ITS_{wet}}}{\mathrm{ITS_{dry}}} \times 100 \tag{8}$$

*3.3.6 Binder drain down test*

The stability of the mixture was evaluated through the mesh basket drain down test according to European Standard EN 12697 – 18. The test calculates the amount of binder in percentage ($BD$) of an uncompacted PA mixture which separates itself from the total mixture and it is deposited outside of the mesh basket during the test. In the case of samples manufactured with conventional 50/70 penetration grade binder, the test was carried out 25°C above the mixing temperature. In the same way, mixes prepared with polymer modified binders, the test was performed at 15°C higher than the manufacturing temperature.

**3.4 Experimental designs performed in the phase one of the research**

*3.4.1 Experimental designs at porous asphalt mixture scale*

To evaluate the reinforcing effect of POA and PAN fibers in PA mixtures, a total of eight different experimental designs and fourteen replicates per each mixture design were produced by varying the type of fiber (No fiber, POA 19 mm, PAN 4 mm and PAN 12 mm) and the amount of filler (4.9% and 4.3% by weight of the aggregate fraction). A total of 112 specimens were manufactured. In all the samples, the amount of bitumen was 4.3% by weight of the mixture. It must be said that in this phase it was wanted to check the reinforcing effect of fibers in the porous mixture without influencing its ability to retain bitumen. For the above, a low percentage of asphalt binder was considered.  The nomenclature of the different designs was defined based on the type of fiber in the mixture, the length of the fiber, and the filler content in the mixture. Thus, the designed mixture PAN 12 – A corresponds to the PA mixture with PAN 12 mm long fibers and filler content of 4.9%. Similarly, the mixtures used as references were named RA and RB depending on the filler content. Table 5 details the different designs carried out. In this part, all the experimental tests described in section 3.3 with the exception of the binder drain down test were done. The above because this test was not required due to low percentage of bitumen employed.

*Table 5 Experimental designs of FRPA with synthetic fibers*

| ID. Nº | Mixture Design | Bitumen | | Fibers | | | Filler |
|---|---|---|---|---|---|---|---|
| | | Type | Dosage (%) | Type | Length | Dosage (%) | Dosage (%) |
| 1 | RA | 50/70 | 4.3 | - | - | - | 4.9 |
| 2 | POA 19 - A | 50/70 | 4.3 | POA | 19 | 0.05 | 4.9 |
| 3 | PAN 12 - A | 50/70 | 4.3 | PAN | 12 | 0.05 | 4.9 |
| 4 | PAN 4 - A | 50/70 | 4.3 | PAN | 4 | 0.05 | 4.9 |
| 5 | RB | 50/70 | 4.3 | - | - | - | 4.3 |
| 6 | POA 19 - B | 50/70 | 4.3 | POA | 19 | 0.05 | 4.3 |
| 7 | PAN 12 - B | 50/70 | 4.3 | PAN | 12 | 0.05 | 4.3 |
| 8 | PAN 4 - B | 50/70 | 4.3 | PAN | 4 | 0.05 | 4.3 |

### *3.4.2 Experimental designs at asphalt mortar scale*

To evaluate the reinforcing effect of POA and PAN fibers at asphalt mortar scale, a total of 21 asphalt mortar mixes and three replicates per each mixture design were prepared with a different type of fibers (No fiber, 19 mm long POA fibers and 4 mm long Pan fibers) with different fiber contents (0.0%, 0.1%, 0.2% 0.3%) and tested at three different temperatures (15°C, 0°C, -15°C) through the indirect tensile test. In this stage, a total of 63 asphalt mortar mixes were prepared and the ITS as well as the fracture properties were recorded. A binder content of 9.3% by weight of mortar was adjusted because of the increase in the surface area of the fine aggregates in the mortar. Bituminous mortar only contains filler and fine aggregates with maximum particle size of 2 mm. These particles have greater surface area than the coarse aggregates and hence it was necessary to increase the bitumen content inside the mix to ensure a proper binder film thickness [73]. A method based on the specific surface of the aggregates was employed to achieve a similar structure of the mortar in a typical PA16 [74]. The target air voids content of 2.5% was kept as constant for all the asphalt mortar designs.

### *3.4.3 Statistical analysis*

At the Porous asphalt scale as well as asphalt mortar scale, all the experimental mixtures were analyzed statistically. MINITAB software was used to support the analysis of the results. Anderson Darling Normality tests were carried out to determine if the data obtained followed a normal or non – normal data distribution. Besides, homogeneity of variance was checked through the Levene test. Parametric statistical tests were used if the data followed a normal distribution and presented homogeneity of variance; otherwise, non – parametric tests were used. The confidence interval considered was 95%. Table 6 shows the statistical tests used to compare the data obtained from each mix design.

Table 6 Parametric and non-parametric tests to analyze data

| Data | Parametric tests | Non-parametric tests |
|---|---|---|
| 2 groups | 2 samples t-test | U Mann-Whitney Test |
| k groups | One way ANOVA | Kruskal-Wallis Test |

## 3.5 Experimental designs performed in phase two of the research

### *3.5.1 Taguchi Design of Experiments*

The Taguchi technique was proposed in this phase to plan and model the design of experiments. Full and fractional orthogonal arrays can be developed to analyze the different interactions between the parametric levels. Although fractional factorial design gives information concerning the interaction among the different parameters with reduced experimentation, in this study, the full factorial orthogonal array was applied since some of the input parameters are categorical and most complete reliable information for the interaction between parameters is necessary. Therefore, a robust and consistent $L_{18}$ orthogonal array was planned for experimentation. Binder type (BT), Fiber content (FC) and Binder content (BC) were the principal control factors considered whereas total air voids, interconnected air voids, particle loss in dry and wet conditions and binder drain down test were the main responses to be analyzed individually. BT control factor contains two parametric levels, whereas the FC and BC control factors were formulated with three parametric levels. The particle size distribution of the mixtures was kept as a constant. The combination of the different parametric levels for the experimental design according to the Taguchi method is shown in Table 7. Details of the eighteen experimental designs are shown in Table 8. Three replicates per each design and per each test were recorded.

*Table 7 Control factors with their corresponding parametric levels*

| Input parameter | Notation | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| Binder type | BT | 50/70 | PMB | - |
| Fiber content (%) | FC | 0 | 0.05 | 0.15 |
| Binder content (%) | BC | 4.5 | 5.0 | 5.5 |

*Table 8 Full factorial design Taguchi L18 orthogonal array*

| Design Number | Experimental ID | Binder type | Fiber content | Binder content |
|---|---|---|---|---|
| 1 | 50/70-FC:0.00-BC:4.50 | 50/70 | 0.00 | 4.50 |
| 2 | 50/70-FC:0.00-BC:5.00 | 50/70 | 0.00 | 5.00 |
| 3 | 50/70-FC:0.00-BC:5.50 | 50/70 | 0.00 | 5.50 |
| 4 | 50/70-FC:0.05-BC:4.50 | 50/70 | 0.05 | 4.50 |
| 5 | 50/70-FC:0.05-BC:5.00 | 50/70 | 0.05 | 5.00 |
| 6 | 50/70-FC:0.05-BC:5.50 | 50/70 | 0.05 | 5.50 |
| 7 | 50/70-FC:0.15-BC:4.50 | 50/70 | 0.15 | 4.50 |
| 8 | 50/70-FC:0.15-BC:5.00 | 50/70 | 0.15 | 5.00 |
| 9 | 50/70-FC:0.15-BC:5.50 | 50/70 | 0.15 | 5.50 |
| 10 | PMB-FC:0.00-BC:4.50 | PMB45/80-65 | 0.00 | 4.50 |
| 11 | PMB-FC:0.00-BC:5.00 | PMB45/80-65 | 0.00 | 5.00 |
| 12 | PMB-FC:0.00-BC:5.50 | PMB45/80-65 | 0.00 | 5.50 |
| 13 | PMB-FC:0.05-BC:4.50 | PMB45/80-65 | 0.05 | 4.50 |
| 14 | PMB-FC:0.05-BC:5.00 | PMB45/80-65 | 0.05 | 5.00 |
| 15 | PMB-FC:0.05-BC:5.50 | PMB45/80-65 | 0.05 | 5.50 |
| 16 | PMB-FC:0.15-BC:4.50 | PMB45/80-65 | 0.15 | 4.50 |
| 17 | PMB-FC:0.15-BC:5.00 | PMB45/80-65 | 0.15 | 5.00 |
| 18 | PMB-FC:0.15-BC:5.50 | PMB45/80-65 | 0.15 | 5.50 |

Based on the Taguchi method, *SN ratio* was obtained per each response value. *SN ratio* is an indicator of the variation of a specific response under different noise conditions. Accordingly, in this investigation, the smaller-the-better scenario was applied to minimize the particle loss in both dry and wet conditions as well as the binder drain down. Meanwhile, the larger-the-better was employed to maximize the total and interconnected air voids.

### *3.5.2 Multi-Criteria Decision-Making methods*

Multi-Criteria Decision-Making methods are powerful tools that serve to lead with decision-making problems with a multiple number of criteria. In this phase, as more than one experimental response was obtained, it was necessary to transform the multiple-response problem into a single-one response problem. As commented in section 2.4, a large variety of MCDM methodologies have been proposed. However, in this research the TOPSIS method was selected since is an approach based on the concept of closeness coefficient theory. The above means that the most preferred alternatives would be those with the shortest geometric Euclidean distance from the Positive Ideal Solution (PIS) and the Longest geometric Euclidean distance from the Negative Ideal Solution (NIS) [75]. In other words, the PIS values maximizes the beneficial criteria and minimizes the non-beneficial criteria whereas the NIS decreases the beneficial criteria and increases the non-beneficial criteria. The advantage of the algorithm is that is easy applicable, with low computational costs and proper for solving decision-making problems with large amount of responses and alternatives. The mathematical procedure of TOPSIS method can be consulted in the article 3 of the current research. A comparison with other algorithms such as EDAS and WASPAS was also made to check the similitudes and differences in the preference ranking.

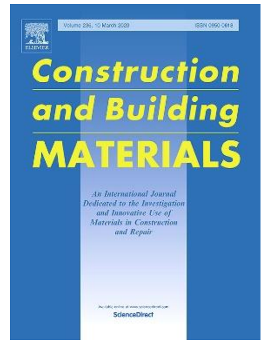
To overcome the criteria elicitation, the CRITIC multi-objective approach was chosen, since it makes part of the automated decision-making as the human participation is not necessary. Based on the method, the relative weights are assigned based on the concept of contrasted intensity of each one of the responses and the conflict assessment among the criteria involved in the decision-making problem. Details about the procedure and equations involved in CRITIC method are explained in article 3 of the present study.

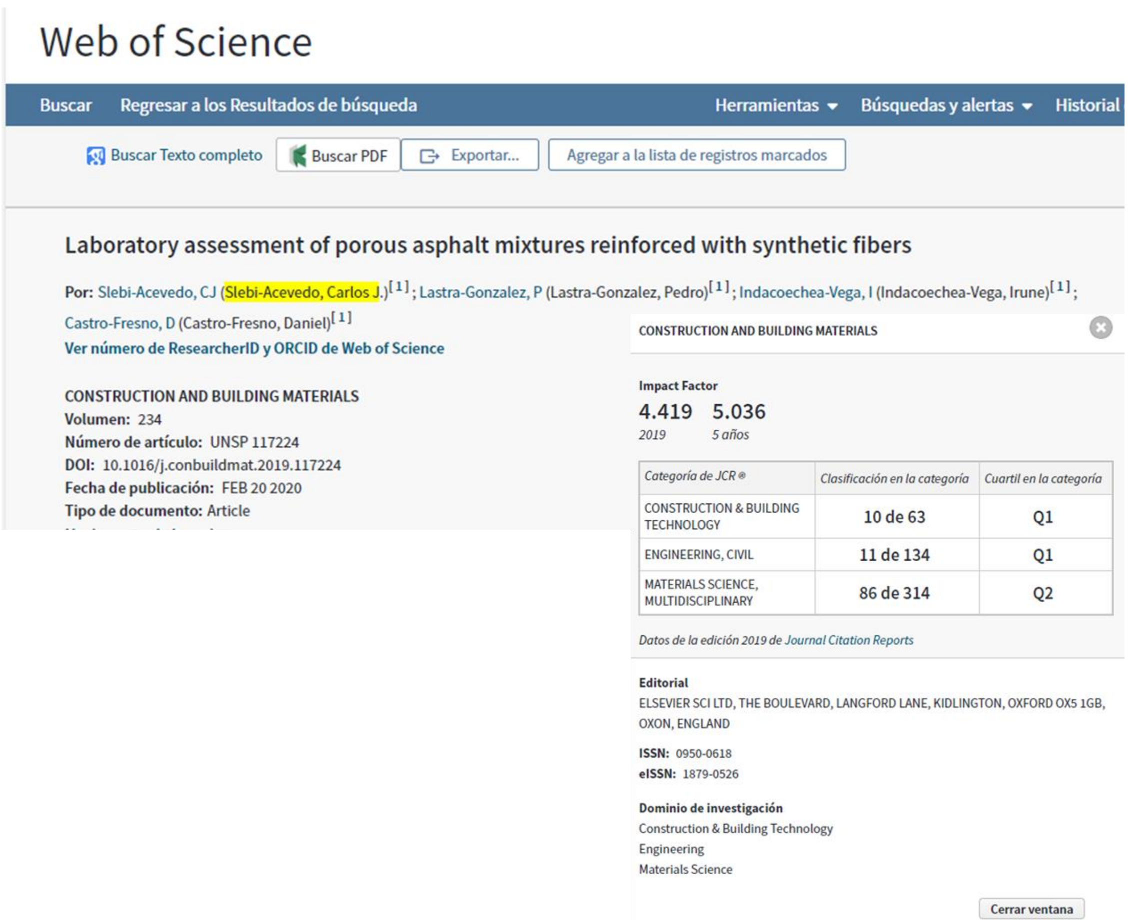
# 4. PUBLISHED ARTICLES

## 4.1 Article 1. Laboratory assessment of porous asphalt mixtures reinforced with synthetic fibers

### *4.1.1 Basic information and impact factor concerning article 1*

- **Authors**: **Carlos J. Slebi-Acevedo**, Pedro Lastra-González, Irune Indacoechea-Vega, Daniel Castro-Fresno
- **Year**: 2020
- **Journal**: Construction and Building materials
- **Available online:** 1 November 2019
- **DOI**: 10.1016/j.conbuildmat.2019.117224



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Laboratory assessment of porous asphalt mixtures reinforced with synthetic fibers

Por: Slebi-Acevedo, CJ (Slebi-Acevedo, Carlos J.)[1]; Lastra-Gonzalez, P (Lastra-Gonzalez, Pedro)[1]; Indacoechea-Vega, I (Indacoechea-Vega, Irune)[1]; Castro-Fresno, D (Castro-Fresno, Daniel)[1]

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*Figure 9 Authors and impact factor of journal regarding article 1*

*4.1.2 Transcription of article 1*

# Laboratory assessment of porous asphalt mixtures reinforced with synthetic fibers

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**Abstract**

Porous asphalt (PA) mixtures have become a new alternative in the development of new road pavement surface layers given their multiple advantages such as surface runoff improvement, the decrease of the urban heat island effect, the reduction of road traffic noise and the minimization of the spray and aquaplaning effect leading to a safer driving. However, the durability of these mixtures is not as good as for dense graded mixtures. This research studies the effectiveness of adding a blend of polyolefin/aramid fibers and homopolymer polyacrylonitrile fibers in PA mixtures in terms of functionality and mechanical performance. Furthermore, changes in the filler content were assessed. The experimental testing plan includes air voids characterization, permeability, moisture sensitivity and particle loss in dry and wet conditions. Improvements on the mechanical performance can be observed in dry conditions. Finally, the fracture energy, postcracking energy and toughness were also analyzed. The results show that the addition of fibers brings ductility to the PA mixture improving toughness while maintaining functionality since the air void content remains over 20%.

**Highlights**

- PA mixtures with 0.05% of synthetic fibers were assessed.
- The influence of filler content on the fiber modified asphalt mixture performance was considered.
- The addition of synthetic fibers did not produce significant effects on the air voids.
- Fibers addition improves the PA mechanical properties in dry conditions.

**Keywords**

Polyolefin, aramid, polyacrylonitrile, fibers, porous asphalt, water sensitivity, toughness.

## 1. Introduction

Porous asphalt (PA) mixtures have become an alternative to conventional dense asphalt mixtures due to their several advantages such as their mitigation effect on storm water runoff, the improvement on the drivability in wet weather conditions and their road traffic noise reduction ability [76,77]. Other researchers recommend these mixtures due to their potential to enhance surface frictional resistance, minimize aquaplaning, improve visibility in night conditions and decrease splash and spray [78,79]. Moreover, thanks to its high voids content, these mixtures allow the flowing of water through the pores preventing its accumulation on the road surface [80]. Additionally, due to their higher porosity, PA mixtures exhibit a rough surface texture which increases the friction between the tire and the asphalt surface, thus contributing to reduce road accidents [81].

These mixtures have been used since 1950 to improve the frictional resistance of asphalt pavements [82]. In this sense, porous friction courses (PFC) are commonly used as non – structural wearing courses in the United States and Europe [83]. Nonetheless, in the United States the experience on this type of mixture has been contradictory, with some states reporting good performance, while others limiting their use due to poor performance [84]. On the other hand, Massahi et al. [85] reported that raveling can be considered a substantial pavement distress that affects the security of road users and increases the need of more frequent road maintenance. In addition, given the mineral skeleton presented by the PA mixtures and the high content of voids (i.e. 20%), these mixtures show greater problems of durability [86]. In this sense, high percentages of air voids cause the bituminous binder to be more exposed to the impact of weather, increasing the aging of the bitumen and producing a detriment effect on its cohesive and adhesive capacity [44,87–89]. The need to improve the mechanical performance and increase the service life of PA mixes has brought to the development of a new generation of PA mixes that incorporate polymers and other additives such as fibers [1,3].

To date, the effect of different types and sizes of fibers on the mechanical performance has been investigated specially in asphalt concrete (AC). Thus, Lee et al. [32] reported an increase of about 85% in the fracture energy properties of an AC by adding 1.0% by volume of 12 mm long nylon fibers to the mixture. On the other hand, Kaloush et al. [35] reported that the use of a blend of polypropylene and aramid fibers in an asphalt concrete improved the performance of the mixture specially in permanent deformation, fatigue cracking and thermal cracking. Finally, Xu et al. [42] conducted laboratory tests on a fiber reinforced asphalt concrete (FRAC). The strength, strain and fatigue behavior of the FRAC were measured. Results showed an improvement in the flexural strength and the ultimate flexural strain due to the addition of polymer fibers (polyester and polyacrylonitrile). Rutting resistance, fatigue life and indirect tensile strength (ITS) were also improved with the incorporation of the polymer fibers due to their networking function. A polyester fiber content of 0.35% by mass of mixture was suggested to achieve the best performance in terms of permanent deformation and ITS.

Less research has been carried out on the modification of porous asphalt mixtures with fibers. Chowdhury et al [90] studied the effect of tire fibers in PA mixtures. Drain-down, dynamic modulus, indirect tensile strength and Hamburg wheel tracking test were applied reporting that tire fibers could be an alternative to cellulose fibers. In another research, Xiang Ma et al. [91] employed various additives in a porous asphalt mixture concluding that polyester fibers should be used in a PA mixture because significant improvements on the durability and low cracking resistance were found. Andrés-Valeri et al. [1] assessed the durability of using Tetra brick aseptic (TBA) fibers in PA mixtures as an environmentally friendly additive. The authors reported an increment in the indirect tensile strength (ITS) in the range of 22% when the fiber is added compared to the reference mixtures. In a much wider study, Punith and Veeraragavan [78] incorporated reclaimed polyethylene (PE) fibers in open graded friction course (OGFC) mixtures. Several laboratory tests were carried out on these mixtures to determine tensile strength, moisture sensitivity and fatigue damage. Results indicated that the incorporation of PE fibers in the mixture improved the three properties in comparison to the control mixtures without fibers. Finally, Lopes et al. [77] evaluated the performance of PA mixtures with cellulose fibers, being these fibers one of the most common additives in hot mix asphalts (HMA) [44,92–94]. In this research, the Indirect Tensile Stiffness Modulus (ITSM), water sensitivity, permeability and permanent deformation tests were carried out. The authors concluded that the absorption of the bitumen by the cellulose fibers improved the water drainage through the pores and therefore the PA mixture permeability. In addition, a reduction in the particle loss of around 11% was observed with the addition of this type of fibers.

While published studies have demonstrated positive results when aramid and polyacrylonitrile fibers are added to dense asphalt mixtures, the incorporation of this type of reinforcement in PA mixtures has not been investigated in depth. Thus, the main aim of this paper is to evaluate the mechanical performance of PA mixtures that include in their composition a blend of polyolefin/aramid fibers or polyacrylonitrile fibers and compare it with the performance of a reference PA mixture without fibers. To assess this mechanical performance, the porous asphalt mixtures were designed according to European standard methods and the following experimental laboratory plan test was performed: bulk density, total and interconnected air voids, permeability test, Cantabro particle loss test in dry and wet conditions, indirect tensile strength (moisture sensitivity) and fracture energy.

## 2. Materials

### 2.1. Aggregates

Previous laboratory tests were carried out to determine the properties of the natural aggregate. Coarse ophite aggregate and fine limestone aggregate were used in this study to produce the PA mixtures. The physical properties and the limits of the Spanish Standard specifications for the highest traffic level are shown in Table 1. In this research, the grading curve employed was a PA16 in accordance with the specifications given in the Spanish guidelines [29] as shown in Figure 1.

*Table 1. Properties of coarse ophite and fine limestone aggregate*

| Characteristic | Value | Standard | Specification |
|---|---|---|---|
| Coarse Aggregate | | | |
| Specific Weight (g/cm$^3$) | 2.794 | EN 1097 - 6 | - |
| Water absorption (%) | 0.60 | EN 1097 - 6 | < 1% |
| L.A abrasion (%) | 15 | EN 1097 - 2 | ≤ 15% |
| Slab Index (%) | < 1% | EN 933 - 3 | ≤ 20% |
| Polishing Value | 60 | EN 1097 - 8 | ≥ 56 |
| Fine Aggregate | | | |
| Specific Weight (g/cm$^3$) | 2.724 | EN 1097 - 6 | - |
| Sand Equivalent | 78 | EN 933-8 | > 55 |

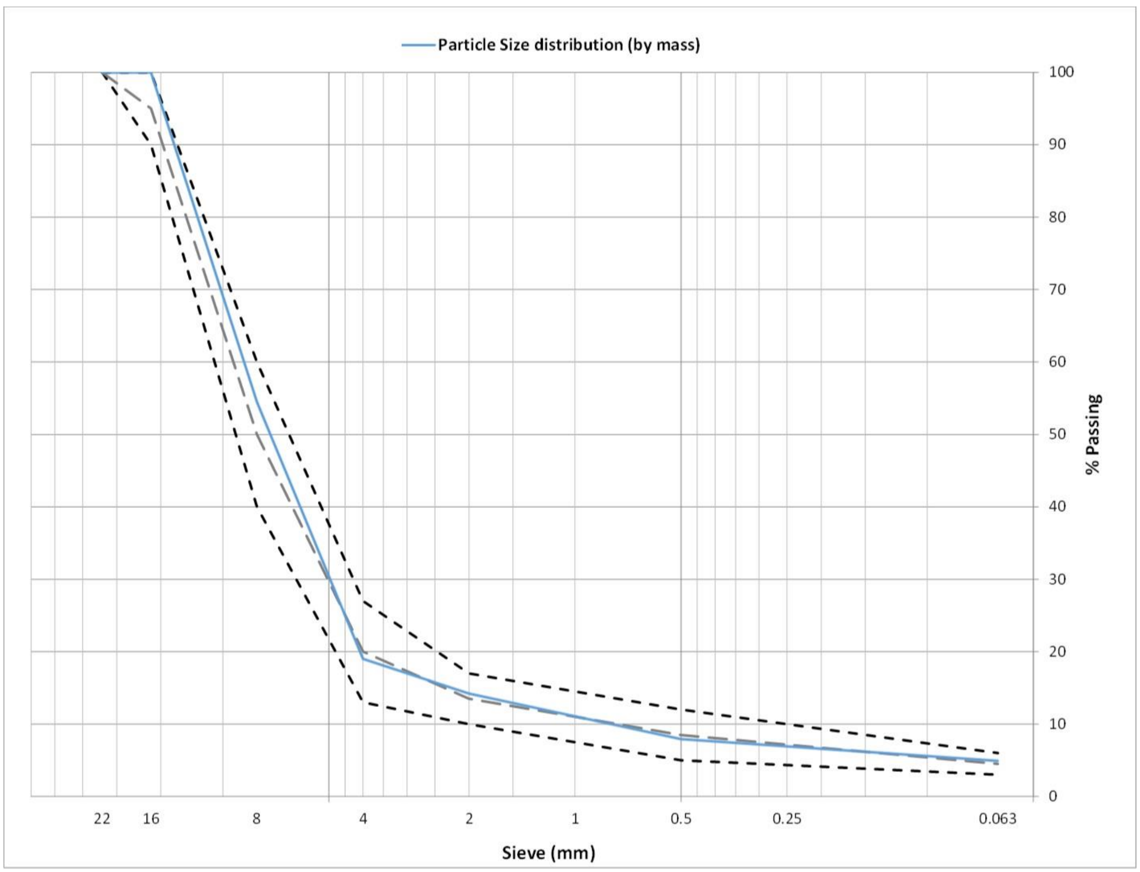


*Figure 1. Particle size distribution PA mixture*

### 2.2 Bituminous binder

A conventional 50/70 penetration grade bituminous binder was employed in this research. Although usually a polymer modified asphalt is used in PA mixtures, in this research the reinforcement effect of the fibers in the PA mixture is studied with a conventional binder. The physical properties of the asphalt binder are presented in Table 2.

*Table 2. Characteristics of a 50/70 penetration grade binder*

| Characteristic | Standard | Value |
|---|---|---|
| Specific weight (g/cm$^3$) | EN 15326 | 1.035 |
| Penetration at 25 °C | EN 1426 | 57 |
| Softening point (°C) | EN 1427 | 51.6 |
| Fraass brittle point (°C) | EN 12593 | -13 |

## 2.3 Fibers

Two different fiber types were studied by the authors (see Figure 2). The first one consisted of a blend of synthetic fibers (aramid plus polyolefin) that has given good results in dense graded asphalt mixtures [35,95]. The density of this blend according to the standard method UNE-EN 1097-6 was 0.947 g/cm$^3$. The physical properties of the polyolefin/aramid fibers (PO/A) according to the manufacturers are given in Table 3. The second fiber used in this study is a homopolymer polyacrylonitrile (PAN) synthetic fiber. For this type of fiber, two different sizes, 4 mm and 12 mm, were considered. For both types of fibers, the fiber content was fixed in 0.05% w/w according to the suppliers. The physical properties provided by the manufacturers are presented in Table 4.


*Figure 2. Types of synthetic fibers used in this work: (a) PO/A fibers and (b) PAN fibers*

*Table 3. Characteristics and properties of PO/A fibers*

| Fiber | Aramid | Polyolefin |
|---|---|---|
| Form | Monofilament | Serrated |
| Color | Yellow | Yellow |
| Density (g/cm$^3$) | 1.44 | 0.91 |
| Length (mm) | 19 | 19 |
| Tensile Strength (MPa) | 2758 | 483 |
| Decomposition temperature (°C) | 157 | > 450 |
| Acid/Alkali Resistance | Inert | Inert |

*Table 4. Characteristics and properties of PAN fibers*

| Fiber | Polyacrylonitrile |
|---|---|
| Form | Staple fibers |
| Color | Bright straw yellow gold |
| Density (g/cm3) | 1.18 |
| Length (mm) | 4 - 12 |
| Tenacity (MPa) | > 708 |
| Elastic modulus (MPa) | 16500 |
| Elongation at break (%) | < 13 |
| Diameter (mm) | 0.0127 |

## 3. Experimental Program

### 3.1 Mix design and specimen preparation

In this work, PA mixes incorporating polyolefin/aramid (PO/A) or PAN fibers were designed. Eight different experimental designs were produced by varying the type of fiber (No fiber, PO/A, PAN 4 and PAN 12) and the amount of filler (4.9% and 4.3% by weight of the aggregate fraction). In all the samples, the amount of bitumen was 4.3% by weight of mixture. The nomenclature of the different designs was defined based on the type of fiber in the mixture, the length of the fiber (mm) and the filler content in the mixture. Thus, the designed mixture PAN 12 – A corresponds to the PA mixture with PAN 12 mm long fibers and a filler content of 4.9%. Similarly, the mixtures used as references were named RA and RB depending on the filler content. Table 5 details the different designs carried out.

*Table 5. Porous asphalt mixtures designs*

| ID. N° | Mixture Design | Bitumen | | Fibers | | | Filler |
|---|---|---|---|---|---|---|---|
| | | Type | Dosage (% b/w of mix) | Type | Length | Dosage (%b/w of mix) | Dosage (%b/w of aggregate) |
| 1 | RA | 50/70 | 4.3 | - | - | - | 4.9 |
| 2 | PO/A 19 - A | 50/70 | 4.3 | PO/A | 19 | 0.05 | 4.9 |
| 3 | PAN 12 - A | 50/70 | 4.3 | PAN | 12 | 0.05 | 4.9 |
| 4 | PAN 4 - A | 50/70 | 4.3 | PAN | 4 | 0.05 | 4.9 |
| 5 | RB | 50/71 | 4.3 | - | - | - | 4.3 |
| 6 | PO/A 19 - B | 50/70 | 4.3 | PO/A | 19 | 0.05 | 4.3 |
| 7 | PAN 12 - B | 50/70 | 4.3 | PAN | 12 | 0.05 | 4.3 |
| 8 | PAN 4 - B | 50/70 | 4.3 | PAN | 4 | 0.05 | 4.3 |

All the PA mixtures presented in this paper were designed according to the European Standards for Bituminous mixtures (EN 13108-7) and the Spanish specification “General Technical Requirements for Works of Roads and Bridges” [29], document approved by the Ministry of Public Works of the Government of Spain.

The asphalt samples were prepared as follows. Coarse and fine aggregates were heated in an oven at 170°C for six hours and then thoroughly mixed with the fibers for 20s. Afterwards, the asphalt binder was added at 150°C into the mixture and continuously blended to achieve that the combination fiber-aggregate was well coated by the bitumen. It is worth mentioning that in the case of PO/A fibers, the polyolefin was added together with the asphalt binder. Finally, PA mixtures were compacted with 50 blows per side according to EN 12697 – 30.

### 3.2 Experimental tested plan

An assessment of the mixture volumetric properties, durability, functionality and stability were performed in this research as shown in Table 6. Mixture volumetric properties were focused on the macroscopic evaluation [3] including bulk specific gravity of the compacted mixture, total air voids (AV), and interconnected air voids (IAV) . Closed air voids were also calculated like the difference between AV and IAV [1].

*Table 6. Experimental work plan*

| Parameter | Standard method | Comments | Test Replicate |
|---|---|---|---|
| Bulk density | EN 12697–6 | | 14 |
| Total Air voids (AV) | EN 12697–8 | | 14 |
| Interconnected Air voids (IAV) | ASTM D7063 – 05 | | 4 |
| Vertical Permeability | Falling head permeameter | falling head from 30 to 10 cm | 4 |
| Particle loss | EN 12697-17 | Dry condition | 4 |
| Particle loss | NLT 362/92 | Wet condition | 4 |
| Indirect Tensile Strength (ITS) | EN 12697-23 | Dry and wet conditions | 3 |
| FE, PE, Toughness | - | Dry and wet conditions | 3 |
| Moisture Sensitivity | EN 12697-12 | - | 3 |

Regarding the mixture mechanical performance, the Cantabro loss particle test was carried out to assess the raveling of the porous asphalt mixtures [22,23,30,96,97]. This test measures the percentage of particle loss that occurs when the specimen is subjected to abrasion in the Los Angeles machine. The Cantabro test was also performed in wet conditions according to the NLT 362/92 Spanish standard. In this case, the specimens were submerged in water at 60 °C for 24 hours. Then the samples were kept at 25°C for another 24 hours before performing the test. In both cases, the loss in mass is expressed as the percentage after 300 turns and is calculated according to Equation 1.

$$Particle\ loss\ (\%) = \frac{m_i - m_f}{m_i} * 100 \tag{1}$$

Where $m_i$ and $m_f$ correspond to the initial and final mass of the specimens.

Concerning the indirect tensile strength (ITS) test, specimens were tested both in dry and wet conditions ($ITS_{dry}$ and $ITS_{wet}$). The ITS was measured by loading diametrically the samples across the circular cross section and recording the load to failure. From this test, toughness can also be determined by analyzing the area under the stress-strain curve as shown in Figure 3. The toughness consists of two parameters, the Fracture Energy (FE) and the Post-cracking Energy (PE). The former corresponds to the area under the stress-strain curve until the strain at the maximum stress is reached, $\varepsilon_p$ [72]. The PE is calculated as the area under the stress-strain curve from $\varepsilon_p$ to $2\varepsilon_p$ as suggested in [72]. According to said authors, ITS and FE have proven to be good indicators of the cracking resistance prior to major crack development and PE gives an idea of the mixture ductility and its resistance to crack propagation. In this study, the toughness, FE and PE were determined for all the specimens, dry and wet conditioned.

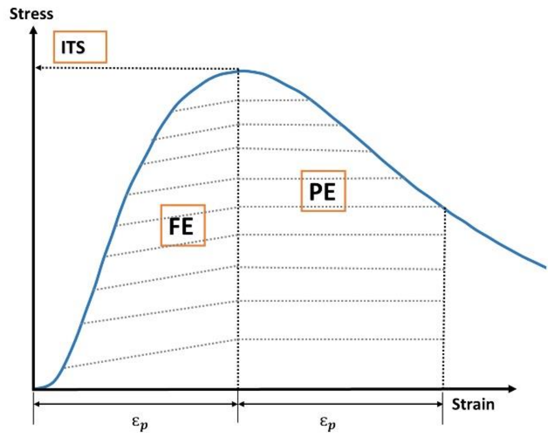


*Figure 3. Scheme of toughness calculation*

On the other hand, moisture sensitivity was evaluated based on the indirect tensile strength ratio (ITSR). The ITSR is the ratio of the wet ITS to the dry ITS and is expressed in percentage as follows (see Equation 2).

$$ITSR\ (\%) = \frac{ITS_{wet}}{ITS_{dry}} * 100 \quad (2)$$

The functionality of the PA mixture is linked with its permeability. In this work, the permeability (K) of the specimens was measured with the radial flow falling head permeameter as previously done by other researchers [1,6,30,83,98]. Based on Darcy's law, the permeability of the mixture can be calculated according to Equation 3.

$$k = \frac{aL}{At}\ln\left(\frac{h_1}{h_2}\right) \quad (3)$$

Where *a* and *A* are the cross sections of the standpipe and the specimen in $mm^2$ respectively; *L* is the height of the specimen in *mm* and *t* is the time required for the water to fall from an initial height of 300 *mm* above the sample ($h_1$) to a height of 100 *mm* above the sample ($h_2$).

**3.3 Statistical analysis**

Fourteen specimens of each PA mix design were performed with a total of 112 manufactured samples including the reference PA mixtures. The variability and uncertainty of the results in the experimental tests were statistically analyzed. The test replicates of each mixture design can be seen in the experimental tested plan (see Table 6). Minitab software was used to support the analysis of the results. Anderson Darling Normality tests were carried out to determine if the data obtained followed a normal or non – normal data distribution. In addition, homogeneity of variance was checked through Levene test. Parametric statistical tests were used if the data followed a normal distribution and presented homogeneity of variance; otherwise, non – parametric tests were used. The confidence interval considered was 95%. Table 7 shows the statistical tests used to compare the data obtained from each mix design.

*Table 7. Statistical tests to analyze the obtained data*

| Data | Parametric tests | Non-parametric tests |
|---|---|---|
| 2 groups | 2 samples t - test | Mann-Whitney Test |
| k groups | One way ANOVA | Kruskal-Wallis Test |

## 4. Results and Discussion

Before carrying out the design of the PA mixtures, some previous tests were performed in the reference mixture to determine the optimal asphalt content based on the air void content, indirect tensile strength and Cantabro test results. According to the results, the bitumen content was fixed at 4.3% by weight of mixture. A binder drainage test was also carried out on the reference mixtures following the European standard procedure EN 12697 – 18. According to the results, no binder drain-down was detected in any case. In order to isolate the reinforcement effect of the fiber on the experimental PA mixtures, the same binder content as for the reference mixture was used. Additionally, the influence of the filler content in the performance of the fiber reinforced PA mixture was considered by using two different filler concentrations.

### 4.1 Permeability and volumetric properties

The results concerning the volumetric properties and the permeability of the studied PA mixtures are summarized in Figure 4 and Figure 5, respectively. According to the results, the addition of the fiber did affect both the permeability and volumetric properties. It may be expected that the reduction of the total voids in the mixture implies a reduction of the permeability and the interconnected voids. In this case, the interconnected voids were positively correlated with the permeability values with a correlation coefficient of 0.88, indicating a direct relationship between these two variables. Similarly, a positive relationship between the total air voids and the permeability was found with a correlation coefficient of 0.29. Although in both cases a relation between the variables is observed, it can be concluded that the interconnected voids could be considered a better parameter to relate to permeability.

The results obtained before were statistically analysed. All the air void results followed a normal distribution and therefore a one way Anova Test was performed to determine if statistical differences among the results existed. Indeed, significant differences were observed between the reference mixture (RA) and the fiber reinforced mixtures with the same percentage of filler ($p_{value}$=0.000). However, not statistical differences were reported among the results of the fiber reinforced mixtures ($p_{value}$=0.198). Thus, although the addition of fibers significantly decreases the air voids with respect to the reference mixture, no differences among the air void content of the different type of fibers were observed. Regarding to the interconnected voids and bulk density, the same phenomena occurred and no significant differences were found between the effect of the different fiber type ($p_{value}$=0.397). On the other hand, the filler content has proved to be a relevant factor that affects the air void content in PA mixtures. In this sense, the close voids of RA and RB were found to be significantly different ($p_{value}$=0.016). However, no significant differences were observed in the case of the fiber reinforced PA mixes independently of the filler content (pvalue=0.244). It can be concluded that in terms of the volumetric properties, the type and the length of the fiber are not determining. This is likely due to the low fiber content that is added to the mixture. Probably a higher amount could have a more relevant impact. Concerning the permeability results, the least permeable PA mixture was RB with 59.6% less permeability than RA mixture ($p_{value}$=0.014). This phenomenon is likely due to the increased of close voids in RB (see Figure. 4) caused by the reduction of the filler content. On the other hand, focusing on the mixtures with higher filler content (i.e. Nomenclature A), PAN 4-A showed the lowest decrease in permeability, 14.7% reduction comparing to the reference (RA). It is likely that the longer the fiber length, the higher the negative impact on the permeability.

However, no significant differences were found within the fiber reinforced PA mixtures in terms of permeability. This is probably due, as suggested before, to the low fiber content ($p_{value}$=0.498). Focusing on the mixtures with low filler content, the addition of fibers seems to increase the permeability of the PA mixture (Figure 4). According to the statistical analysis, this effect is significant and the mixture that presented the highest improvement comparing to the reference mixture (RB) was the PO/A-B design ($p_{value}$=0.050). The observed phenomenon could be due to the fact that by decreasing the filler/binder ratio, the fibers can absorb a higher amount of the light components of the bitumen. Similarly, focusing again on the PA mixes with the lower filler content, the addition of fibers appears to increase the interconnected voids leading to a higher permeability. In general terms, although slightly changes of permeability were found, the minimum recommended value in ASTM D7064-04 [1,99] was fulfilled (1.2 mm/s).

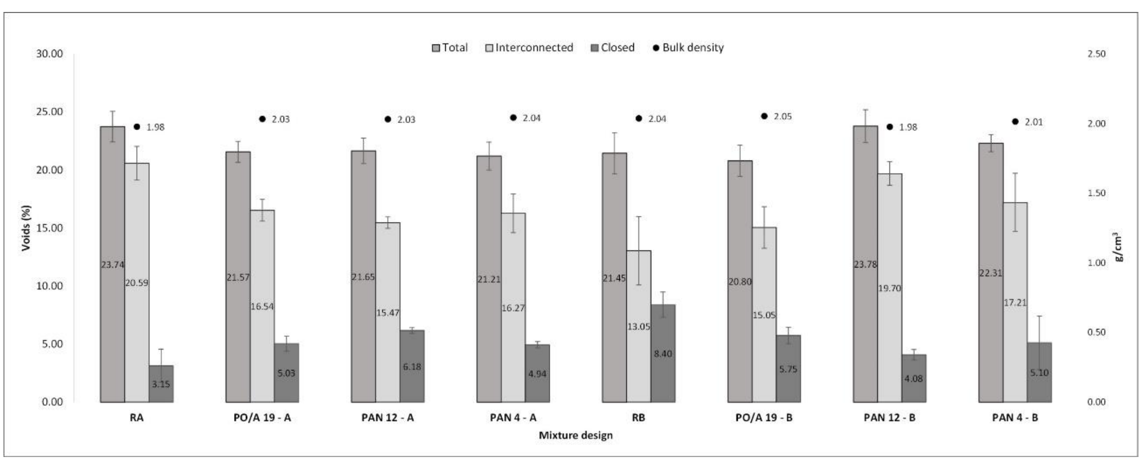


*Figure 4. Volumetric properties of the PA mixture designs. The standard deviation from the mean is indicated by an error bar*

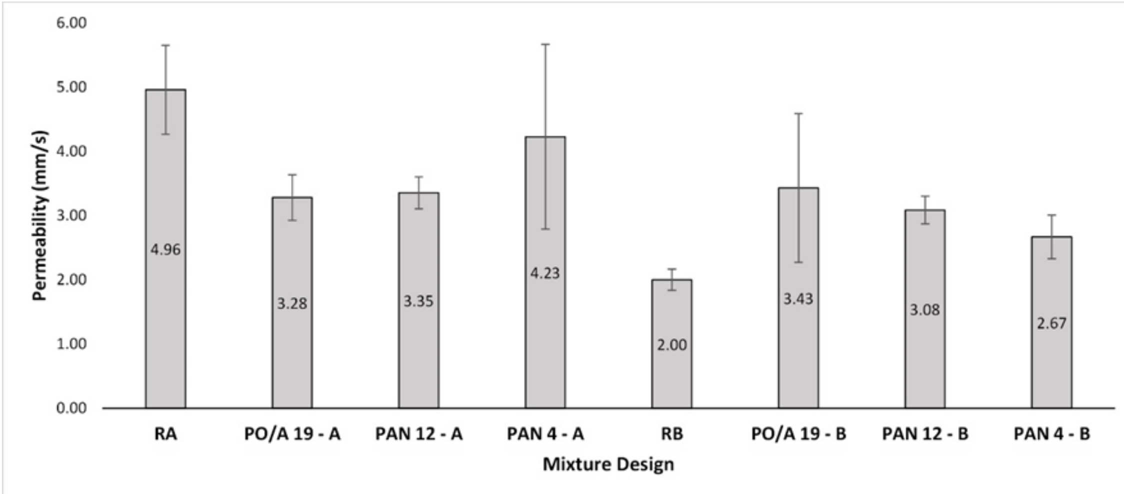


*Figure. 5 Mean permeability values of PA mixture designs. The standard deviation from the mean is indicated by an error bar*

### 4.2 Particle loss (Cantabro test)

The results concerning the particle loss in dry conditions are shown in Figure 6. According to the results, the use of fibers in the PA mixture positively affected its particle loss resistance. Specifically, the samples PO/A 19-A and PAN 4-A showed particle loss improvements of 33.7% and 15%, respectively, respect the reference mixture RA. In addition, considering data dispersion, the differences among the reference mixture and the fiber reinforced mixture with PO/A were found to be statistically significant ($p_{value}$= 0.047). According to results, the higher impact provided by the polyolefin plus aramid fibers could be explained by the higher elastic modulus and tensile strength presented by the aramid fibers, which increase the reinforcement of the three-dimensional network formed in the asphalt mortar, leading to a lower susceptibility to particle losses. In the same way, similar improvements were reported in PA mixtures when crumb rubber was added [100]. On the other hand, it is worth mentioning that polyolefin fibers were fully dissolved due to the temperature of the mixing process. In this sense, Hejazi et al. [101] reported that slightly dissolved fibers provided a better bond strength with the bitumen within the hot mix asphalt. A more recent study indicated that an increase in the kinematic viscosity of the bitumen reduces the particle loss in the Cantabro test [102]. Regarding the impact of the filler content, no statistical differences were observed in the resistance to particle loss of RA and RB PA mixtures ($p_{value}$=0.554). However, the addition of PO/A fibers to the PA mixtures with low filler content showed a higher increase in the particle loss resistance, observing a rise of 40-41% comparing to the reference mixtures being these results statistically different ($p_{value}$=0.017). Furthermore, PAN fibers provided similar results to those provided by PO/A fibers. Specifically, PAN 12-B and PAN 4-B improved the resistance to particle loss by 31.7% and 22.3%, respectively, in relation to the reference mixture (RB). Despite this, only the addition of the 12mm PAN fibers turned out to be statistically significant ($p_{value}$=0.050). As mentioned before, when the filler/binder ratio is reduced, there is a free amount of bitumen that can be absorbed by the fibers leading to a reinforcement of the three dimensional fiber-mortar networking matrix.

The results obtained in the Cantabro test carried out in wet conditions did not turn out as promising. Actually, reference mixture RA and fiber reinforced mixture PO/A 19-A presented the best results with a particle loss of 18.2 and 18.0, respectively. However, the differences among the results proved not to be statistically significant ($p_{value}$=0.949). Overall, the addition of fibers did not provide significant improvements in the mixture in wet conditions. This could indicate that these fibers are sensitive to water absorption. Focusing on the asphalt mixes with lower filler content, the initial hypothesis was that less filler content would increase the coating of the fibers by the bitumen and, therefore, increase the resistance to ravelling in wet conditions. However, similar results were obtained and no significant differences were found. As suggested by other researchers, lower filler contents decrease the viscosity and the amount of bituminous mastic that coats the aggregate particles leading to low thickness asphalt binder films on said particles. This will likely increase the susceptibility to moisture damage and decrease the resistance to the particle loss [1,30]. Thereby, these results suggest that the incorporation of fibers probably requires the addition of higher amounts of bitumen to completely coat the fibers and to prevent their exposition to the weather conditions.

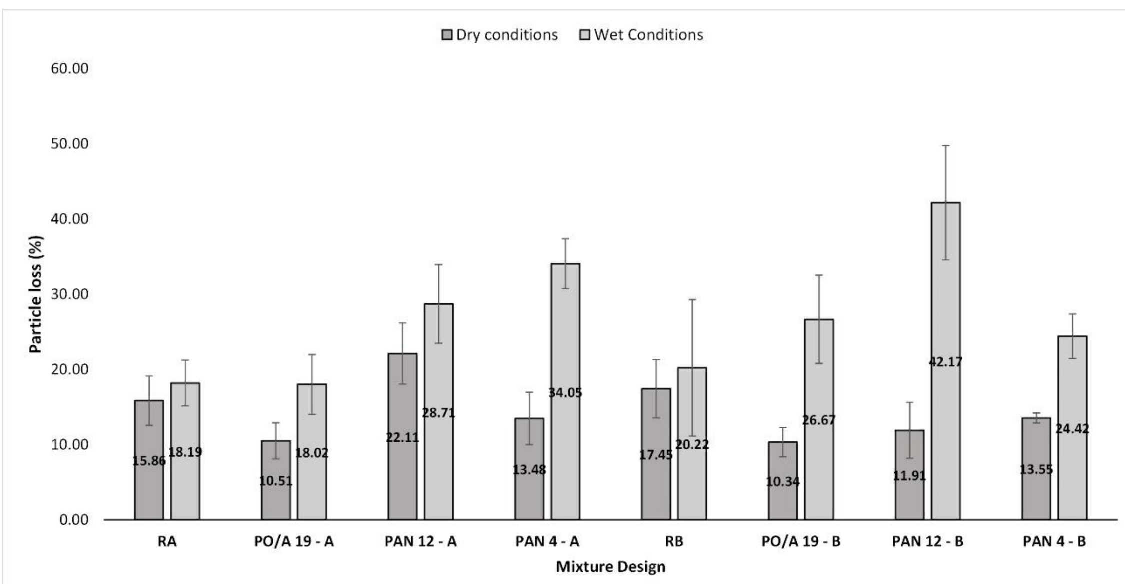


*Figure 6. Mean values of the Cantabro loss particle test in dry and wet conditions. The standard deviation from the mean is indicated by an error bar*

### 4.3 Indirect tensile strength and moisture sensitivity

The indirect tensile strength results in dry conditions are shown in Figure 7. Based on these results, the increase of the ITS due to the addition of the different fibers is clearly observed. It should be noted that the length of the fiber has also an influence in the ITS, obtaining the highest improvements when long fibers are used. Thus, considering the mixtures with higher filler/binder ratio, the addition of PO/A fiber (19mm) increases the indirect tensile strength in 22% as compared to the reference mixture (RA), being this difference significant ($p_{value}$=0.019). However, in the case of the mixtures with low filler content, 13.5% improvement achieved by the PO/A fiber has turned out to be insignificant ($p_{value}$=0.060), although close to the limit of 0.05 with the 95% confidence interval. On the other hand, neither 12mm nor 4mm PAN fibers showed significant increases in the ITS values with $p_{values}$ of 0.156 and 0.530, respectively. Moreover, the filler content was found to play an important role in the ITS of the asphalt mixtures. When the filler content is reduced, improvements of 20%, 11.7% and 7.01% were achieved in the reference mixture ($p_{value}$=0.020), the PO/A fiber reinforced mixture ($p_{value}$=0.136) and the 12mm PAN fiber reinforced mixture ($p_{value}$=0.450), respectively. Nevertheless, only the result obtained in the reference mixtures is significantly different.

Concerning the ITS results in wet conditions (Figure 7), the highest strength was also obtained when PO/A fibers were added to the PA mixture, with an increase of 9.4% comparing to the reference mixture (RA). This is the only result significantly different ($p_{value}$=0.050). The other fiber reinforced mixtures did not show any significant improvement. Based on these results, it can be concluded that the addition of fibers to the PA mixture improves only the ITS in dry conditions. In this sense, the ITSR values confirm the aforementioned conclusions (see Figure 7). According to the results, RB mixture showed the highest ITSR value (86%). However, it should be noted that the main reason for the observed reduction in ITSR when the fiber is added is caused by the increase of the ITS in dry conditions.

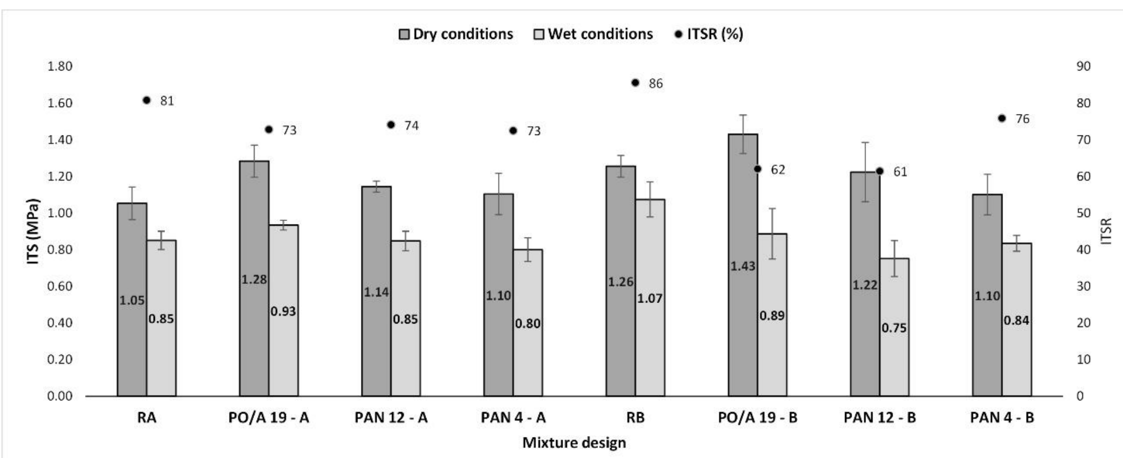


*Figure 7. Mean values of the Indirect Tensile Test (ITT). The standard deviation from the mean is indicated by an error bar*

### 4.4 Toughness and Cracking resistance

The Indirect Tensile Test (ITT) is considered by many researchers as the most adequate test to measure toughness given its simplicity, because not specialized instrumentation is required and because less than 1 minute is needed to perform it [103]. In this research, typical indirect tensile stress-strain curves were recorded in dry and wet conditions as shown in Fig. 8a and 8b, respectively.

With a total of 48 specimens tested, the fracture energy (FE), post cracking energy (PE) and toughness mean values (series of three samples) are shown in Fig. 9 and 10 also in dry and wet conditions, respectively. Regarding the failure occurred, it was observed that the fracture took place in the mortar zone (cohesion failure) and in the zones closer to mortar-coarse aggregate interface. Similar than reference mixture, changes in the breaking process were not noticed with the inclusion of fibers.

According to the results, in dry conditions, a slight increase of the initial stiffness is observed when adding fibers (Fig. 8a). Consequently, fracture energy is also increased providing the mixture with a more ductile behaviour. In this sense, the PAN 4-A mixture presented the major fracture energy with an increase of 46% comparing to the reference mixture RA ($p_{value}$=0.009). Similarly, this mixture also reported the highest PE and toughness with increases of 23.5% and 32.1%, respectively, compared to the reference mixture RA, being only the increase in toughness statistically significant ($p_{value}$=0.024). This is likely due to the fact that short fibers are completely embedded in the asphalt mortar of the PA mixture, forming a three dimensional network in the mortar matrix and increasing the cohesive forces within the mortar [104]. Focusing on the samples with a lower filler content (B), the FE is slightly increased when PO/A fibers are added compared to the reference mixture (RB). In addition, it is interesting to note that, in dry conditions, the mixtures reinforced with PAN fibers (both 12 and 4 mm) presented similar FE for both low and high filler content and although the PO/A19-A mixes presented 40% higher FE than PO/A19–B mixes, the result turned out to be not statistically significant ($p_{value}$=0.116). Therefore, changes in the filler content seem not to significantly affect the fracture energy of the PA mixtures. Similarly, slight increases in the post-cracking energy are generally observed in Figure 9 when using fibers. It should be noted that an increase in the post-cracking energy means a delay in the crack propagation when the pavement structure is subjected to traffic loads. Based on the results, PO/A fibers seem to achieve the greatest improvement in the post cracking energy. However, although PAN fibers reported improvements in relation of the reference mixture RA, lower PE results were obtained comparing to RB mixture.

Finally, when analysing the results obtained in the ITT test in wet conditions, no significant improvements are observed when fibers are added to the PA mixture (Figure 10). This is probably due to a potential negative effect of water on the fiber reinforced PA mixtures tested. In this sense, Chen and Xu [105] measured the water absorption of different type of fibers, reporting an absorption of 11% in the case of PAN fibers. According to this, the fibers are also expected to contribute to prevent bitumen drainage so the use of a higher bitumen content in these mixtures is not only possible but also highly recommended to avoid the negative water affection.

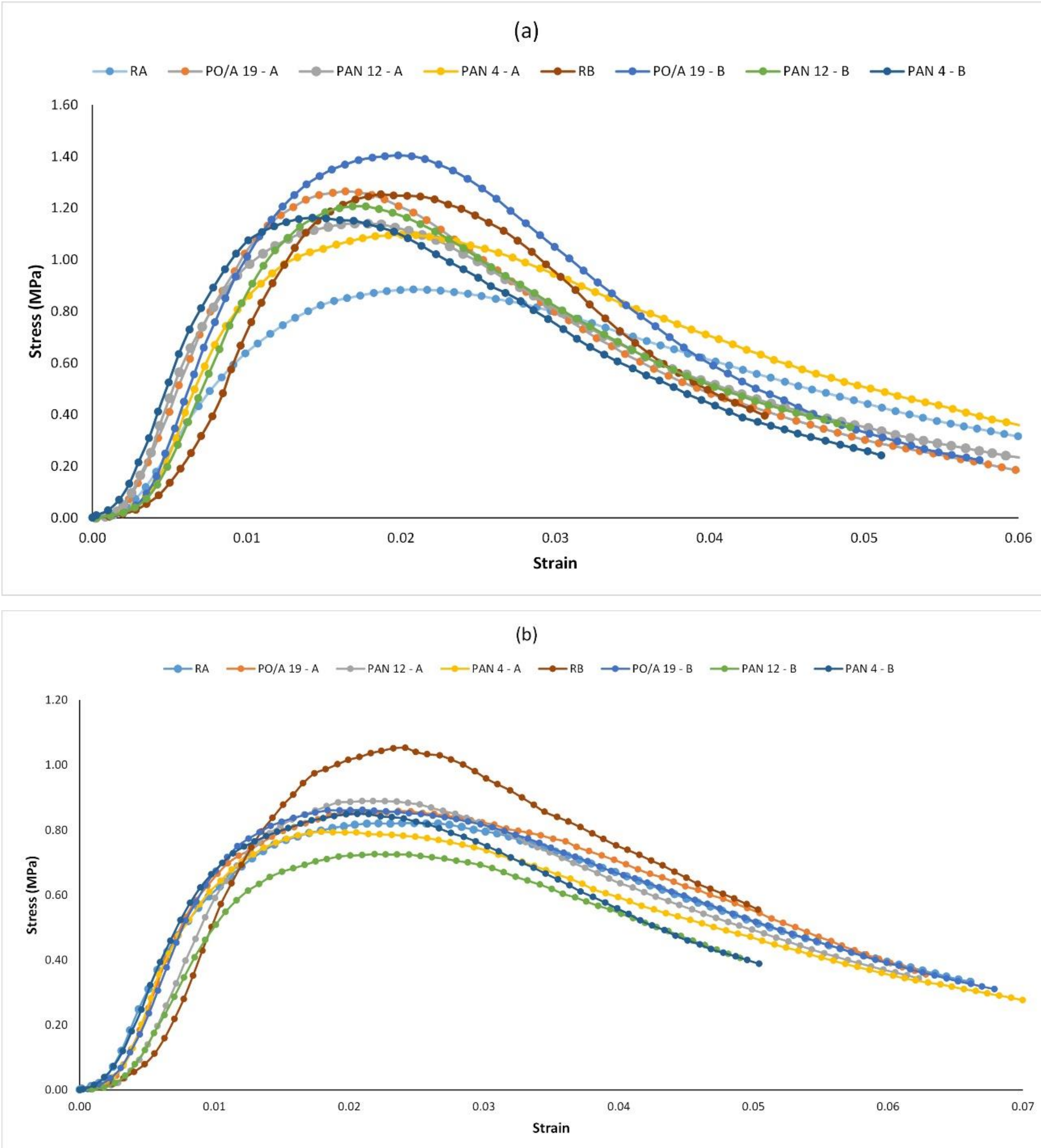


*Figure 8. Indirect Tensile Stress-Strain curves of PA mixtures: (a) Dry conditions; (b) Wet conditions*

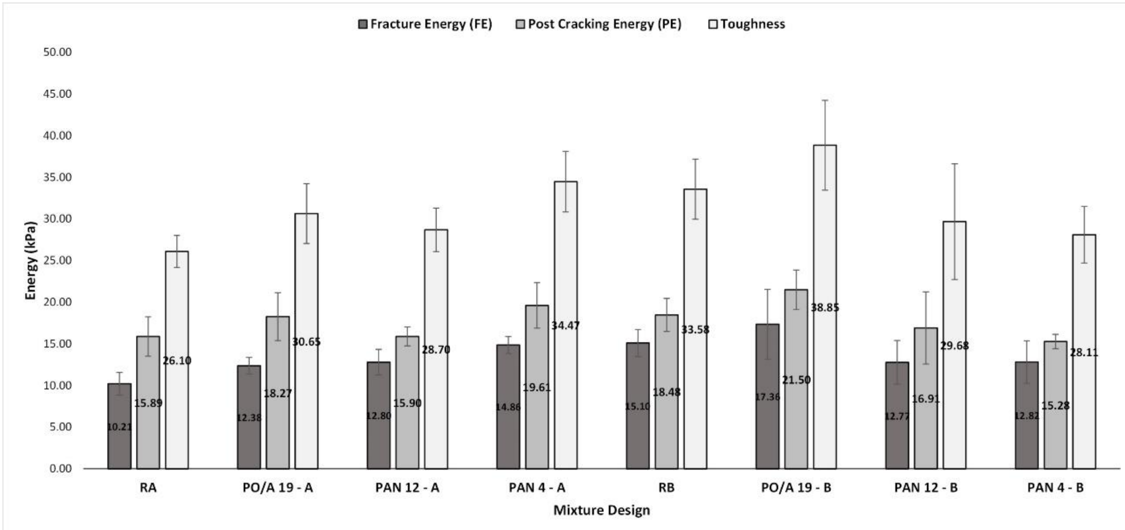


*Figure 9. Mean values of the fracture energy, post cracking energy and toughness in dry conditions. The standard deviation from the mean is indicated by an error bar*

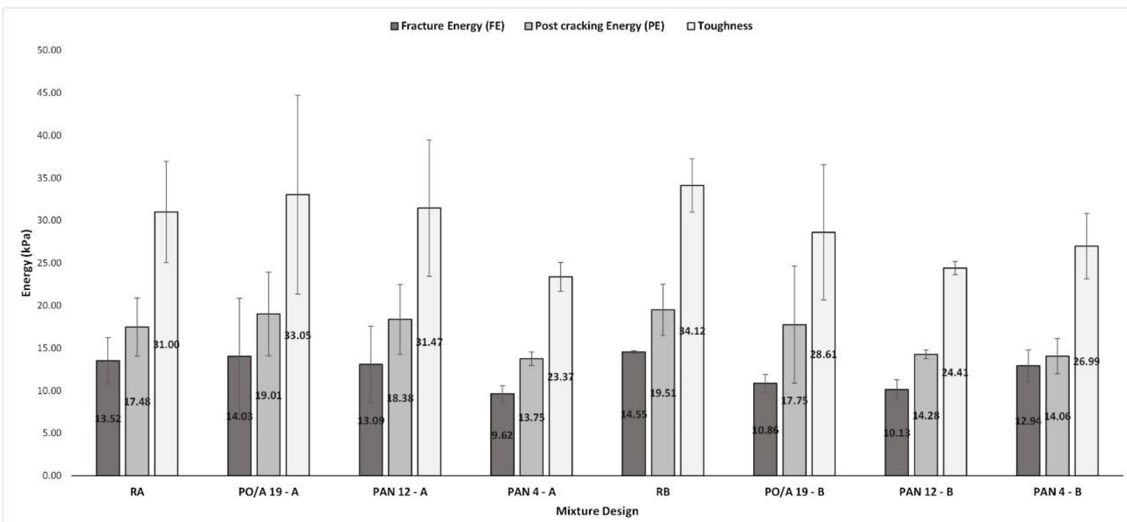


*Figure 10. Mean values of the fracture energy, post cracking energy and toughness in wet conditions. The standard deviation from the mean is indicated by an error bar*

## 5. Conclusions

A laboratory assessment was performed to study the effect on the mechanical and functional performance of using synthetic fibers in porous asphalt mixtures. Specifically, a blend of polyolefin-aramid fibers and polyacrylonitrile were evaluated in this work. It should be noted that the same bitumen content was used in all the specimens in order to isolate the mechanical improvement provided by the fibers without considering their potential anti-drainage capacity. On the other hand, the impact of the filler/bitumen ratio on the results was analysed. Taking this into account, a set of PA mixtures were designed, manufactured and tested. Based on the results obtained, the following conclusions are presented.

- The use of the fibers in the PA mixture slightly reduces the total air void content when comparing to the reference mixtures. In any case, the minimum air void content established by the Spanish specifications was accomplished (20%).
- The addition of fibers to the PA mixture improved their mechanical performance in dry conditions. However, no significant improvements were observed in wet conditions. It is believed that to fully incorporate the fibers in the binder-aggregate matrix, a higher amount of bitumen is needed, thus also taking advantage of the anti-drainage capacity of the fibers. Otherwise, the use of the fibers in dense graded mixtures (AC or SMA) is recommended.
- Concerning the particle loss test, the addition of PO/A fibers to the PA mixture influenced positively the resistance to particle loss, reducing the rate of weight loss in the Cantabro test. On the other hand, the filler content seemed not to affect significantly the particle loss results.
- The addition of fibers to the PA mixture resulted in an increase of the indirect tensile strength (ITS) of the dry conditioned specimens. On the other hand, similar or lower strengths than the reference were found when wet conditioned specimens of fiber reinforced PA mixtures were tested.
- The addition of PAN4-A and PO/A19–B type of fibers to the PA mixture showed the highest improvements in terms of the fracture energy, post cracking energy and toughness of the dry conditioned specimens comparing to the reference mixtures RA and RB respectively. No improvements were observed concerning toughness for the fiber reinforced wet conditioned specimens.
- Overall, considering the obtained results, the highest mechanical and functional performance of the PA mixtures were provided by the addition of the PO/A fibers.
- Further investigations are needed in order to evaluate the performance of these type of fibers in PA mixtures considering other variables such as fiber concentration, bitumen content, and bitumen type or particle size distribution. Life cycle cost analysis of the reinforced porous asphalt mixtures with fibers is also recommended to be another research topic.

## Acknowledgements

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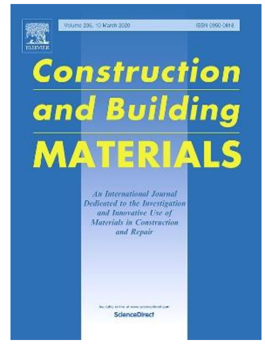
## 4.2 Article 2. An experimental laboratory study of fiber-reinforced asphalt mortars with polyolefin-aramid and polyacrylonitrile fibers

### *4.2.1 Basic information and impact factor concerning article 2*

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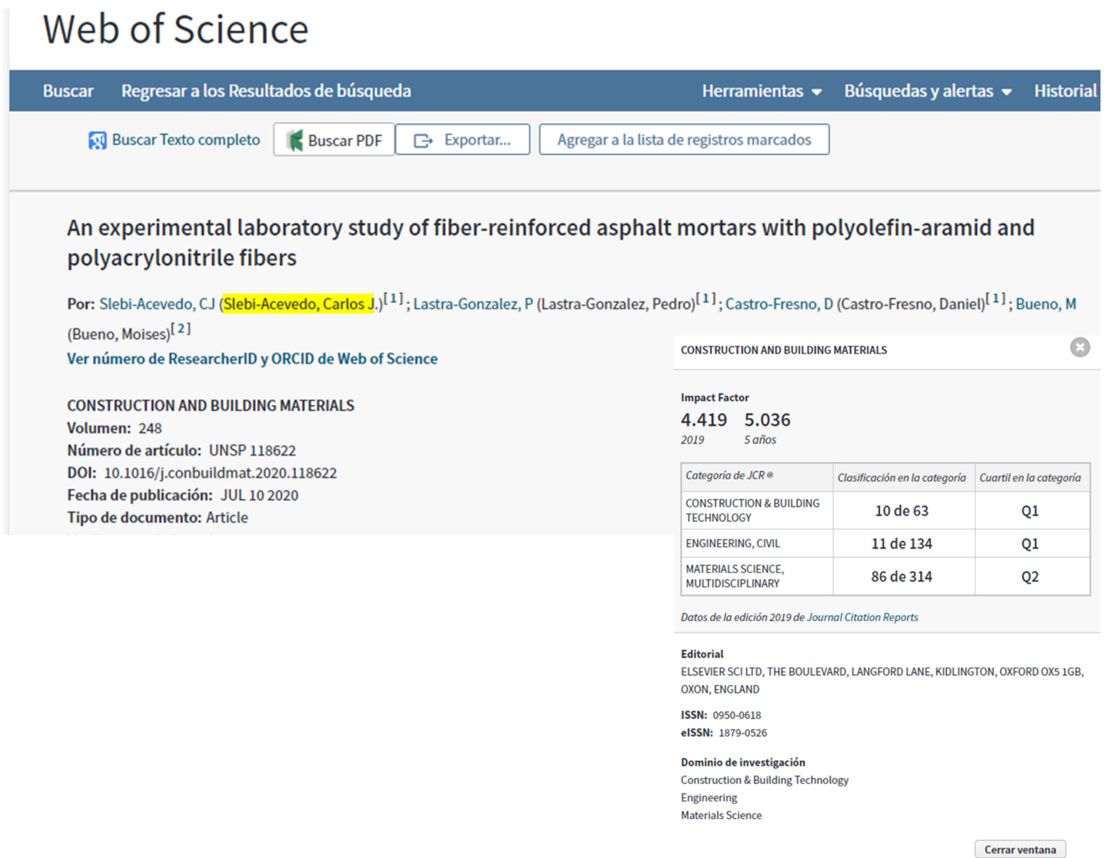


*Figure 10 Authors and impact factor of journal regarding article 2*

*4.2.2 Transcription of article 2*

# An experimental laboratory study of fiber reinforced asphalt mortars with polyolefin-aramid and polyacrylonitrile fibers

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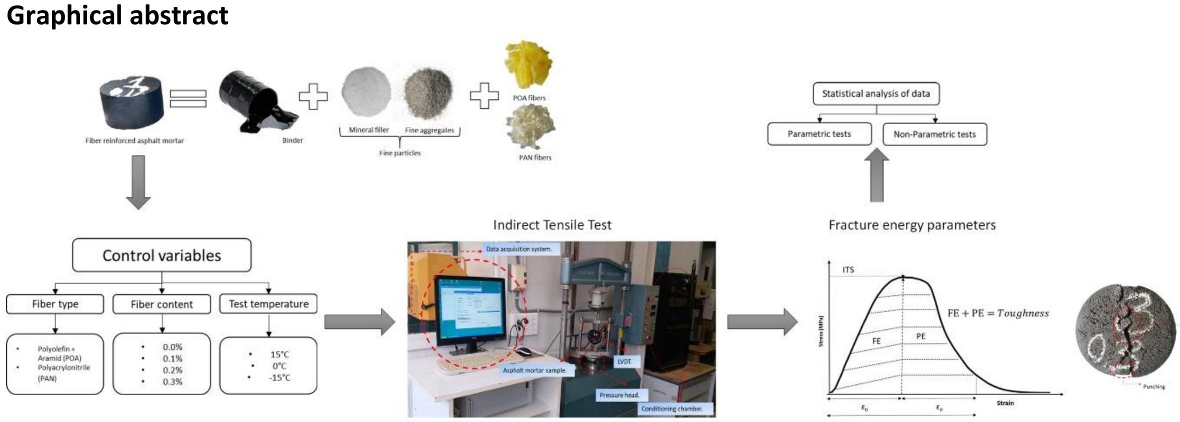
**Abstract**

Promising results have been found in the literature with the use of synthetic fibers in hot mix asphalt. However, few research efforts have focused on studying the effect of these fibers at asphalt mortar scale. In this research, the reinforcing effect of polyolefin-aramid (POA) fibers and polyacrylonitrile (PAN) fibers is investigated in asphalt mortars through the indirect tensile test. Fiber Reinforced Asphalt Mortar (FRAM) specimens were prepared with different fibers contents (0.1wt%, 0.2wt% and 0.3 wt%) and tested at three temperatures (15°C, 0°C, -15°C). Indirect tensile strength, fracture energy, post-cracking energy and toughness were the parameters obtained and analyzed from the test in order to understand the behavior of the different FRAM designs. Moreover, the obtained failure types are also analyzed. According to the experimental results, a significant improvement of strength at low temperature (-15°C) were observed by adding 0.3% of POA or PAN fibers. Furthermore, the fracture energy properties were enhanced due to the addition of fibers.

**Graphical abstract**




**Highlights**

- Fracture parameters of fiber reinforced asphalt mortars were investigated.
- A blend of polyolefin-aramid fibers and polyacrylonitrile fibers were employed as reinforcement additives.

- At low temperature (-15°C) the behavior of the FRAM appears to be elastic-brittle.
- Significant improvement was observed with both types of fibers at low temperature (-15°C).

**Keywords**. Asphalt mortar, fibers, indirect tensile strength, fracture.

## 1. Introduction

### 1.1 Background of fibers in asphaltic materials

In asphalt pavements, bituminous materials are constantly exposed to different environmental conditions such as rainfall, freezing and sunny days which affecting directly the long term performance of the mixture[106]. Besides, due to the repetitive passage of the traffic loads cracking by fatigue and rutting are one of the most common type of failures observed in hot mix asphalt [107]. Previous studies have demonstrated that the addition of special types of fibers into bituminous mixtures can improve some of their mechanical properties leading to a better overall performance [70]. Asphalt concrete (AC) is one of the most common types of mixture where the use of fibers has become more frequent. Different types of fibers have been employed to reinforce hot mix asphalt mixtures including basalt, nylon, cellulose, steel, aramid, polyester or polypropylene fibers among others [31,35,108–110]. In general, it has been shown that fibers influence the cracking process bringing ductility to the mixture and increasing the toughness [37]. Similarly, fibers can work as a crack barrier that helps to prevent the formation and propagation of cracks [111]. Furthermore, fibers can change the viscoelasticity of bituminous materials [112]. In fact, some experimental results have shown that fibers can improve the rheological properties of asphalt binder across a wide range of loading frequencies and temperatures [113]. Additionally, the fiber addition into the asphalt binder increases the softening point and viscosity and decreases the penetration point leading to an improvement in rutting resistance [113]. Based on scanning electron microscope results, it was found that fibers can be arranged in a three-dimensional network structure in the asphalt matrix which contributes to form a thick film of mastic preventing the binder drainage [114]. Fibers also contribute positively to the sustainable development of flexible pavements. While the use of polymers generally requires to increase the temperature in the production process of hot mix asphalt [115], fibers can be added directly to the mix by dry method at environment temperature so additional energy requirements are not necessary. The healing capability of metallic fibers and the incorporation of recycled waste fibers in hot mix asphalt are also attractive solutions to mitigate the negative impact on the environment and the production and maintenance costs of pavement infrastructures [46,111,116].

Kim et al. [117] evaluated the effect of asphalt concrete reinforced with nylon fibers. Different parameters such as Marshall Stability, indirect tensile strength, moisture susceptibility, dynamic stability and flexural strength were calculated. The authors concluded that the addition of 1.0% nylon fibers provided suitable reinforcing efficiencies with an exception in dynamic stability. In another study, Morea and Zerbino [37] explore the possible improvements of adding glass macro-fibers in an asphalt concrete mixture. A number of fiber reinforced asphalt concrete mixtures were produced applying different quantities of fibers without optimizing the binder content. It was concluded that the rutting behavior of the fiber reinforced mixtures was improved in comparison to the reference mixture. In addition, it was reported an improvement regarding fracture behavior at intermedium and low temperatures. Similar effects were found by Mahrez et al. [118] who evaluated the use of glass fiber in stone matrix asphalt (SMA) mixtures. It was shown that fiber addition had the potential to enhance the cracking resistance as well as the permanent deformation. On another study, García et al. [119] evaluated the influence of wool steel fibers on the volumetric and mechanical properties of a dense asphalt mixture. They reported that the steel fibers suffered damages during mixing and compaction process and were broken into pieces. Furthermore, clusters of fibers were found after the mixing process, which negatively affected the final mechanical performance of the experimental mixtures. Alternatively, Park et al. [72] studied the reinforcing effect of adding steel fibers in asphalt concrete at low temperature. In this work, indirect tensile strength, fracture energy and post cracking energy were considered the main parameters to assess the toughness and cracking resistance of fiber reinforced asphalt concrete. It was concluded that fibers significantly enhanced the cracking resistance at low temperature with an improvement superior to 62.5% in indirect tensile strength and up to 370% in fracture energy. Concerning the use of fibers in porous asphalt mixtures, cellulose fibers are commonly used as stabilizer agent to avoid the binder drainage [120]. Experimental results showed that fibers reduce the drain down better than other additives like polymers [120]. Marcia et al.[77] assessed the overall performance of a PA mixture with the inclusion of cellulose fibers. Based on the results, the authors concluded that the binder drainage decreases as the cellulose fiber increases [121]. Additionally, fibers addition helped to increase the binder content inside the mix and consequently coated the aggregates better allowing an increment in the durability of the mix. Similar results were concluded by Valeri et al. [1] who substitute cellulose fibers by recycled Tetra Brick aseptic containers as an environmentally friendly alternative. In this sense, new promising solutions have been started using for asphalt mixtures. In the current work, a combination of polyolefins-aramid (POA) fibers and polyacrylonitrile (PAN) fibers have been investigated. Next, the state of the art of these two types of fibers as additives for asphalt mixtures is detailed.

### 1.2 Polyolefin-Aramid (POA) fibers

Aramid fibers present remarkable properties to be considered as asphalt mixture additives. For example, its high strength to weight ratio is approximately five times higher than steel [122]. Due to these properties, aramid fibers have been broadly used in many applications such as composites, ballistics, aerospace, protective clothing, ropes and cables [122]. In addition, due to high-thermal performance properties these fibers have been used in fire protection products and for high-temperature dust removal applications [123]. Furthermore, polypropylene and polyethylene as thermoplastic polyolefins widely used in the production of world-scale plastics [124] could be an interesting material for asphalt modification as well. As fibers, these type of polymers present high tensile strength values, good abrasion resistance, low specific gravity, hydrophobic properties and the potential to be thermally bonded [125]. Due to their different properties, in recent years, scientists and engineers have been attracted to incorporate these types fibers in hot mix asphalt [44]. For example, Klinsky et al. [35] investigated the benefits of adding polypropylene-aramid fiber in a modified asphalt mixture commonly used in Brazil. They concluded that the use of compound fibers helps to reinforce the hot mix asphalt from different perspectives. It is claimed that aramid improves the mixture because it provides a three-dimensional reinforcement while polypropylene contributes to disperse the fibers better and to improve the adhesion of the mix. Following a similar approach, Mirabdolazimi and Shafabakhsh [126] investigated the rutting resistance of hot mix asphalt modified with polyolefin-aramid fibers. Accordingly, the results indicated that adding fibers reduced the permanent deformation. Similarly, the authors reported that an interlocking effect between aggregates and compound fibers allows to reduce the deformation. Noorvand et al. [127] studied the effect and distribution of aramid fibers in an AC mixture. Microscopy imaging was used to analyze fiber distribution and the rutting. The fatigue tests were employed to evaluate the mechanical performance. They claimed that a more dispersed and distributed fibers set affects positively the overall performance of the mix. It was shown that fibers were oriented to reinforce cracks. Another study carried out by Kaloush et al. [128] addressed the evaluation of the mechanical properties of AC mixtures reinforced with polyolefin-aramid compound fibers. Different experimental tests were performed such as triaxial shear strength, dynamic modulus, crack propagation and indirect tensile strength tests. The results indicated that the fiber-reinforced asphalt mixture had better performance to shear deformation and permanent deformation when compared to reference mixture without fibers. Moreover, the fiber addition led to an increment of 25-50% in the tensile strengths and 50-75% for the fracture energies. In more recent study, Aliha et al. [95] analyze the crack growth resistance of warm mix asphalt (WMA) reinforced with polyolefin-aramid fibers and jute fibers through the semi-circular bending test. Different fracture modes tests were carried out showing that synthetic fibers improve the fracture toughness in comparison with WMA mixtures reinforced with natural fibers. Recently, Apostolidis et al. [39], analyzed the effects of adding polyolefin-aramid fibers of different lengths in asphalt mortar. Different modes of pull-out tests and direct tension tests were carried out to explore the interactions between the fiber-mortar matrixes. Upon monotonic tension, there was no significant effect at low temperature on the tensile strength of fiber reinforced asphalt mortar compared with those without fibers addition. On the other hand, results from the cyclic loading tension testing showed that 0.1%wt long fibers had similar influence on the mortars than a dosage of 0.5% short fiber. The authors finally suggest that polyolefin fibers help to increase the interfacial bonding generated between the fiber and the mortar.

### 1.3 Polyacrylonitrile (PAN) fibers

Polyacrylonitrile fibers, also known in literature as PAN fibers, are nowadays the most preferred chemical precursor of high quality carbon-fiber [129] due to its higher carbon yield as well as its great tensile and compressive strength [130]. This fiber produced by the additional polymerization of acrylonitrile (the main component) has been extensively used in the textile sector in the production of warm and bulky fabrics and mainly as an alternative to wool [131]. Polyacrylonitrile staple fibers, because of their high tensile strength, thermal and chemical resistance, have been considered interesting to reinforce concrete and bituminous materials. Sheng-Jun [132] studied the toughness of concrete specimens reinforced with PAN fibers. The author reported an increment of toughness adding PAN fibers. According to the results, the incorporation of 1.0 vol.% PAN fibers is suitable to increase the fracture energy properties of concrete specimens. On another research, Cao et al. [133] carried out an experimental investigation on cemented tailing backfills reinforced with polyacrylonitrile fibers. Uniaxial compression strength (UCS) tests were performed on the specimens and the results indicated that the addition of fibers slightly increases the UCS value. Concerning bituminous materials, Xu et al. [42] analyzed the reinforcing effects of four different types of fibers (asbestos, lignin, polyester and polyacrylonitrile) in AC mixtures under different environment conditions (temperature and water effects). It was shown that AC mixtures reinforced with synthetic fibers (polyester and polyacrylonitrile) obtained higher values of rutting resistance, fatigue life and ITS. It was claimed that polymer fibers have greater networking function while mineral and organic fibers are more recommended as stabilizer additives. Similar conclusions were found by Chen and Xu [105] who analyzed the mechanisms for reinforcing and stabilizing asphalt binder adding fibers. Focused on other type mixture (SMA, stone mastic asphalt), Weise and Zeissler [134] also evaluated the impact of adding PAN fibers concluding that they contribute to minimize plastic strain values and hence enhancing the rutting resistance.

### 1.4 Main objective of the research.

While numerous studies have been reported in literature respect hot mix asphalt, few research efforts have focused on studying the reinforcement effect of fibers on the asphalt mortar which is an essential part in porous asphalt mixtures. Moreover, asphalt mortar is a material very sensitive to changes in temperature. Therefore, the main objective of this research is to evaluate the impact of polyacrylonitrile (PAN) and polyolefin-aramid (POA) fibers on fracture energy properties at asphalt mortar scale. More specifically, this study seeks to understand better the toughness and the cracking resistance of asphalt mortar modified with two types of fibers with different contents at intermediate and low temperatures.

## 2. Materials and methods

### 2.1 Materials

The asphalt mortar gradation is displayed in Figure 1. The filler and fine aggregate employed in this study was limestone. A conventional 50/70 penetration grade bituminous binder was used. The physical properties of the bituminous binder and fine aggregates are listed in Table 1. The binder content used in the mortar mix was adjusted on 9.3% by weight of mortar because of the increase in the surface area of the fine aggregates in the mortar. It is worth mentioning that asphalt mortar only contains filler and fine aggregates with maximum particle size of 2 mm. These particles have greater surface area than coarse aggregates and hence it is necessary to increase the binder content in the mix to ensure the same aggregate binder film thickness [73,135].

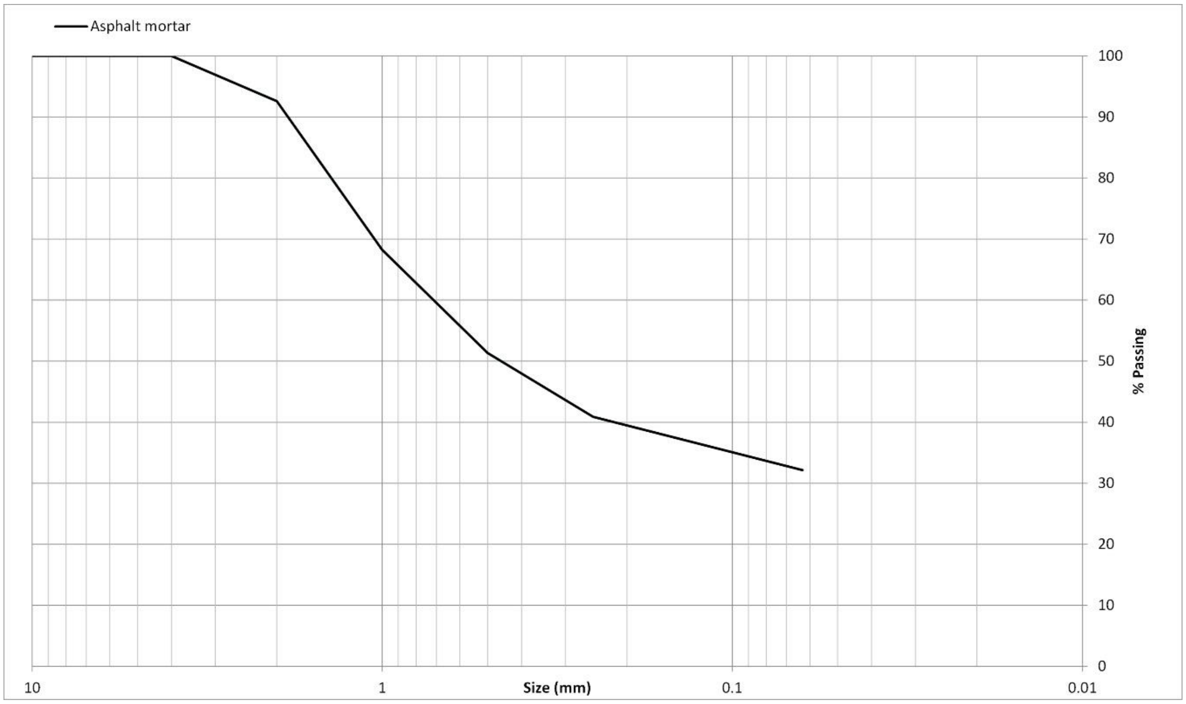



*Figure 1. Gradation curve of the asphalt mortar employed in the research*

*Table 1. Characteristics of 50/70 penetration grade binder and fine aggregate*

| Characteristic | Standard | Value |
|---|---|---|
| 50/70 penetration grade | | |
| Specific weight (g/cm$^3$) | EN 15326 | 1.035 |
| Penetration at 25 °C | EN 1426 | 57 |
| Softening point (°C) | EN 1427 | 51.6 |
| Fraass brittle point (ºC) | EN 12593 | -13 |
| Fine aggregate | | |
| Specific Weight (g/cm$^3$) | EN 1097 - 6 | 2.724 |
| Sand Equivalent | EN 933 - 8 | 78 |

Two types of fibers were studied in the current research. The first type comprises a blend of polyolefin-aramid fibers (POA). The proportion of the set is 86% of polyolefin fibers and 14% of aramid fibers. The second fiber used was polyacrylonitrile fiber (PAN). Table 2 and Table 3 show the physical properties of both fibers according to the provider. Moreover, the density of the blend POA, determined according to the European standard UNE-EN 1097-6, was 0.947 g/cm$^3$. Details of the synthetic fibers can be observed in Figure 2.

*Table 2. Characteristics and physical properties of POA fibers.*

| Fiber | Aramid | Polyolefin |
|---|---|---|
| Form | Monofilament | Serrated |
| Color | Yellow | Yellow |
| Density (g/cm$^3$) | 1.44 | 0.91 |
| Length (mm) | 19 | 19 |
| Tensile Strength (MPa) | 2758 | 483 |
| Decomposition temperature (°C) | 157 | > 450 |
| Acid/Alkali Resistance | Inert | Inert |

*Table 3. Characteristics and physical properties of PAN fibers*

| Fiber | Polyacrylonitrile |
|---|---|
| Form | Staple fibers |
| Color | Bright straw yellow gold |
| Density (g/cm3) | 1.18 |
| Length (mm) | 4 |
| Tenacity (MPa) | > 708 |
| Elastic modulus (MPa) | 16500 |
| Elongation at break (%) | < 13 |
| Diameter (mm) | 0.0127 |

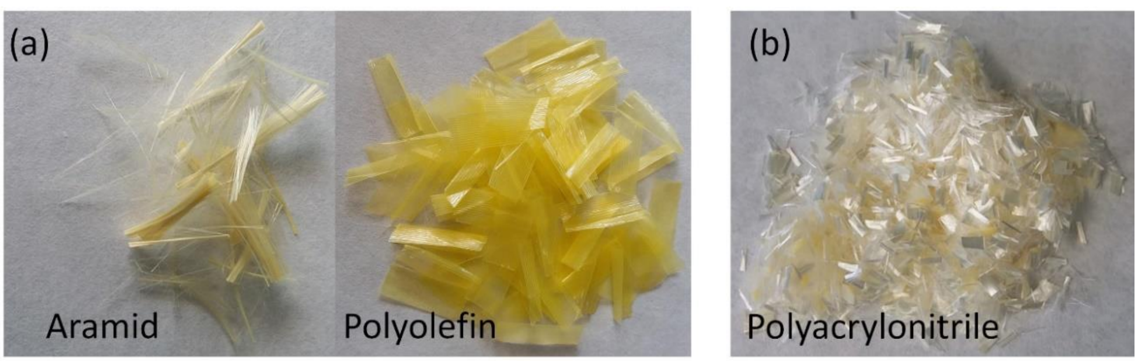



*Figure 2. Set of polyolefin-aramid (POA) fibers (a); Polyacrylonitrile (PAN) fibers (b)*

### 2.2 Sample preparation

The mixing procedure is described as follows: first, mineral filler and fine aggregates were heated in an oven at 175°C during six hours prior to the addition to the fibers followed by a mixing process of one minute. Next, the pre-heated bituminous binder was added to the fiber-fine aggregate mix at 155°C and mixed for five minutes guaranteeing a good homogeneity of the mixture. In order to optimize the asphalt mortar mixes, compactability tests (EN 12697-10) were carried out for both types of fibers at three different fiber contents (0.1%, 0.2%, and 0.3%) by weight of mortar to determine the air void content in the mix in function of the number of cycles. Cylindrical specimens with a diameter of 100 mm and a height of 61 mm approximately were compacted at 150°C using the gyratory compactor machine. The test was performed applying a load of 600 kPa, the angle of rotation was 0.82° and the speed movement was 30 rpm. Figure 3 shows the effect of the number of cycles on the air void content. Three replicates per each mortar design were performed and the average value was plotted (see Figure 3). It can be observed that adding fibers leads to a slight increase the air voids in the mortar. A higher air void content could influence the mechanical behavior of the mixture. Therefore, to minimize this effect, a target air voids content of 2.5% was chosen for all the asphalt mortar designs. Likewise, since this research emphasizes the reinforcing effects of the fibers in the mortar, the binder content was also kept constant.

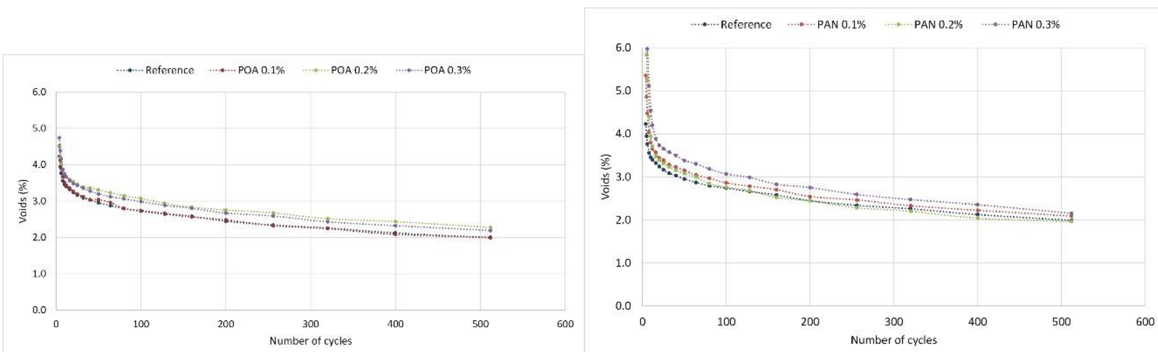



*Figure 3. Compactability test performed in non-reinforced and reinforced asphalt mortar specimens. (a) POA fibers. (b) PAN fibers.*

### 2.3 Experimental design

In the present study, the experimental testing program comprises 21 groups of asphalt mortar mixes considering the reference mortar with no fiber addition and hence 63 total specimens were prepared with different types of fibers with different contents and tested at different temperatures. Table 4 presents the mortar designs with their respective input parameters.

*Table 4. Asphalt mortar designs carried out in the present research*

| Asphalt mortar design | Testing temperature (°C) | Fiber content (%) | Type of fiber | Replicates |
|---|---|---|---|---|
| 1 | 15 | - | - | 3 |
| 2 | 15 | 0.1 | POA | 3 |
| 3 | 15 | 0.2 | POA | 3 |
| 4 | 15 | 0.3 | POA | 3 |
| 5 | 15 | 0.1 | PAN | 3 |
| 6 | 15 | 0.2 | PAN | 3 |
| 7 | 15 | 0.3 | PAN | 3 |
| 8 | 0 | - | - | 3 |
| 9 | 0 | 0.1 | POA | 3 |
| 10 | 0 | 0.2 | POA | 3 |
| 11 | 0 | 0.3 | POA | 3 |
| 12 | 0 | 0.1 | PAN | 3 |
| 13 | 0 | 0.2 | PAN | 3 |
| 14 | 0 | 0.3 | PAN | 3 |
| 15 | -15 | - | - | 3 |
| 16 | -15 | 0.1 | POA | 3 |
| 17 | -15 | 0.2 | POA | 3 |
| 18 | -15 | 0.3 | POA | 3 |
| 19 | -15 | 0.1 | PAN | 3 |
| 20 | -15 | 0.2 | PAN | 3 |
| 21 | -15 | 0.3 | PAN | 3 |

*2.3.1 Mechanical performance*

Indirect tensile test (ITT) has been considered a practical and efficient test for measuring fracture parameters and for cracking resistance evaluation. Some advantages of this method are the type of specimens and the simple instrumentation [136]. Additionally, no further specimen preparation such as cutting, gluing, drilling or notching processes are required to conduct the test [103]. In this sense, since no artificial crack is induced, the failure in the specimen occurs in the region where the tensile stress is relatively uniform. In all cases, the localized failure occurred in the middle part of the specimens. Indirect tensile tests were performed following the European standard EN 12697 – 23 for hot mix asphalt. To condition them, the specimens were removed from the molds and kept at environment temperature for 24 hours. Then, the specimens were conditioned for eight hours at test temperature in a conditioning chamber. The ITT was carried out in a material testing system (MTS) with a maximum load capacity of 100 kN. All the specimens were tested until the failure keeping a constant rate displacement of 50 mm/min during the test. The loading data as well as the vertical displacement were recorded by a data acquisition system.

From the recorded data, the indirect tensile strength (ITS) in MPa was calculated using the Equation 1 as shown below.

$$ITS = \frac{2 \cdot F}{\pi \cdot t \cdot D_s} \quad (1)$$

Where F is the maximum force (N), $t$ is the thickness of the specimen (mm) and $D_s$ corresponds to the diameter of the specimen (mm). Moreover, the stress-strain curve during the entire failure process was recorded and fracture parameters derived from the ITT were determined as defined in Figure 4. As suggested by Park et al. [72], Fracture energy (FE) can be quantified as the area under stress-strain curve up to the strain where the maximum strength is reached ($\varepsilon_p$). Post-cracking energy (PE) corresponds to the area under stress-strain curve from the $\varepsilon_p$ to 2 $\varepsilon_p$. Finally, the sum of these two parameters is equal to the toughness of the asphalt mortar mix. The ITT results are the average of three replicates of each asphalt mortar mix.

*2.3.2 Statistical analysis*

In order to support the discussion of the results, statistical analysis was carried out to determine the statistical significance of the mortar mixes. The normality of data was initially checked through the Anderson-Darling test as well as the homogeneity of variance using the Levene's test. In those cases where data are normally distributed and with homogeneity of variance 2 sample-t parametric test was performed. Otherwise, Mann Whitney U non-parametric test was applied. The statistical analysis was carried out with a confidence interval of 95%. In that sense, the significance level is measured based on the p-values obtained from the statistic tests. In consequence, p-values lower than 0.05 means that the tested hypothesis is significant.

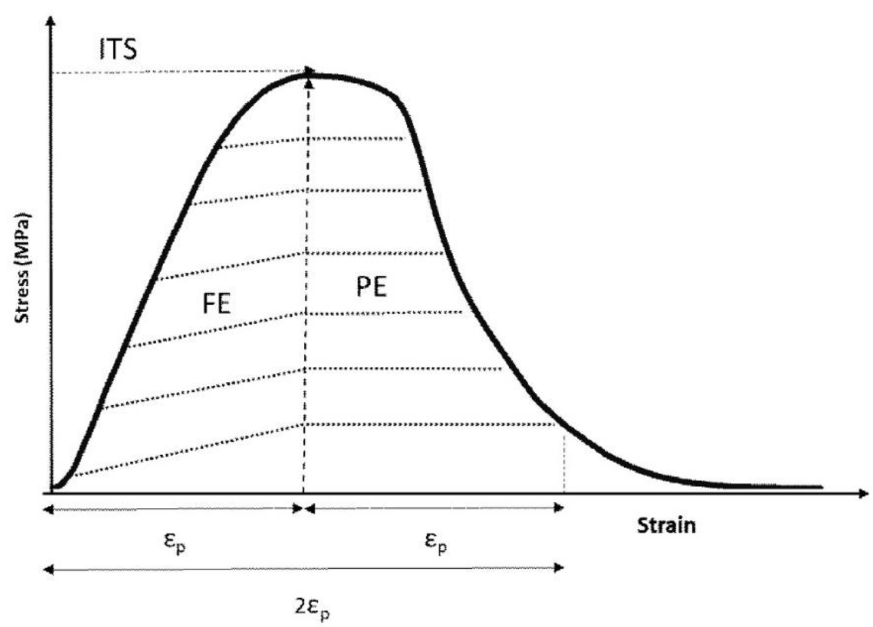



*Figure 4. Fracture parameters obtained from the ITT. Indirect tensile strength (ITS), Fracture Energy (FE), Post-cracking Energy (PE)*

## 3. Test results and analysis

Figure 5 shows the average stress-strain curves of the fiber reinforced asphalt mortar (FRAM) compared to the reference asphalt mortar without fibers at 15°C. From the graphs, it can be observed that asphalt mortar at this temperature starts with an elastic component followed by a plastic component until the peak load is reached. Although bituminous materials have a viscous component, the high loading rate contributes to minimize the potential of creep of the mortar and, therefore, behaves like an elastic-plastic material.

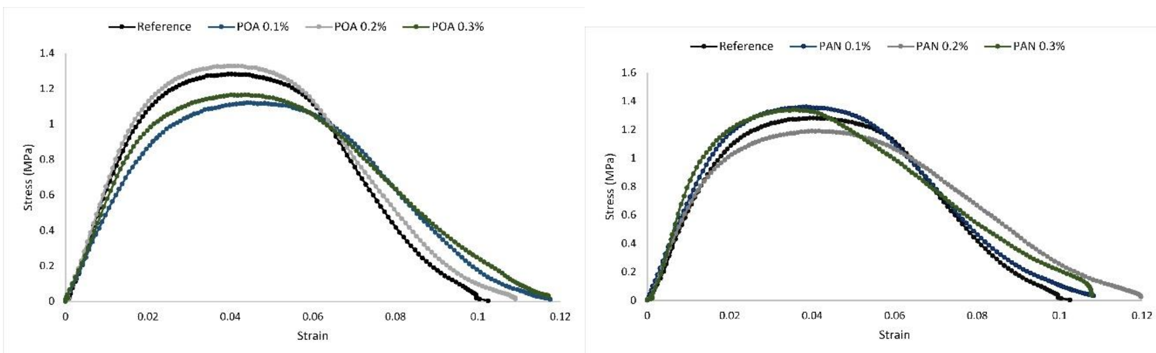



*Figure 5. Average stress-strain curves of FRAM at 15°C. (left) FRAM with POA fibers. (right) FRAM with PAN fibers*

The mean results of the obtained ITS and fracture parameters of FRAM at 15°C are displayed in Figure 6. The error bars indicate the standard deviation from the mean. The ITS value is a good indicator of the mortar mixture cohesion strength. Likewise, ITS and FE can be considered suitable measures of cracking resistance prior to the development of major cracks [72]. Based on the results, the addition of fibers could improve the ITS to some extent. Slight improvement of 3.10% can be observed adding 0.2%wt of POA fibers when compared to non-reinforce mortar mix. Concerning PAN fibers, adding 0.1% and 0.3%wt increased the ITS in 5.43% and 4.65%, respectively. In order to see the statistical differences with respect the reference mortar, two sample t-tests were performed since all data are normally distributed and have homogeneity of variance. The statistical significances of FRAM in relation to reference are shown in Table 5 in terms of p-value. It can be concluded that these improvements were not significant.

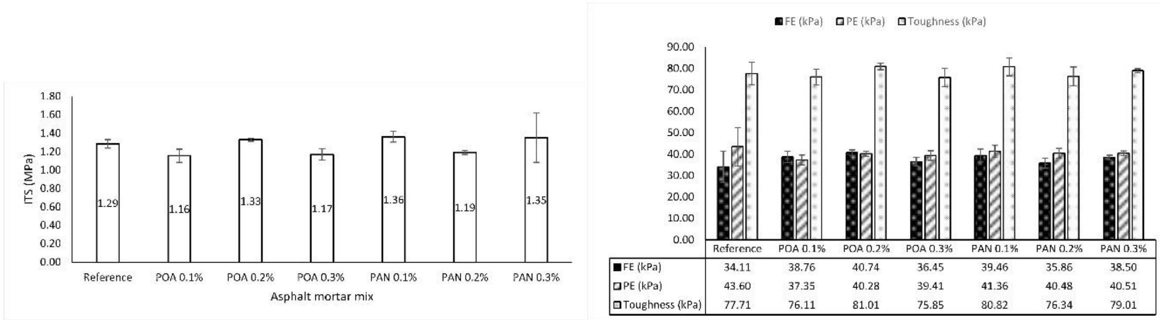



*Figure 6. ITS and fracture parameters results at 15°C. (left) ITS values (right) Fracture parameters*

*Table 5. Statistical differences of ITS and fracture parameters at 15°C*

| | ITS (MPa) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Reference | POA 0.1 | POA 0.2 | POA 0.3 | PAN 0.1 | PAN 0.2 | PAN 0.3 |
| p - value | - | 0.07 | 0.255 | 0.08 | 0.175 | 0.093 | 0.71 |
| Significance | - | NO | NO | NO | NO | NO | NO |
| | FE (kPa) | | | | | | |
| p - value | - | 0.413 | 0.267 | 0.652 | 0.367 | 0.735 | 0.418 |
| Significance | - | NO | NO | NO | NO | NO | NO |
| | PE (kPa) | | | | | | |
| p - value | - | 0.364 | 0.59 | 0.515 | 0.72 | 0.62 | 0.615 |
| Significance | - | NO | NO | NO | NO | NO | NO |
| | Toughness (kPa) | | | | | | |
| p - value | - | 0.691 | 0.40 | 0.663 | 0.477 | 0.75 | 0.71 |
| Significance | - | NO | NO | NO | NO | NO | NO |

Regarding FE results, it can be observed that the amount of energy required for the initiation of the cracking increases when fibers are added. Although it did not present statistical differences, the behaviors of the FRAMs were different showing a tendency to increase the FE in all cases. This initial phase (Figure 5) comprises two different zones: the first one, that consists on an elastic zone and the second one, which is an inelastic zone where micro-cracks are generated until the maximum load capacity of the specimen. Fibers within the asphalt matrix helped to increase the cohesive bridges and to mitigate the formation of micro-cracks. On the other hand, PE that is associated with the amount of energy to resist the crack propagation was found lower for the samples with fibers addition. This phenomenon could be due to the fact that in the FRAM a major crack was developed after the peak strength, while in the reference mortar, minor cracks were developed and then were merged. Nevertheless, similar to FE responses, statistical differences were not observed.

Similar effect can be observed in Figure 7 where the different stress-strain curves at 0°C are shown. Again, it can be said that the behavior is equally elastic-plastic. In this sense, at both temperatures (15°C and 0°C), two types of failure were mainly observed on FRAM. A so-called punching failure due to the loading strips and certain tensile break lines that occur in the middle of the specimen. Figure 8 shows a typical type of failure observed at 15°C and 0°C. Although the fracture behavior of the mortar could be considered similar at both temperatures, there is an increment in the ITS results as well as fracture parameters at 0°C. As suggested by Son et al. [137], the behavior of bituminous materials is strictly linked to changes in temperature. At low temperatures the mortar mixture becomes stiffer although it retains its ductile properties. The ITS values and fracture parameters obtained from the tests carried out at 0°C are shown in Figure 9. Based on the results, adding 0.3% of POA fibers and 0.3% of PAN fibers exhibited an improvement of 2.07% and 4.83%, respectively. However, these were not significant with respect to reference mortar mix as shown in Table 6.

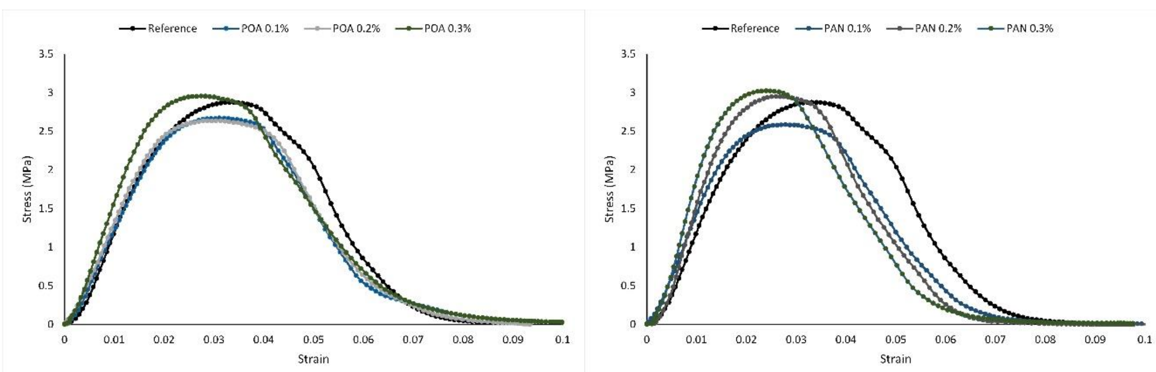



*Figure 7. Average stress-strain curves of FRAM at 0°C. (left) FRAM with POA fibers. (right) FRAM with PAN fibers*

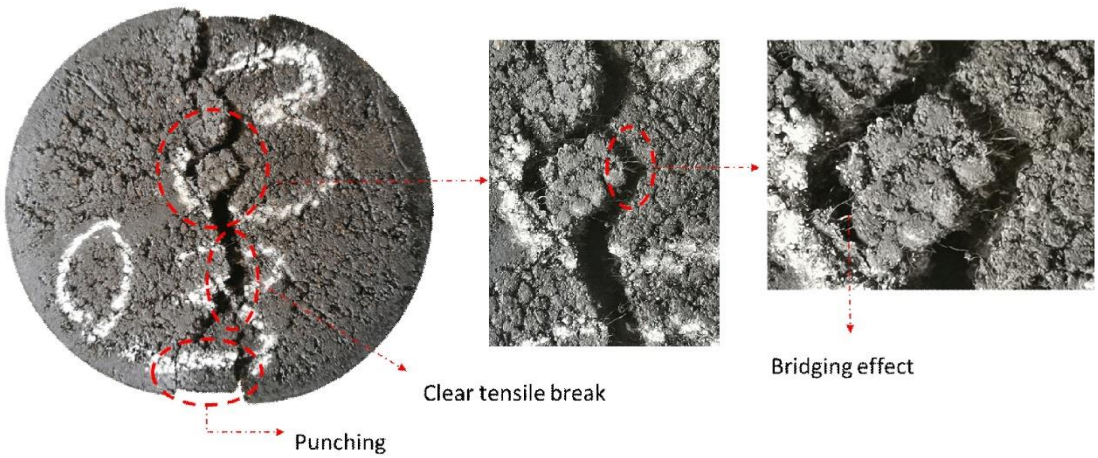



*Figure 8. Failure types observed in FRAM*

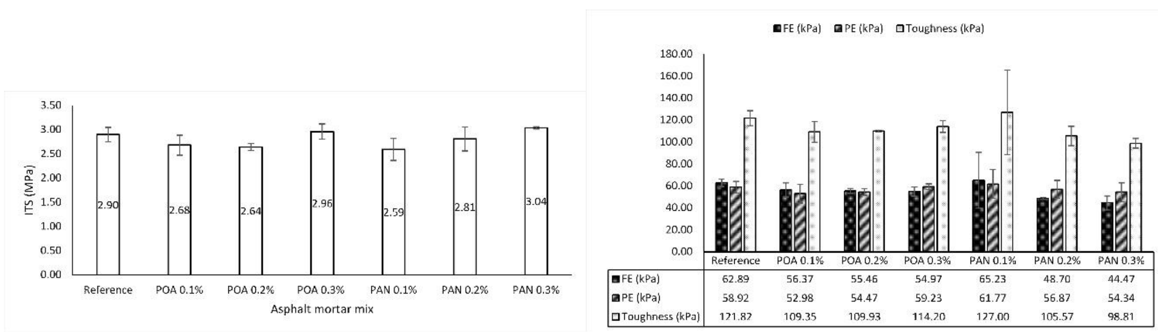



*Figure 9. ITS and fracture parameters results at 0°C. (left) ITS values (right) Fracture parameters*

Concerning fracture parameters, an aspect to remark is that none of the types of fibers, regardless their content, provide a significant positive impact on FE properties at this temperature. Another interesting point to highlight is that FRAM which exhibited high values of ITS evidenced low values of FE at this temperature. This fact could be related to a stiffness increase in the elastic zone consequence of the fiber. However, the strain at failure occurs faster for the FRAM compared to the reference material, reducing the amount of energy. On the other hand, adding 0.1% of PAN fibers slightly improved the FE, but displayed the lowest value in terms of ITS. Concerning PE, there is not a clear trend between the results and the type and content of fibers. Nonetheless, in line with FE results, the highest value of PE was obtained adding 0.1% of PAN fibers.

*Table 6. Statistical differences of ITS and fracture parameters at 0°C*

| | ITS (MPa) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Reference | POA 0.1 | POA 0.2 | POA 0.3 | PAN 0.1 | PAN 0.2 | PAN 0.3 |
| p - value | - | 0.22 | 0.043 | 0.616 | 0.136 | 0.623 | 0.168 |
| Significance | - | NO | YES | NO | NO | NO | NO |
| | FE (kPa) | | | | | | |
| p - value | - | 0.249 | 0.024 | 0.075 | 0.889 | 0.004 | 0.044 |
| Significance | - | NO | YES | NO | NO | YES | YES |
| | PE (kPa) | | | | | | |
| p - value | - | 0.366 | 0.23 | 0.924 | 0.756 | 0.728 | 0.471 |
| Significance | - | NO | NO | NO | NO | NO | NO |
| | Toughness (kPa) | | | | | | |
| p - value | - | 0.147 | 0.04 | 0.171 | 0.839 | 0.076 | 0.005 |
| Significance | - | NO | YES | NO | NO | NO | YES |

Toughness, which is the sum of FE and PE, serves as an indicator to describe the behavior of the material. Overall, the lower the toughness, the lower the ductility of the material [125]. FRAM with 0.3% of PAN fibers showed the lowest value respect this property and yet obtained the highest value of ITS. Based on the above, it could be hypothesized that fibers within the mortar stiffen the matrix but reduce the total amount of energy that the mix can absorb.

Finally, it was found that at -15°C the behavior of the mortar mixes was observed as elastic-brittle, what means that when the tensile strength reaches its maximum value, the specimens break instantly, and the stress drops to zero after the first cracking. Similar observation was also reported by Park et al. [72], who studied the fracture properties of AC mixtures at low temperatures (-20°C). Once the specimen has achieved the maximum strength, it is broken apart in two pieces in a brittle mode. In this case, the post-cracking energy is negligible and, therefore, FE and ITS are the only parameters that can be calculated. Figure 10 shows the average stress-strain curves obtained at the lowest temperature evaluated in this study. The failure type observed was a clear tensile break, where the specimens broke along the diametrical line and there was not an observation of a punching failure closer to the loading strips as shown in Figure 11. Inside the mortar matrix, fibers could interlock with the fine aggregates acting like connections and cohesive bridges preventing the formation of micro-cracks. Moreover, since the mortar becomes more rigid and is behaving as a brittle solid at low temperature, fibers get in tension mode more easily contributing to support the tensile loads generated in the mortar. The ITS results and FE properties are displayed in Figure 12. Concerning to fiber reinforcement, at -15 °C, adding fibers to the mortar increases ITS values (see Figure 12a) in comparison to the samples without fibers (reference). Analyzing the influence of fiber content on the results, it can be observed that as the fiber content increases, the ITS values also increase. Concerning POA fibers, the best improvement was observed in the samples that incorporate 0.3% of POA fibers. This improvement is statistically significant in relation to the reference mortar (Table 7). Moreover, improvements of 16.50% and 18.04% were obtained by adding 0.1% and 0.2% of POA fibers. However, these differences proved not to be statistically significant. With regards to PAN fibers, FRAM reinforced with 0.2% and 0.3% of PAN fibers exhibited an improvement of 32.73% and 31.44%, respectively, respect the reference mortar. However, only the addition of 0.3% of PAN fibers proved to be statistically significant. The FE properties were also influenced by the fiber dosing. In this sense, improvements of 25.76% and 21.79% were obtained adding 0.3% of POA and PAN fibers, respectively. These results were also found statistically significant as shown in Table 7. In the other cases, although there were no significant differences, there is a clear tendency where higher fiber content, the better the fracture energy properties were observed. The relationship between the temperature and the different responses are displayed in Figure 13. Only ITS and FE were taken in consideration since at -15°C the other responses cannot be obtained, and hence not enough points are disposed to find a clear trend. In relation to ITS values, linear relationships of mean ITS and temperature to the different FRAM were found. In all cases the linear correlation coefficient $R^2$ is higher than 0.95 indicating that ITS values of the mortar depend linearly from the temperature. From the results, it can also be observed that, at 15°C, the effect of fibers is not significant. However, at lower temperatures the effect of fibers tends to be more important. It can be clearly concluded that the fibers impact on the asphalt mortar depends strongly on the behavior of the mix, what is closely linked with the temperature. Concerning FE results, this parameter increases from 15°C to 0°C but, then goes back to lower values at -15°C. This happens in parallel to the behavior of response since the mortar changes from an elastic-plastic to an elastic-brittle material. Concerning mortars modified with fibers, significant effects are observed at -15°C. However, the reinforcement effect of fibers is negligible at higher temperatures. The reason behind this response could be related to the mortar nature which is becoming more rigid in the elastic-plastic range. After analyzing the results, it could be hypothesized that the tensile strength is governed by the binder-aggregate interaction and the effect of fibers is reduced.

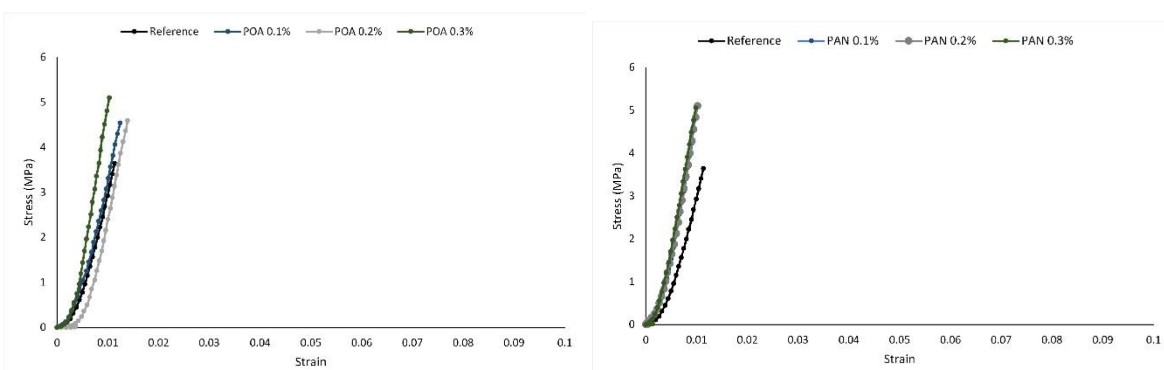



*Figure 10. Average stress-strain curves of FRAM at -15°C. (left) FRAM with POA fibers. (right) FRAM with PAN fibers*

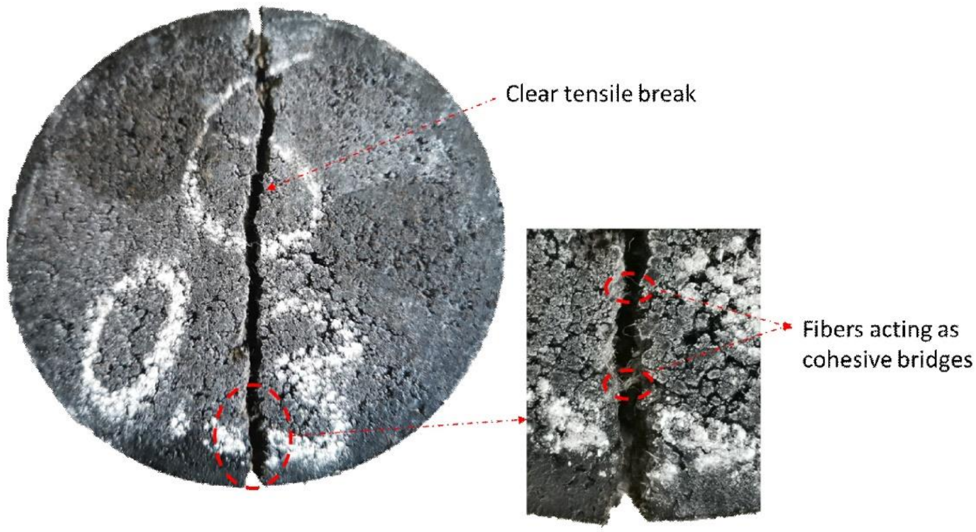



*Figure 11. Type of failure observed in FRAM at -15°C*

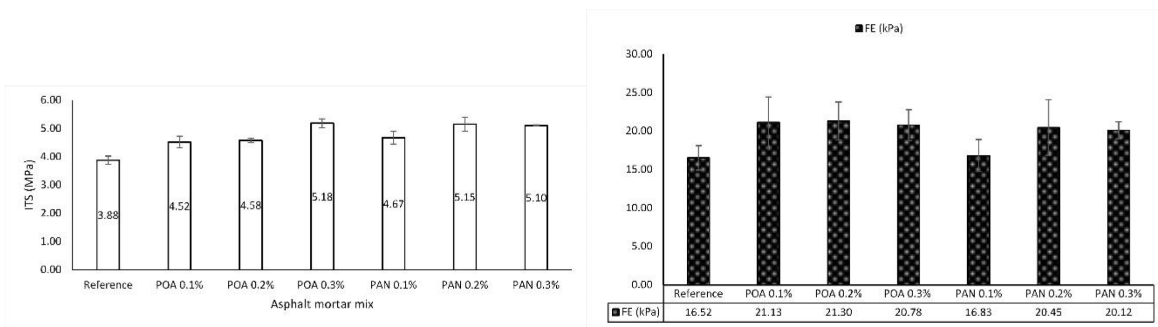



*Figure 12. ITS and fracture parameters results at -15°C. (left) ITS values (right) Fracture parameters*

*Table 7. Statistical differences of ITS and fracture parameters at -15°C*

| | ITS (MPa) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Reference | POA 0.1 | POA 0.2 | POA 0.3 | PAN 0.1 | PAN 0.2 | PAN 0.3 |
| p - value | - | 0.356 | 0.146 | 0.042 | 0.147 | 0.079 | 0.021 |
| Significance | - | NO | NO | YES | NO | NO | YES |
| | FE (kPa) | | | | | | |
| p - value | - | 0.161 | 0.067 | 0.045 | 0.849 | 0.226 | 0.048 |
| Significance | - | NO | NO | YES | NO | NO | YES |

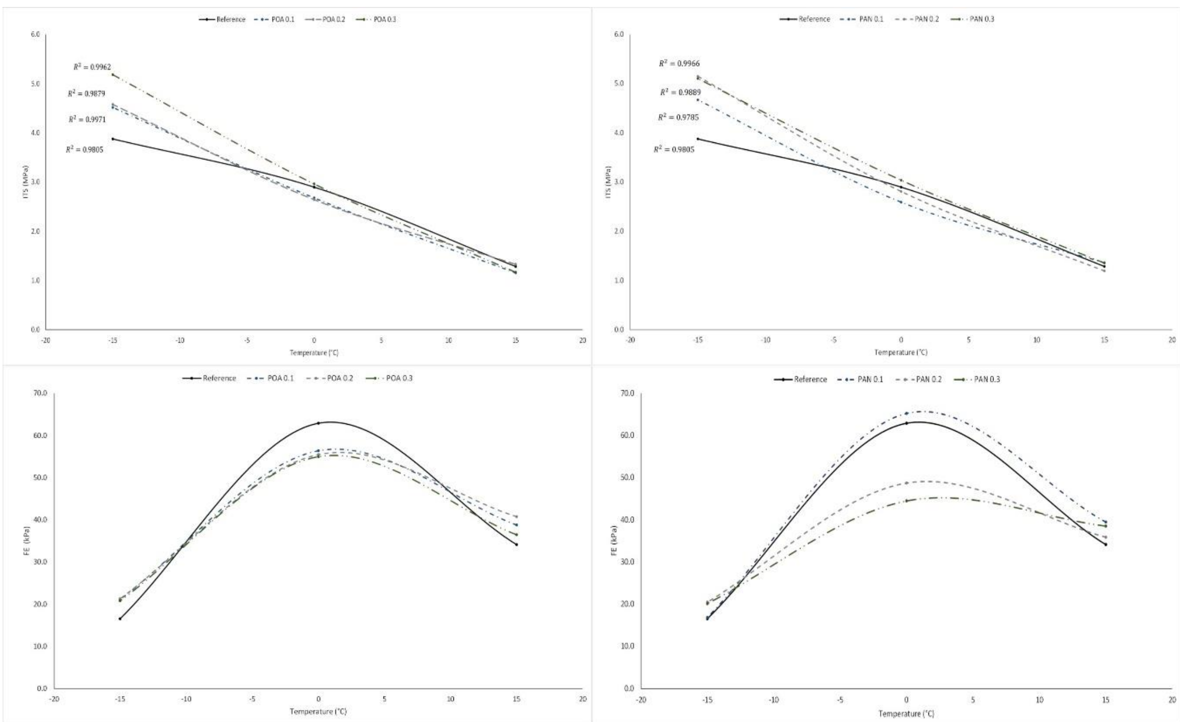



*Figure 13. Relationship between the temperature of the test and ITS and FE responses for both types of fibers*

## 4. Conclusions

In the current research, an experimental laboratory testing work on asphalt mortar mixes reinforced with synthetic fibers has been carried out. The aim of this study was to investigate the effect of the fiber type, fiber content and testing temperature on mechanical (i.e. tensile strength) and fracture properties through indirect tensile tests. A reference mortar (no fibers addition) and fiber reinforced asphalt mortars with two types of fibers, polyolefin-aramid (POA) fibers and polyacrylonitrile (PAN) fibers) and three fiber contents (0.1wt%; 0.2wt% and 0.3wt %) were tested at three different temperatures (15°C, 0°C and -15°C). According to the experimental results, the following conclusions can be drawn:

- At 15°C no significant effects were observed in any of the parameters measured. Minor improvements were obtained by adding 0.2% POA fibers and 0.1% and 0.3% of PAN fibers in terms of ITS values. The addition of fibers contributes to increase the fracture energy properties of the mortar despite not being significant. However, the post-cracking energy is reduced when fibers were added.
- At 0°C there were no statistical differences among all mortar designs. Nonetheless, minor improvements in relation to ITS values were observed by adding 0.3% of POA fibers and 0.3% of PAN fibers. Concerning fracture parameters, FE is reduced for FRAMs with both types of fibers. In addition, 0.1% of PAN fibers exhibited the lowest value in terms of ITS but the highest value in terms of energy properties.
- At -15°C, due to changes in the behavior of mortar, only ITS and FE property could be measured. Regarding ITS, statistical differences were observed by adding 0.3% POA fibers and 0.3% PAN fibers. Moreover, the addition of fibers contributed to increase the FE with a greater influence in the case of POA fibers.
- Concerning the behavior of mortar mixes, at 15°C and 0°C the behavior observed was elastic-plastic. At 0°C the behavior of the mix turns to be stiffer although it retains ductile properties and, therefore, ITS and fracture parameters are higher. At -15°C the behavior of the mix turned to be elastic-brittle. At this temperature, the mortar becomes stiffer and ITS value increases while FE abruptly decreases.
- Concerning the type of failure, at 15°C and 0°C two types of failures were observed. A crushing zone closer to the loading strips and tensile breaks in the middle of the specimen. At -15°C the type of failure observed on FRAM was a clear tensile break along the diametrical line.
- As future research line, evaluate other control factors such as binder content, voids content and monotonic loading speed is also recommended in fiber reinforced asphalt mortars. The application of dynamic tests as fatigue cracking could be also considered.

## Acknowledgements

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## 4.3 Article 3. Multi-Response Optimization of Porous Asphalt Mixtures Reinforced with Aramid and Polyolefin fibers employing the CRITIC-TOPSIS Based on Taguchi Methodology

### *4.3.1 Basic information and impact factor concerning article 3*

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*Figure 11 Authors and impact factor regarding article 3*

*4.3.2 Transcription of article 3*

# Multi-response optimization of porous asphalt mixtures reinforced with aramid and polyolefin fibers employing the CRITIC-TOPSIS based on Taguchi methodology

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**Abstract**

For the optimum design of a Porous Asphalt (PA) mixture, different requirements in terms of functionality and durability have to be fulfilled. In this research, the influence of different control factors such as binder type, fiber content, and binder content were statistically investigated in terms of multiple responses such as total air voids, interconnected air voids, particle loss in dry conditions, particle loss in wet conditions, and binder drainage. The experiments were conducted based on a Taguchi L18 orthogonal array. The best parametric combination per each response was analyzed through signal to noise ratio values. Multiple regression models were employed to predict the responses of the experiments. As more than one response is obtained, a multi-objective optimization was performed by employing Criteria Importance through Criteria Inter-Correlation (CRITIC) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methodologies. The weights for the selection of the functional and mechanical performance criteria were derived from the CRITIC approach, whereas the ranking of the different experiments was obtained through the TOPSIS technique. According to the CRITIC-TOPSIS based Taguchi methodology, the optimal multiple-response was obtained for a polymer-modified binder (PMB) with fiber and binder contents of 0.15% and 5.0%, respectively. In addition, good results were obtained when using a conventional 50/70 penetration grade binder with a 5.0% binder content and 0.05% fiber content.

**Keywords:** porous asphalt; fibers; Taguchi; Critic; Topsis.

## 1. Introduction

In the last 20 years the use of porous asphalt (PA) mixtures in wearing courses has increased considerably around the world due to the multiple advantages that this type of hot mix asphalt (HMA) offers [11]. This mixture is characterized by the predominant use of high quality open-graded crushed coarse aggregates along with a small amount of fine aggregates in order to obtain a stone-on-stone contact and high interconnected air voids [3]. As a result, the granular skeleton formed is capable of resisting permanent deformation, whereas the connected voids allow the water to be evacuated from the surface of the pavement. Besides, when the water is removed, the splash and spray is minimized as well as the aquaplaning effect [138]. Other advantages include the improvement of the pavement friction, especially in wet conditions, mist attenuation on rainy days, mitigation of the urban heat island effect and enhancement of the surface reflectivity, especially in nighttime [16,139].

The porous structure of the PA mixture also contributes to mitigate the noise generated by the traffic loads [140]. In fact, porous asphalt pavements are today the most widely used pavements worldwide when it comes to the reduction of the traffic noise [140–143]. As suggested by other researchers [140,144,145], the connected porous structure helps to dissipate the sound energy whereas the surface pores and the macrotexture contribute to limit noise generation phenomena (i.e. air pumping or air sucking) in the tire-road contact.

Despite their multiple benefits, the high voids content makes the open graded mixtures prone to suffer raveling [139], which can be defined as the loss of aggregate on the top of the surface during the service life of pavement structure [85]. Moreover, due to their high porosity, a lower mortar content is present in PA mixtures when compared to dense graded mixtures and hence, the adhesion between binder and aggregates is worse. Similarly, as the mixture is highly exposed to the air and the wet conditions of the environment, the binder film is susceptible to oxidation and consequently, the strength of the binder-aggregate bonding is affected severely.

In order to improve the durability of the mix, several agencies around the world have employed different admixtures. Open graded friction course (OGFC) mixtures, as they are called in the United States (US), began to be used in the 1970s in response to the Federal Highway Administration program (FHWA) to increase the frictional resistance on surface courses [146]. However, the applicability of OGFC mixtures was relatively low until the 1980s, when the mix designs were improved by using polymer modified binder (PMB) and fiber additives to stabilize the mix and prevent the drain down [147]. Similarly, China began to apply porous asphalt courses in the 1980s. Nowadays, high-viscosity modified asphalt binder are used [139] for that purpose. Regarding Europe, Spain was one of the first countries that focused on the study of PA mixtures [11,148]. In the 1980s, the University of Cantabria carried out a study based on developing a design and control methodology [148]. As a result, the Cantabro test to evaluate the particle loss [22,23] was developed and started to form part of the European standard methods (EN 12697 -17). Also during that period, the employment of porous asphalt mixtures as wearing course in The Netherlands became very popular and widely used not only due to the road safety aspects, but also because of the potential to mitigate the noise pollution from the traffic loads [20]. In this country, the modified binders are only employed for special purposes [11]. Although the general tendency in Europe is towards the use of modified binders as they possess higher flexibility and lead to thicker binder films with no binder drainage [149], other researchers suggest that there is a lack of information proving the higher durability of the PA mixtures using PMB [150]. In addition, although PMB brings ductility to the mixture due to the elastic recovery properties and let the binder content to be increased [151], the use of additives such as fibers has attracted much attention as it could prevent the drain down of binder while improving the mix durability [77].

Several types of fibers have been used in hot asphalt mixtures: cellulose, polyester, carbon, basalt, glass, polyacrylonitrile, nylon or aramid, among others [13,32,35,44,46,152,153]. Asphalt concrete (AC) is the type of mixture where the use of fibers as a reinforcement has been extensively used [13]. For example, Tapkin et al. [154] reported 20% higher Marshall stability values when adding 0.3% polypropylene fibers by weight of aggregates. Xu et al. [42] reported that polymer fibers such as polyester and polyacrylonitrile have greater effects on the resistance to permanent deformation, fatigue life and indirect tensile strength in comparison to lignin and asbestos fibers. Similarly, the authors suggested an optimum fiber content of 0.35% by mass of mixture in order to achieve the best performance outputs with respect to rutting resistance and indirect tensile strength. Takaikaew et al. [155] performed a detailed laboratory experimental plan including Marshall stability, indirect tensile strength and stiffness modulus, resilient modulus, dynamic creep, indirect tensile fatigue and rutting resistance tests on asphalt concrete mixtures with different types of binder (conventional, rubber modified asphalt and polymer modified asphalt) and polyolefin/aramid fibers. According to the results, the addition of 0.05% of fibers by weight of mixtures improved considerably the mechanical performance of the mixture regardless of the asphalt binder type. Similarly, Kaloush et al. [71] reported that polypropylene/aramid fibers notably enhanced the mixture's performance against rutting resistance, fatigue and thermal cracking. Regarding the PA mixtures, cellulose fibers have become the most common stabilizer additive [1,30,77,93]. Lopes et al. [77] evaluated the performance of porous asphalt mixtures having cellulose fibers and polymer modified binder. The authors concluded that cellulose fibers enables the increase of the binder content by providing proper retention, thus resulting in greater aggregates coating and improved durability of the mix. Similar results were obtained by Valeri et al. [1], who assessed the durability of a PA mixture incorporating cellulose fibers but using a conventional 50/70 penetration grade bitumen instead of a modified binder.

While good mechanical performance has been observed when using polyolefin/aramid (POA) fibers in asphalt concrete mixes, the use of this fiber type has not been tested in PA mixtures. Additionally, many studies have focused on the effects of fibers in only one category of bitumen, either a conventional binder or a polymer modified binder, but not both. Likewise, the use of fibers has only been valued as a stabilizer additive and not as a reinforcement additive. Besides, the design of a porous asphalt mixture reinforced with fibers requires optimum binder and fiber contents that guarantees: an adequate resistance to raveling and to the harmful action of the water, the absence of binder drainage, and a big enough air voids content as to enable the water to be removed from the surface and reduce the rolling noise.

In order to comply with the aforementioned, POA fibers are here presented as an alternative additive for the stabilization of the mixtures and the improvement of their raveling resistance with no harm of their optimal functionality. Furthermore, the novel CRITIC – TOPSIS based on Taguchi optimization technique is proposed for the design of porous asphalt mixtures with the aim of finding out the most relevant input parameters from the standpoint of their functionality and durability. In other words, the relationship between type of binder, fiber content and binder content are considered the main control factors to estimate the optimal solution for the mixture. As dependent variables or responses, total air voids, interconnected air voids, raveling resistance in dry conditions, raveling resistance in wet conditions and binder drain down are considered.

The paper begins with an introduction section where the literature review of previous related research works, scope and objectives of this study are referred. This section is followed by a detailed explanation of the CRITIC – TOPSIS based on Taguchi novel technique here employed. Materials and research methods are thoroughly described in the third section, including material properties, sample preparation and experimental testing plan. Results and discussion in section four describes main findings and includes the statistical analysis performed and the different regression models aimed at predicting the response values. The transformation of the multi-response into a single response through the CRITIC – TOPSIS approach is also described. Finally, the main conclusions are drawn in the last section.

## 2. Experimental design

### 2.1 Taguchi method

Taguchi method has been considered by other researchers as an efficient statistical method to optimize the analysis of experimental variables and improve the accuracy of the responses [156,157]. Additionally, this method estimates the contribution of individual control factors that influence the quality of a design process or optimum mix [158]. Although initially developed to improve the quality of manufactured products, its use was extended to the civil engineering field [55,56,159,160].

In this study, the design of experiments was carried out according to the Taguchi $L_{18}$ full factorial orthogonal array ($2^1$ X $3^2$) in order to investigate the relationship between different binder and fiber contents for different types of binders. Their effects on the durability and functionality of the PA mixture were also analyzed.

The signal to noise ratio (SNR) is a measure that enables the determination of significant input parameters by assessing the minimum variance [161]. In other words, higher values of SNR suggest more relevance of the input parameters on the responses. In general SNR can be specified in three different scenarios namely the *smaller-the-better*, the *larger-the-better* and the *nominal-the-better*. In this research, the smaller-the-better scenario is employed to minimize the loss of particles in dry and wet conditions as well as the binder drainage, while the larger-the-better is employed to maximize the total air and interconnected air voids. The equations used for calculating the *smaller-the-better* and the *larger-the-better* scenarios are (1) and (2), respectively:

$$\frac{S}{N} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

$$\frac{S}{N} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right) \tag{2}$$

Where $y_i$ corresponds to the experimental result at the *i*^th^ experiment and *n* refers to the total number of experiments [162]. Binder type (50/70, PMB), Fiber content (FC) and binder content (BC) were selected as control input parameters and their corresponding levels were determined as shown in Table 1. Thus, 18 sets of experiments with three replicates per design were carried out. Table 2 presents the L18 mixed orthogonal array for conducting the design of experiments.

*Table 1. Input parameters and their corresponding levels*

| Input Parameter | Notation | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| Binder type | BT | 50/70 | PMB | - |
| Fiber content (%) | FC | 0.00 | 0.05 | 0.15 |
| Binder content (%) | BC | 4.5 | 5.0 | 5.5 |

*Table 2. Full factorial design with Taguchi orthogonal array L18*

| Design | Binder Type | Fiber Content | Binder Content |
|---|---|---|---|
| 1 | 50/70 | 0.00 | 4.50 |
| 2 | 50/70 | 0.00 | 5.00 |
| 3 | 50/70 | 0.00 | 5.50 |
| 4 | 50/70 | 0.05 | 4.50 |
| 5 | 50/70 | 0.05 | 5.00 |
| 6 | 50/70 | 0.05 | 5.50 |
| 7 | 50/70 | 0.15 | 4.50 |
| 8 | 50/70 | 0.15 | 5.00 |
| 9 | 50/70 | 0.15 | 5.50 |
| 10 | PMB45/80-65 | 0.00 | 4.50 |
| 11 | PMB45/80-65 | 0.00 | 5.00 |
| 12 | PMB45/80-65 | 0.00 | 5.50 |
| 13 | PMB45/80-65 | 0.05 | 4.50 |
| 14 | PMB45/80-65 | 0.05 | 5.00 |
| 15 | PMB45/80-65 | 0.05 | 5.50 |
| 16 | PMB45/80-65 | 0.15 | 4.50 |
| 17 | PMB45/80-65 | 0.15 | 5.00 |
| 18 | PMB45/80-65 | 0.15 | 5.50 |

### 2.1 Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

The TOPSIS approach is considered one of the most popular mathematical models to determine the optimal solution of a multi-criteria decision-making analysis (MCDM). In civil engineering, TOPSIS is considered the second most popular multi-criteria technique right after the analytic hierarchy process (AHP) [61]. Zhang et al. [163] evaluated public transport priority performance by applying TOPSIS. Jato et al. [64] implemented an hybrid decision support model incorporating TOPSIS to rank different wearing courses in highly trafficked European roads. On another study, Egle and Jurgita [164] ranked many alternatives in order to improve the daylighting in vernacular buildings.

Unlike in previous investigations, in this research TOPSIS was adopted to transform the multi response problem resulting from the design of experiments into a single response problem, thus giving the best set of alternatives. Total air voids, interconnected air voids, particle loss in dry conditions, particle loss under the influence of water and binder drainage were considered the quality criteria required for TOPSIS to set those reinforced porous asphalt alternatives.

The algorithm of TOPSIS is structured on the basis of the concept of distance of the alternatives proposed to positive and negative ideal solutions [69]. In other words, a positive ideal solution (PIS) refers to an alternative that maximizes the benefit responses and minimizes the cost responses, whereas a negative ideal solution (NIS) is considered the least preferred solution as it minimizes the benefit responses and maximizes the cost responses. Therefore, the best alternative would be the one closest to the positive ideal solution and farthest from the negative ideal solution [165].

Following, the steps involved in the TOPSIS technique are presented.

**Step 1.** Build the decision-making matrix, with alternatives representing input parameters from the manufacturing of asphalt mixes and criteria (or attributes) corresponding to the responses generated by the experimental results. According to this, the matrix can be expressed as follows:

$$D = \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1j} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2j} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \cdots & \cdots & \vdots \\ p_{i1} & p_{i2} & \vdots & p_{ij} & \cdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mj} & \cdots & p_{mn} \end{pmatrix} \tag{3}$$

Where $p_{ij}$ corresponds to the performance of the $i^{th}$ experimental alternative with respect to the $j^{th}$ attribute.

**Step 2.** Normalize the decision matrix as follows.

$$r_{ij} = \frac{p_{ij}}{\sqrt{\sum_{i=1}^{m} p_{ij}^2}}\ ,\ \ i = 1,2,3,\dots,m\ \ \ j = 1,2,3,\dots,n \tag{4}$$

Where $r_{ij}$ refers to the normalized rating of the attribute. In this step, various attribute dimensions are transformed into non-dimensional attributes in order to make possible the comparisons across the responses.

**Step 3.** Calculate the weighted normalized decision matrix as follows.

$$[v_{ij}] = [w_j r_{ij}] \tag{5}$$

Where $[v_{ij}]$ corresponds to the weighted normalized matrix and $w_j$ refers to the weightage of the *j^th^* criterion. The following should be fulfilled.

$$\sum_{j=1}^{n} w_j = 1 \tag{6}$$

**Step 4.** Calculate the positive (PIS) and negative ideal solutions (NIS). Positive ideal solution is determined as follows.

$$V^{+} = (v_1^+, v_2^+, v_3^+, \dots v_n^+) = \{(max\ v_{ij} | \mathrm{j} \in \mathrm{I}), (min\ v_{ij} | \mathrm{j} \in \mathrm{J})\} \tag{7}$$

Negative ideal solution is determined as follows.

$$V^{-} = (v_1^-, v_2^-, v_3^-, \dots v_n^-) = \{(min\ v_{ij} | \mathrm{j} \in \mathrm{I}), (max\ v_{ij} | \mathrm{j} \in \mathrm{J})\} \tag{8}$$

Where I is related with beneficial criteria and J with non-beneficial criteria; $i = 1,2, \dots, m$; and $j = 1,2, . . , n$.

**Step 5.** Determine the distance of each alternative from positive and negative ideal solutions.

Distance to the positive ideal solution is as follows.

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2}, i = 1,2 \dots, m \tag{9}$$

Distance to the negative ideal solution is as follows.

$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2}, i = 1,2 \dots, m \tag{10}$$

**Step 6.** Calculate the relative closeness from each alternative to the positive ideal solution.

$$C_c^* = \frac{d_i^-}{d_i^- + d_i^+} \tag{11}$$

Where $C_c^*$ is the relative closeness coefficient; $i = 1,2,\ldots,m;\ 0 \leq C_c^* \leq 1.$

**Step 7.** Rank the different alternatives and select the option with $C_c^*$ closest to 1.

### 2.2 Criteria Importance Through Inter-criteria Correlation (CRITIC)

When multiple responses are involved in a decision-making problem, prioritize one criterion against the others turns out to be a complex task due to the nature of subjectivity. To avoid that, the CRITIC methodology developed by Diakoulaki et al. [66] arose as an innovative approach in the category of Multi-Objective Decision Making (MODM) methods. Based on this methodology, weights of relative importance can be determined in an objective manner as correlated to certain criteria [166]. This has been applied in different areas of the engineering as a decision support system, including manufacturing processes, supply chain and risk management [60,167]. As for the combination of design of experiments and multi-criteria decision-making analysis, no research has been carried out so far, being responses commonly assigned based on criteria with equal weightage [168]. Therefore, this research seeks to employ a novel approach by means of using a technique that does not require human participation and helps to automatize decision making, along with the TOPSIS method, which enable going from a multi-response problem to an optimized single response. Following, a brief description of the CRITIC technique is presented as based on [66].

**Step 1.** Define the finite set *A* of *n* alternatives with respect to *m* evaluation criteria as follows:

$$A = \left[a_{ij}\right]_{n*m} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nm} \end{bmatrix} (i = 1,2,\ldots,n \text{ and } j = 1,2,\ldots m) \tag{12}$$

Where $a_{ij}$ represents the response value of the $i^{th}$ alternative on the $j^{th}$criterion.

**Step 2.** Normalize the decision matrix using the following equation.

$$\bar{a}_{ij} = \frac{a_{ij} - a_j^{worst}}{a_j^{best} - a_j^{worst}} \tag{13}$$

Where $\bar{a}_{ij}$ is the normalized performance value of the $i^{th}$ alternative for the $j^{th}$criterion; $a_j^{best}$ corresponds to the best performance value for $j^{th}$ criterion; and $a_j^{worst}$ is the worst performance value for $j^{th}$ criterion.

**Step 3.** Calculate the standard deviation $\sigma$ of each vector $a_j$, which quantifies the contrast intensity of the corresponding criterion.

**Step 4.** Build the symmetric $m$ * $m$ matrix with the generic element $r_{jk}$, which corresponds to the linear correlation coefficient between vectors $a_j$ and $a_k$.

**Step 5.** Determine with the following formula the measure of the conflict created by criterion *j* with respect to the decision situation defined by the rest of the criteria.

$$\sum_{k=1}^{m} 1 - r_{jk} \tag{14}$$

**Step 6.** Calculate $C_j$, which represents the quantity of information contained in *j*$^{th}$ criterion.

$$C_j = \sigma * \sum_{k=1}^{m} 1 - r_{jk} \tag{15}$$

**Step 7.** Determine the objective weights of the $j^{th}$criterion.

$$W_j = \frac{C_j}{\sum_{k=1}^{m} C_j} \tag{16}$$

## 3. Materials and methods

### 3.1 Materials

In this study, ophite and limestone were used as coarse and fine aggregates respectively, for the manufacturing of the PA mixtures. Limestone was also employed as filler material. The gradation curve corresponds to a PA mixture with nominal maximum aggregate of 16 mm commonly known as PA16 by Spanish specifications [29]. The physical properties and gradation of aggregates can be seen in Table 3 and Figure 1, respectively. As for the bituminous binder, in this research a conventional 50/70 penetration grade bitumen (50/70) and a polymer modified binder (PMB 45/80-65) were used. The main properties of the binders are shown in Table 4.

Regarding the fibers, a blend of polyolefin and aramid synthetic fibers (POA) was used for both improving the durability of the PA mixture and as a stabilizing additive. The density of the blend according to the standard method UNE-EN 1097-6 is 0.947 g/cm$^3$. The main physical properties of the POA fibers and a picture of them can be seen in Table 5 and Figure 2, respectively.

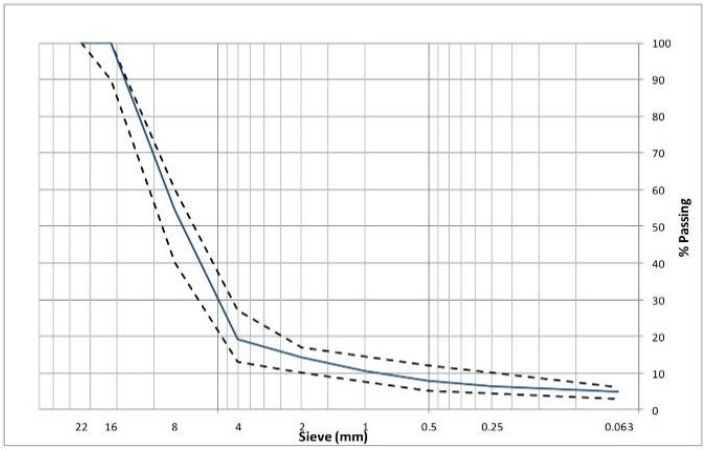



*Figure 1. Gradation curve of the PA16 mixture*

*Table 3. Physical properties of coarse (ophite) and fine (limestone) aggregates*

| Characteristic | Value | Standard | Specification |
|---|---|---|---|
| Coarse Aggregate | | | |
| Specific Weight (g/cm$^3$) | 2.794 | EN 1097-6 | - |
| Water absorption (%) | 0.60 | EN 1097-6 | <1% |
| L.A abrasion (%) | 15 | EN 1097-2 | ≤15% |
| Slab Index (%) | <1% | EN 933-3 | ≤20% |
| Polishing Value | 60 | EN 1097-8 | ≥56 |
| Fine Aggregate | | | |
| Specific Weight (g/cm$^3$) | 2.724 | EN 1097-6 | - |
| Sand Equivalent | 78 | EN 933-8 | >55 |

*Table 4. Main properties of the binders used*

| Binder | Test | Standard Method | Value |
|---|---|---|---|
| 50/70 | Penetration at 25 °C (mm/10) | EN 1426 | 57.00 |
| | Specific Gravity | EN 15326 | 1.04 |
| | Softening point (°C) | EN 1427 | 51.60 |
| | Fraass brittle point (°C) | EN 12593 | −13.00 |
| PMB 45/80-65 | Penetration at 25 °C (mm/10) | EN 1426 | 49.50 |
| | Specific Gravity | EN 15326 | 1.03 |
| | Softening point (°C) | EN 1427 | 72.30 |
| | Fraass fragility point (°C) | EN 12593 | −15.00 |
| | Ductility force at 5 °C (J/cm$^2$) | EN 13589 | 3.11 |
| | Elastic recovery at 25 °C (%) | EN 13398 | 90.00 |

*Table 5. Characteristics of POA fibers*

| Fiber | Aramid | Polyolefin |
|---|---|---|
| Form | Monofilament | Serrated |
| Color | Yellow | Yellow |
| Density (g/cm$^3$) | 1.44 | 0.91 |
| Length (mm) | 19 | 19 |
| Tensile Strength (MPa) | 2758 | 483 |
| Decomposition temperature (°C) | >450 | 157 |
| Acid/Alkali Resistance | Inert | Inert |

*Figure 2. Blend of polyolefin and aramid (POA) fibers*

### 3.2 Manufacturing of the porous asphalt sample

For the manufacturing of the PA samples using conventional 50/70 penetration grade bitumen, coarse and fine aggregates and the filler were first heated for six hours in an oven at 170°C and then thoroughly mixed with the fibers. Afterwards, the binder at 150°C was placed into the mixture and continuously blended until the combination fiber-aggregate was well coated. When the polymer modified binder was used, the aggregates and binder temperatures increased from 170°C to 185°C and from 150°C to 165°C, respectively. Finally, all the test samples were compacted by 50 blows per side according to the EN 12697 – 30.

### 3.3 Laboratory testing plan

In order to optimize the functionality and durability of the PA mixture, total air voids, interconnected air voids, binder drainage and raveling resistance in dry and wet conditions have been considered as porous asphalt quality criteria. Based on the volumetric properties test [169,170], total air voids ($T_{AV}$) and interconnected air voids ($I_{AV}$) were calculated following the Equations (17) and (18), respectively:

$$T_{AV}(\%) = \left(1 - \frac{m}{V * G_{mm}}\right) * 100\% \tag{17}$$

$$I_{AV}(\%) = \frac{V - \frac{m - m_w}{\rho_w}}{V} * 100\% \tag{18}$$

Where $m$ corresponds to the mass of the specimen in the air; $V$ refers to the total volume of the specimen, which is calculated geometrically; $G_{mm}$ is the theoretical maximum specific gravity of the mixture; and $m_w$ is the saturated specimen mass in water.

To assess the durability of the PA mixture in terms of its raveling resistance, the Cantabro loss particle test (EN 12697-17) was carried out. According to this test, the particle loss refers to loss mass of a PA specimen after applying 300 revolutions in the Los Angeles abrasion machine. The particle loss (PL) is calculated as follows:

$$PL\ (\%) = \frac{w_1 - w_2}{w_2} * 100\% \tag{19}$$

Where $w_1$ is the initial weight of the specimen and $w_2$ refers to the final weight of the specimen.

Additionally, the Cantabro test in wet conditions was performed following the Spanish standard method NLT 362/92. Before the test, specimens were conditioned by submerging them in water at 60°C for 24 hours and then exposed to air at 25°C for another 24 hours.

To assess the stability of the mixture, the mesh basket binder drain down test according to the EN 12697 – 18 standard was used. The test consist of quantifying the material lost by drainage after 3h at the test temperature [171]. The binder drainage (BD) in percentage is determined as follows.

$$BD\ (\%) = \frac{m_2 - m_1}{1100 + B} * 100 \tag{20}$$

Where $m_1$ is the initial mass of the tray and foil; $m_2$ refers to the mass of the tray and foil including the drained material; and B corresponds to the initial mass of the binder in the mixture.

The experimental part was developed in the roads laboratory of the University of Cantabria. The structured framework of the multi-objective optimization can be observed in Figure 3.

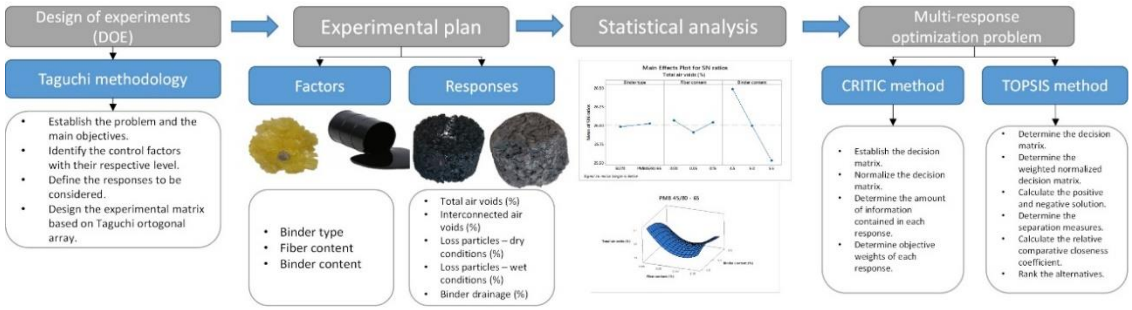


*Figure 3. Structured framework proposed for the multi-objective optimization*

## 4. Results and discussion

### 4.1 Analysis of Signal to noise ratios (SNR) and means on different responses

The different responses obtained by way of the Taguchi L18 orthogonal array can be observed in Table 6. Total and interconnected air voids are considered an important parameters to assess the functionality of the PA mixture in terms of permeability, noise properties and macrotexture [172]. As for the results, mean values of $T_{AV}$ and $I_{AV}$ ranged from 17.50% to 23.20% and 11.20 to 17.26%, respectively (Table 6). Similarly, a direct relation exists between both responses, with a Pearson correlation coefficient of 89%. Following the Taguchi methodology, $T_{AV}$ and $I_{AV}$ were converted into signal-to noise ratio (SNR). The highest values of total and interconnected air voids are very important for improving the functional performance of the mixture. Therefore, the *larger-the-better* equation was employed for calculating the SNR. Figures 4 and 5 show the main effect of the SNR and the means for the total and interconnected air voids, respectively.

A SNR analysis of the effect of the input factors, i.e. binder type (BT), fiber content (FC) and binder content (BC), on the total and interconnected air voids was carried out (Figures 4 and 5). SNR makes it possible to show the optimal levels of the different input factors for the optimal responses ($T_{AV}$ and $I_{AV}$). As an example, the levels and SNR for the factors giving the best $T_{AV}$ response are: level 2 and SNR = 26.03 for BT factor; level 1 and SNR = 26.07 for FC factor; and level 1 and SNR = 26.49 for BC factor. Therefore, the optimum $T_{AV}$ can be obtained by using a polymer modified binder, with the lowest binder content and no fibers. Despite that, it is worth mentioning that the binder content is the input factor that most influences the change in the air voids value in comparison to the binder type or fiber content, as can be observed in Figure 4b and Figure 5b. On the other hand, the type of binder does not have a notable influence on the $T_{AV}$ response.

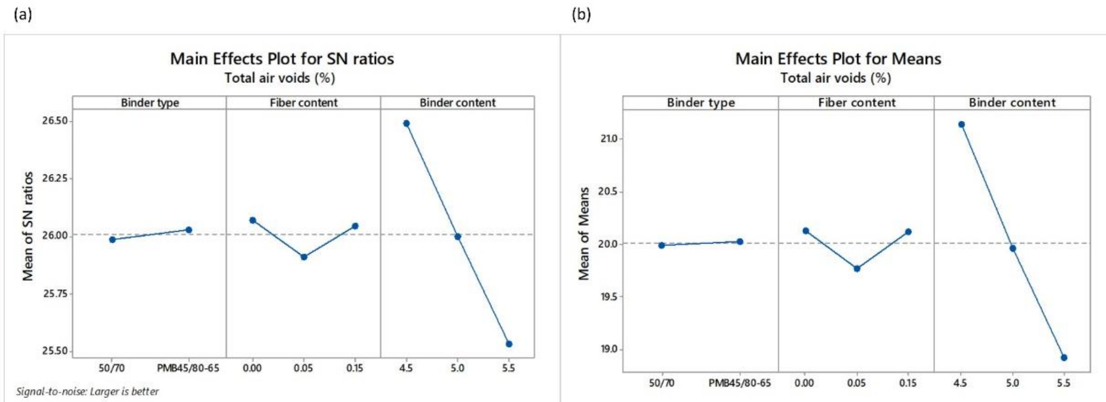



*Figure 4. Main effects plots of (a) SNR and (b) means of the total air voids $T_{AV}$*

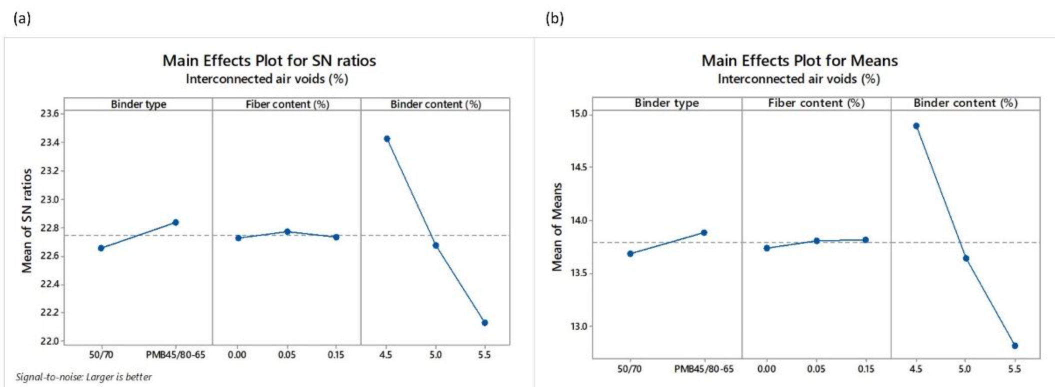



*Figure 5. Main effects plots of (a) SNR and (b) means of the interconnected air voids $I_{AV}$*

*Table 6. L18 Taguchi orthogonal array response variables*

| Design | Total Air Voids ($T_{AV}$) | | Interconnected Air Voids ($I_{AV}$) | | Particle Loss-Dry Condition ($PL_{DRY}$) | | Particle Loss-Wet Condition ($PL_{WET}$) | | Binder Drainage ($BD$) |
|---|---|---|---|---|---|---|---|---|---|
| | mean | *SD* | mean | *SD* | mean | *SD* | mean | *SD* | |
| 1 | 21.39 | 0.75 | 14.59 | 1.32 | 14.96 | 1.99 | 19.12 | 5.51 | 0.01 |
| 2 | 18.85 | 0.14 | 12.45 | 0.70 | 6.76 | 2.65 | 15.32 | 3.20 | 0.40 |
| 3 | 18.68 | 1.12 | 11.94 | 1.48 | 9.37 | 0.75 | 8.28 | 2.03 | 2.25 |
| 4 | 21.36 | 0.35 | 15.59 | 1.01 | 12.52 | 1.99 | 39.85 | 10.23 | 0.01 |
| 5 | 19.67 | 0.40 | 13.57 | 0.61 | 7.90 | 4.27 | 15.71 | 1.89 | 0.03 |
| 6 | 18.85 | 0.14 | 12.45 | 0.70 | 4.90 | 1.68 | 10.70 | 1.40 | 0.59 |
| 7 | 23.22 | 0.22 | 17.26 | 0.38 | 19.71 | 2.01 | 35.95 | 5.05 | 0.02 |
| 8 | 20.38 | 0.88 | 14.14 | 1.06 | 15.66 | 1.86 | 22.74 | 3.15 | 0.01 |
| 9 | 17.49 | 1.30 | 11.22 | 0.99 | 7.01 | 1.39 | 9.08 | 2.15 | 0.16 |
| 10 | 20.59 | 1.89 | 14.36 | 2.22 | 10.57 | 4.80 | 10.81 | 3.54 | 0.00 |
| 11 | 21.12 | 0.40 | 15.16 | 0.80 | 5.16 | 2.77 | 7.19 | 1.68 | 0.28 |
| 12 | 20.18 | 2.18 | 13.93 | 2.91 | 4.73 | 0.78 | 7.49 | 1.72 | 0.97 |
| 13 | 20.81 | 2.14 | 14.47 | 2.66 | 5.94 | 2.20 | 7.80 | 3.52 | 0.00 |
| 14 | 19.54 | 1.88 | 12.39 | 2.80 | 8.12 | 5.19 | 5.62 | 0.26 | 0.04 |
| 15 | 18.42 | 2.51 | 14.39 | 3.43 | 2.52 | 0.96 | 8.25 | 2.47 | 0.12 |
| 16 | 19.50 | 1.14 | 13.12 | 0.91 | 8.47 | 3.70 | 7.73 | 0.45 | 0.04 |
| 17 | 20.22 | 0.17 | 14.15 | 0.11 | 4.77 | 1.02 | 5.26 | 0.76 | 0.05 |
| 18 | 19.91 | 1.03 | 13.03 | 0.97 | 3.30 | 0.34 | 3.48 | 0.62 | 0.21 |

Concerning the evaluation of the mechanical performance, raveling resistance was evaluated on Marshall Samples in dry and wet conditions.

Mean values of the three replicas per design and test along with their corresponding standard deviations can be observed in Table 6. It is also interesting to notice that a direct correlation between the loss particles in dry and wet conditions exists, with a Pearson correlation coefficient of 79%. It means that the lower the values of particle loss in dry conditions ($PL_{DRY}$) are, the lower the values of particle loss in wet conditions ($PL_{WET}$) are, too. Figure 6 and 7 depicts the main effects of SNR as well as the means for the loss of particles in dry and wet conditions, respectively. Contrary to the calculation of air voids, the *smaller-the-better* quality characteristics were used to calculate the SNR. The highest value of SNR determines the best level for each control factor. For example, the levels and SNR for the input factors giving the optimal value of $PL_{DRY}$ are: level 2 and SNR = -14.72 for BT factor; level 2 and SNR = -15.90 for FC factor; and level 3 and SNR = -13.70 for BC factor. This means that the optimum value of $PL_{DRY}$ is obtained when polymer modified binder is used along with 0.05% POA fibers and 5.5% binder content. As for the $PL_{WET}$ value, the highest impact according to SNR values comes from the binder type and the binder content. In fact, the contribution of fibers in terms of raveling resistance under the water action is less appreciable when a polymer modified binder is used, as can be observed in the main effect plots for the means (Figure 7b).

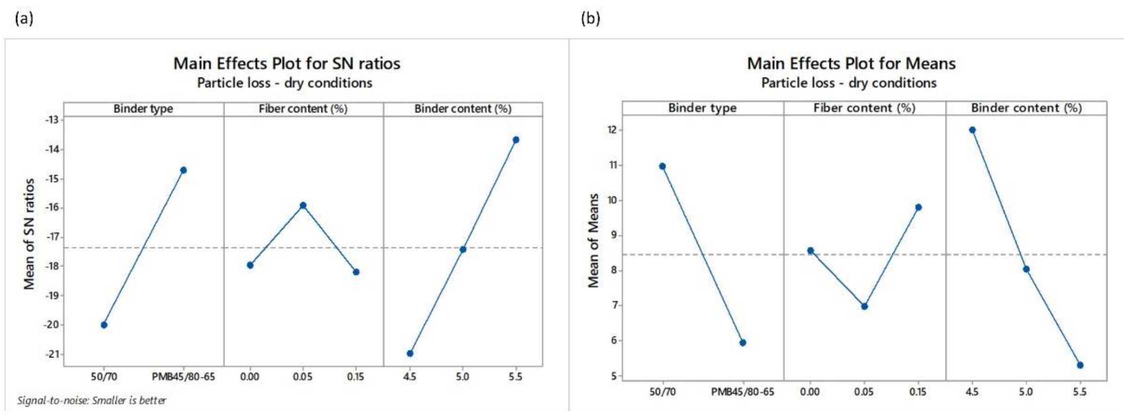



*Figure 6. Main effects plots of (a) SNR and (b) means of the particle loss in dry conditions* $PL_{DRY}$

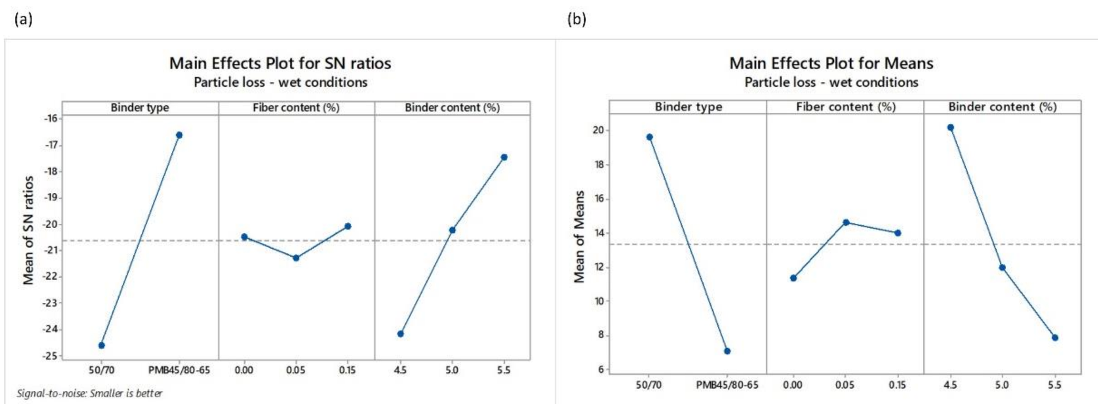



*Figure 7. Main effects plots of (a) SNR and (b) means of the particle loss in wet conditions* $PL_{WET}$

The non-compacted PA mixtures corresponding to all the designs were subjected to evaluation of their drain down characteristics through the mesh basket drain down test as per the EN 12697 – 18 standard. Binder drainage (BD) results are shown in Table 6. As well as to evaluate the raveling resistance, *smaller-the-better* equation was chosen to calculate the SNR values, as can be seen in Figure 8. According to the results, the levels and SNR values for the factors giving the less binder drainage were: level 1 and SNR = 22.87 for BT factor; level 3 and SNR = 26.24 for FC factor; and level 1 and SNR = 35.49 for BC factor. In other words, the lowest binder drainage can be obtained when a conventional 50/70 penetration grade binder is used along with 0.15% POA fibers and 4.5% binder content. The reduced value of BC (Figure 8b) might suggest that fibers can absorb the free binder in the mix.

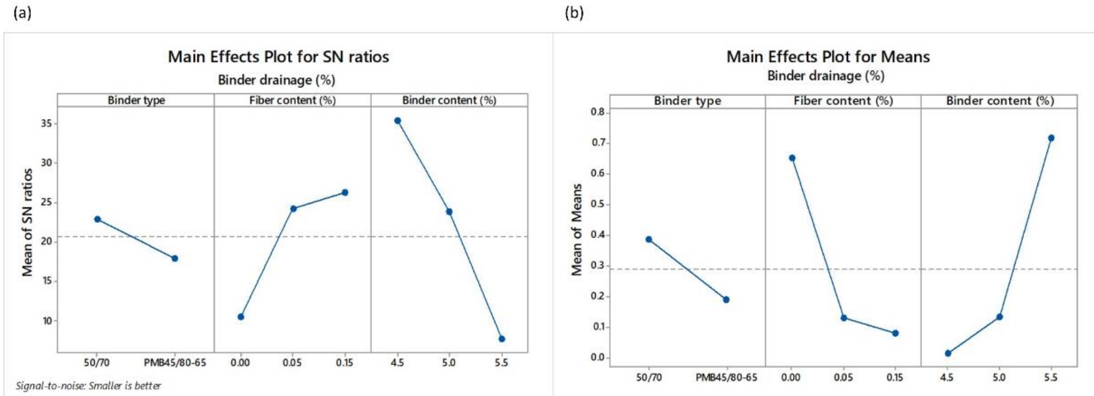
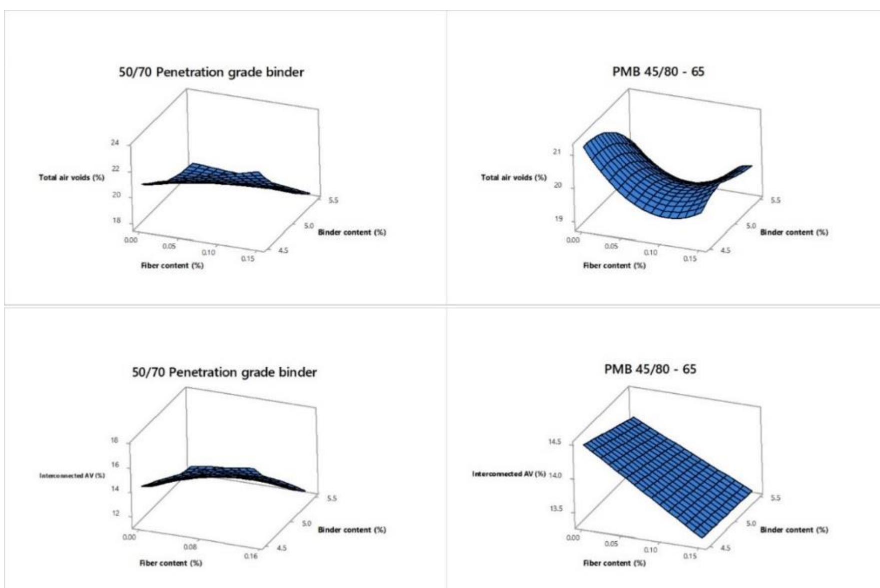



*Figure 8. Main effects plots of (a) SNR and (b) means of the binder drainage (BD)*

### 4.2 Statistical analysis of response results

The changes in the different responses obtained as a result of the experimental research are shown in Figure 9. The interaction effect between binder content and fiber content is plotted as depending of the binder type per each response value ($T_{AV}, I_{AV}, PL_{DRY}, PL_{WET}, BD$). For practical reasons, which are based on the response variable data obtained from tests with mixtures with 50/70 penetration grade binder, an analysis of variance was performed. A 5% significance level and a 95% confidence level were considered for the calculation of the factors affecting the different output parameters (Table 7). The significance of the input parameters in the analysis of variance was identified by comparing the F-values of each input parameter.



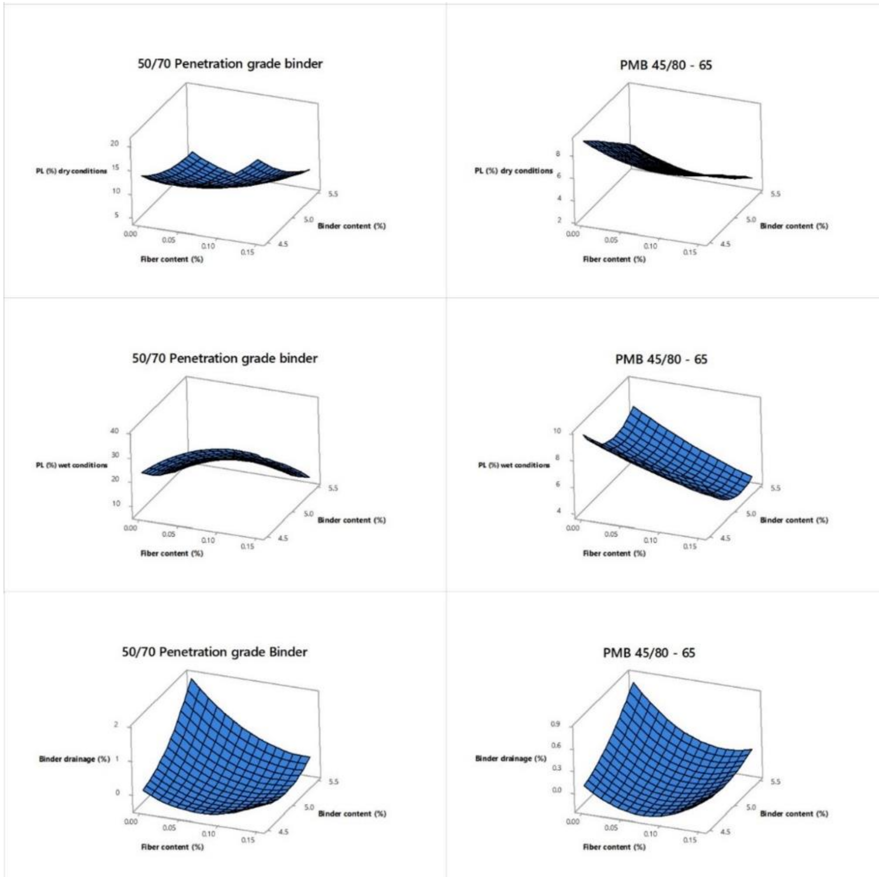



*Figure 9. Interaction effect of fiber content and binder content as a function of the binder type*

Regarding the total and interconnected air voids, binder content (BC) has the highest influence, with contribution factors of 82% and 80%, respectively. It means that the binder content in the mixture influences notably its porosity, reducing functional performance characteristics such as permeability and noise generation. On the other hand, fiber content (FC) seems not to have a significant effect, probably because the amount of fiber used in this research is too low. Other types of fibers such as the cellulose are able to reduce the amount of voids in the mixture when its content is around 0.3% by weight of mixture, as suggested by other researches[1]. However, the FC factor does have a higher influence when it comes to the resulting raveling resistance responses, with contributions of 25% and 13% to the particle loss in dry and wet conditions, respectively. As reported by other researchers, fibers in hot mix asphalt act as a reinforcement, forming a three dimensional network inside the mixture [13,44]. In addition, fibers are normally used as stabilizer agents in PA mixtures with high binder contents. The contribution of the fiber content (FC) with regard to the binder drainage response is actually of 27%, approximately.

*Table 7. Analysis of variance for $T_{AV}$, $I_{AV}$, $PL_{DRY}$, $PL_{WET}$ and BD*

| Variance Source | Degree of Freedom (DoF) | Adj SS | Adj MS | *F*-Value | Contribution (%) |
|---|---|---|---|---|---|
| Total air voids (%) | | | | | |
| Fiber content (%) | 2 | 0.783 | 0.392 | 0.42 | 3.12 |
| Binder content (%) | 2 | 20.565 | 10.282 | 10.98 | 81.95 |
| Error | 4 | 3.747 | 0.937 | | 14.93 |
| Total | 8 | 25.095 | | | 100.00 |
| Interconnected air voids (%) | | | | | |
| Fiber content (%) | 2 | 2.339 | 1.170 | 1.32 | 7.88 |
| Binder content (%) | 2 | 23.794 | 11.897 | 13.48 | 80.21 |
| Error | 4 | 3.531 | 0.883 | | 11.90 |
| Total | 8 | 29.664 | | | 100.00 |
| Particle loss—dry conditions | | | | | |
| Fiber content (%) | 2 | 50.220 | 25.112 | 3.01 | 25.22 |
| Binder content (%) | 2 | 115.440 | 57.722 | 6.91 | 57.98 |
| Error | 4 | 33.420 | 8.354 | | 16.79 |
| Total | 8 | 199.090 | | | 100.00 |
| Particle loss—wet conditions | | | | | |
| Fiber content (%) | 2 | 131.500 | 65.760 | 1.76 | 12.66 |
| Binder content (%) | 2 | 757.900 | 378.970 | 10.16 | 72.97 |
| Error | 4 | 149.100 | 37.290 | | 14.36 |
| Total | 8 | 1038.600 | | | 100.00 |
| Binder drainage | | | | | |
| Fiber content (%) | 2 | 1.157 | 0.579 | 1.68 | 27.21 |
| Binder content (%) | 2 | 1.719 | 0.860 | 2.5 | 40.43 |
| Error | 4 | 1.375 | 0.344 | | 32.34 |
| Total | 8 | 4.252 | | | 100.00 |

In this research, regression analyses were employed for modeling and predicting the response variables. Different models were initially proposed such as linear, linear plus interactions, linear plus squares and full quadratic in order to predict the best response variable. The best fitting models, those with the highest $R^2$ values, were finally selected.

The predictive equations obtained from the analysis of the mixtures with 50/70 binder, are given below.

$$T_{AV}(\%) = 30.65 + 114 * FC\,(\%) - 2.194\ * BC\,(\%)\ - 21.85\ * FC\,(\%) * BC\,(\%) \quad (19)$$

$$I_{AV}(\%) = 25.09 + 125 * FC\,(\%)\ - 2.379 * BC\,(\%) - 23.52 * FC(\%) * BC(\%) \quad (20)$$

$$PL_{DRY}(\%) = 167 + 169 * FC\,(\%) - 57.7 * BC(\%) + 635 * FC^2(\%) + 5.23 * BC^2(\%) - 47.9 * FC(\%) * BC(\%) \quad (21)$$

$$Pl_{WET}\,(\%) = 352 + 649 * FC(\%) - 119 * BC(\%) - 1012 * FC^2(\%) + 10.13 * BC^2(\%) - 88.3 * FC(\%) * BC(\%) \quad (22)$$

$$BD\,(\%) = 27.5 + 45.6 * FC(\%) - 12.6 * BC\,(\%) + 80.4 * FC^2(\%) + 1.44 * BC^2(\%) - 12.63 * FC(\%) * BC(\%) \quad (23)$$

Similarly, the predictive equations obtained from the analysis of the mixtures with PMB 45/80 – 64 are as follows.

$$T_{AV}(\%) = -11.5 - 72.1 * FC\,(\%) + 14.3\,BC\,(\%) + 158 * FC^2(\%) - 1.57 * BC^2(\%) + 8.7 * FC(\%) * BC(\%) \quad (24)$$

$$I_{AV}(\%) = 14.4 - 28.3 * FC\,(\%) + 0.4 * BC(\%) + 77 * FC^2(\%) - 0.07 * \mathrm{BC}^2\,(\%) + 1.9 * \mathrm{FC}\,(\%) * \mathrm{BC}(\%) \quad (25)$$

$$PL_{DRY}(\%) = 30.51 - 7.47 * FC(\%) - 4.81 * BC(\%) \quad (26)$$

$$PL_{WET}\,(\%) = 172 + 32 * FC(\%) - 64.4 * BC(\%) + 54 * FC^2(\%) + 6.28 * BC^2(\%) - 12.0 * FC(\%) * BC(\%) \quad (27)$$

$$BD\,(\%) = 6.7 + 12.7 * FC\,(\%) - 3.28 * BC(\%) + 51.6 * FC^2(\%) + 0.400 * BC^2(\%) - 4.50 * FC(\%) * BC(\%) \quad (28)$$

All the regression models for the mixtures using the conventional bitumen fitted very well the experimental results, with $R^2$ values closer to 90%. Specifically, for total air voids a linear plus interaction regression model was used with a $R^2$ value of 93.84%. A linear plus interaction regression model was used also for the interconnected air voids, with a $R^2$ value of 96.11%. Concerning the raveling resistance, the particle loss in dry and wet conditions was fitted using full quadratic regression models. In this case, $R^2$ values of 89.93% and 90.02%, respectively, were obtained. Similarly, a full quadratic regression equation was used to model the binder drainage, with the $R^2$ being equal to 89.53%. As for the mixtures using PMB 45/80 – 65, full quadratic regression models were applied to total air voids, interconnected air voids, particle loss in wet conditions and binder drainage, with $R^2$ values of 64.86%, 30.02%, 80.04% and 84.00%, respectively. In the case of particle loss in dry conditions, a linear regression model was applied with $R^2$ value of 67.07%.

Figure 10, shows the graphs where $T_{AV}, I_{AV}, PL_{DRY}, PL_{WET}$ and *BD* response variables obtained experimentally and those predicted by the regression model for each binder type are compared. In the case of the mixtures with 50/70 penetration grade binder, predicted and experimental values are slightly closer to each other as compared to the case of the mixtures with PMB 45/80 – 65. As an example, the mean errors for the total air voids were of 1.61% and 2.01% when 50/70 penetration grade binder and PMB 45/80 – 65 were used, respectively. About the functionality responses, results suggest that the deviation between experimental data and regression models was minimal, with errors lower than 5%. However, the errors in the mechanical performance responses were in the range between 10% and 20%.

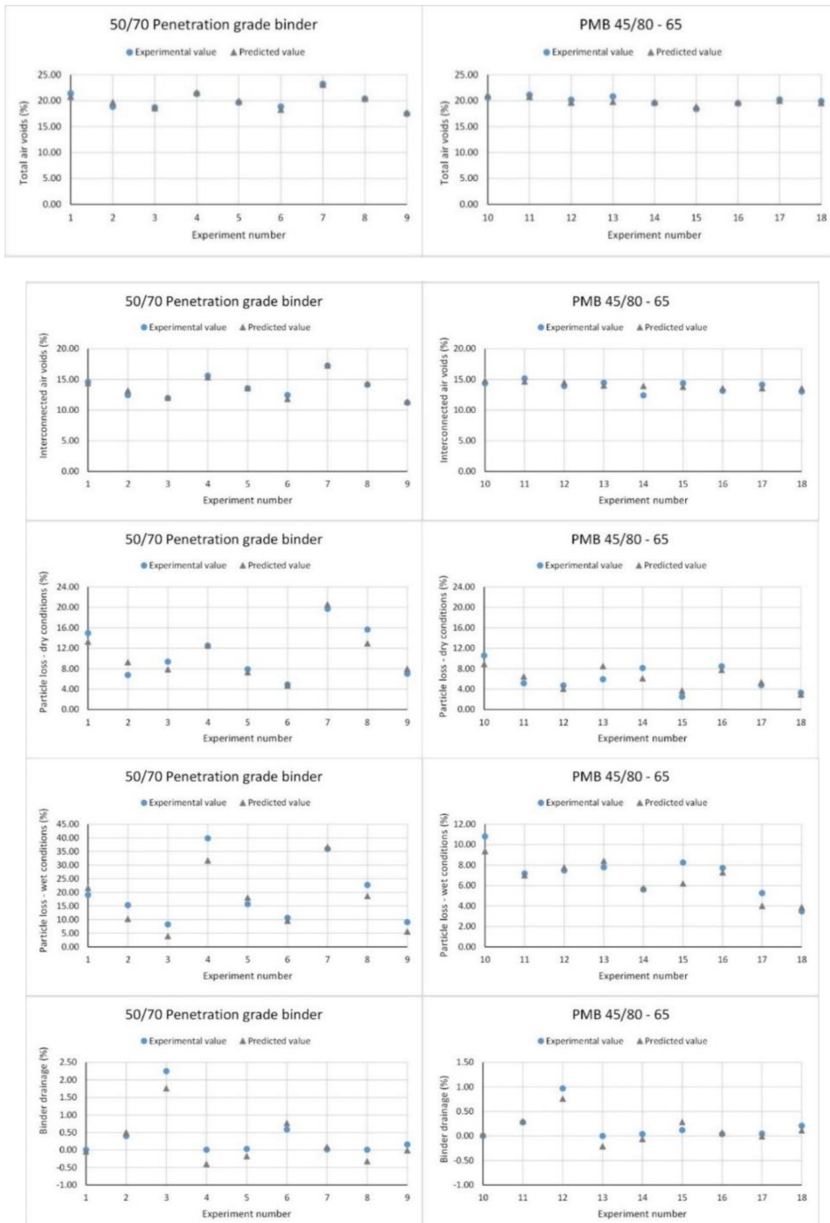



*Figure 10. Experimental vs predicted values of the different response variables*

### 4.3 CRITIC method

As said before, the CRITIC methodology is employed in this research for the purpose of finding out the weights of each criterion. The weights assigned to each response variable are based on the contrast intensity and conflict assessment of the decision making problem [167]. According to the methodology, the decision matrix is firstly normalized using Eq. (13), as shown in Table 8. The standard deviation (SD) values for all the criteria are also calculated. The correlation coefficients of the different response variables were then calculated (Table 9). Finally, the weights of the different response variables were determined with the help of equations (14) to (16), as shown in Table 10. As can be seen in Table 10, total air voids and interconnected air voids have similar weights, which is due to the high correlation that exists between these two variables. On the other hand, particle loss in dry and wet conditions have the highest weights with, values of 0.24 and 0.25, respectively suggesting that raveling resistance have a notable incidence in the overall performance of the PA mixture. Finally, the weight assigned to binder drainage was equal to 0.17, almost equal than $T_{AV}$ and $I_{AV}$ weights. As it is well known, when weights are assigned equally, a subjective bias is involved in the decision-making process. To deal with this, CRITIC approach defines the criteria weightage in an objective manner, attempting to reveal the intensity of the contrast in the decision making problem [173].

*Table 8. Normalized decision matrix for the CRITIC method*

| Design | $T_{AV}$ (%) | $I_{AV}$ (%) | $PL_{DRY}$ (%) | $PL_{WET}$ (%) | $BD$ (%) |
|---|---|---|---|---|---|
| 1 | 0.68 | 0.56 | 0.28 | 0.57 | 1.00 |
| 2 | 0.24 | 0.20 | 0.75 | 0.67 | 0.82 |
| 3 | 0.21 | 0.12 | 0.60 | 0.87 | 0.00 |
| 4 | 0.68 | 0.72 | 0.42 | 0.00 | 1.00 |
| 5 | 0.38 | 0.39 | 0.69 | 0.66 | 0.99 |
| 6 | 0.24 | 0.20 | 0.86 | 0.80 | 0.74 |
| 7 | 1.00 | 1.00 | 0.00 | 0.11 | 0.99 |
| 8 | 0.50 | 0.48 | 0.24 | 0.47 | 1.00 |
| 9 | 0.00 | 0.00 | 0.74 | 0.85 | 0.93 |
| 10 | 0.54 | 0.52 | 0.53 | 0.80 | 1.00 |
| 11 | 0.63 | 0.65 | 0.85 | 0.90 | 0.88 |
| 12 | 0.47 | 0.45 | 0.87 | 0.89 | 0.57 |
| 13 | 0.58 | 0.54 | 0.80 | 0.88 | 1.00 |
| 14 | 0.36 | 0.19 | 0.67 | 0.94 | 0.98 |
| 15 | 0.16 | 0.53 | 1.00 | 0.87 | 0.95 |
| 16 | 0.35 | 0.32 | 0.65 | 0.88 | 0.98 |
| 17 | 0.48 | 0.49 | 0.87 | 0.95 | 0.98 |
| 18 | 0.42 | 0.30 | 0.95 | 1.00 | 0.91 |
| *SD* | 0.23 | 0.24 | 0.27 | 0.28 | 0.25 |

*Table 9. Correlation coefficients of the different response variables*

| | $T_{AV}$ (%) | $I_{AV}$ (%) | $PL_{DRY}$ (%) | $PL_{WET}$ (%) | $BD$ (%) |
|---|---|---|---|---|---|
| $T_{AV}$ (%) | 1.00 | 0.89 | −0.63 | −0.59 | 0.34 |
| $I_{AV}$ (%) | 0.89 | 1.00 | −0.50 | −0.62 | 0.40 |
| $PL_{DRY}$ (%) | −0.63 | −0.50 | 1.00 | 0.79 | −0.16 |
| $PL_{WET}$ (%) | −0.59 | −0.62 | 0.79 | 1.00 | −0.24 |
| $BD$ (%) | 0.34 | 0.40 | −0.16 | −0.24 | 1.00 |

*Table 10. Weights of the different response variables*

| Criteria | $C_j$ | $W_j$ |
|---|---|---|
| $T_{AV}$ (%) | 0.93 | 0.18 |
| $I_{AV}$ (%) | 0.92 | 0.17 |
| $PL_{DRY}$ (%) | 1.25 | 0.24 |
| $PL_{WET}$ (%) | 1.31 | 0.25 |
| $BD$ (%) | 0.90 | 0.17 |

**4.4 TOPSIS method**

In this research, the Taguchi methodology was applied for the optimization of the single responses (e.g., total air voids, interconnected air voids, etc.) in the same way that other experimental design methods might have been used such as the central composite design, the response surface method or the full factorial design. Moreover, in this study more than one response was evaluated and hence, it is necessary to transform the multiple response variables into one single response variable. Therefore, TOPSIS methodology was employed as a multi-criteria decision-making technique built into the Taguchi experiment design method.

Once the weights of the different response variables were calculated by applying the CRITIC approach, closeness comparative coefficient (CCC) for each design of experiments was determined employing equations (4) to (11). Table 11 shows the weighted normalizes decision matrix for each response variable, with higher values of CCC indicating more optimum conditions. In this sense, the design ranked number 1 corresponds to the best combination of input parameters among all the set of experiments carried out. The positive ideal solution (PIS) values for each response is as follows: $V_{TAV}^{+} = 0.0491$, $V_{IAV}^{+}$ = 0.0499, $V_{PL-dry}^{+} = 0.0149$, $V_{PL-wet}^{+} = 0.0123$ and $V_{BD}^{+} = 0.0000$. Similarly, the negative ideal solution (NIS) values for each response is $V_{TAV}^{-} = 0.0370$, $V_{IAV}^{-} = 0.0324$, $V_{PL-dry}^{-} = 0.1162$, $V_{PL-wet}^{-} = 0.1410$ and $V_{BD}^{-} = 0.1480$. After PIS and NIS were calculated, experiment designs were ranked based on CCC scores (Table 11). The experimental design number 17 resulted the best design, with response values of 20.22%, 14.15%, 4.77%, 5.26% and 0.05% for $T_{AV}, I_{AV}, PL_{DRY}, PL_{WET}$ and *BD*, respectively. This design involves the use of polymer modified binder with 0.15% fiber content and 5.0% binder content. On the other hand, experimental design number 3 was found to be the design with the lowest CCC value and hence, the last potential choice. Overall, the preference ranking of experimental designs can be given as 17 > 18 > 15 > 13 > 11 > 14 > 16 > 9 > 10 > 5 > 6 > 2 > 12 > 1 > 8 > 7 > 4 > 3.

*Table 11. Weighted normalized response, CCC values and final ranking*

| Design No. | Weighted Normalized Values | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $T_{AV}$ (%) | $I_{AV}$ (%) | $PL_{DRY}$ (%) | $PL_{WET}$ (%) | *BD* (%) | $S_i^+$ | $S_i^-$ | $S_i^+ + S_i^-$ | *CCC* | Rank |
| 1 | 0.045 | 0.042 | 0.088 | 0.068 | 0.001 | 0.09 | 0.17 | 0.26 | 0.65 | 14 |
| 2 | 0.040 | 0.036 | 0.040 | 0.054 | 0.026 | 0.06 | 0.16 | 0.22 | 0.73 | 12 |
| 3 | 0.040 | 0.035 | 0.055 | 0.029 | 0.148 | 0.16 | 0.09 | 0.25 | 0.37 | 18 |
| 4 | 0.045 | 0.045 | 0.074 | 0.141 | 0.001 | 0.14 | 0.15 | 0.29 | 0.51 | 17 |
| 5 | 0.042 | 0.039 | 0.047 | 0.056 | 0.002 | 0.06 | 0.18 | 0.23 | 0.76 | 10 |
| 6 | 0.040 | 0.036 | 0.029 | 0.038 | 0.039 | 0.05 | 0.16 | 0.21 | 0.76 | 11 |
| 7 | 0.049 | 0.050 | 0.116 | 0.127 | 0.001 | 0.15 | 0.16 | 0.32 | 0.52 | 16 |
| 8 | 0.043 | 0.041 | 0.092 | 0.080 | 0.001 | 0.10 | 0.16 | 0.27 | 0.61 | 15 |
| 9 | 0.037 | 0.032 | 0.041 | 0.032 | 0.011 | 0.04 | 0.19 | 0.23 | 0.82 | 8 |
| 10 | 0.044 | 0.042 | 0.062 | 0.038 | 0.000 | 0.06 | 0.19 | 0.24 | 0.77 | 9 |
| 11 | 0.045 | 0.044 | 0.030 | 0.025 | 0.018 | 0.03 | 0.19 | 0.22 | 0.87 | 5 |
| 12 | 0.043 | 0.040 | 0.028 | 0.026 | 0.064 | 0.07 | 0.14 | 0.21 | 0.68 | 13 |
| 13 | 0.044 | 0.042 | 0.035 | 0.028 | 0.000 | 0.03 | 0.21 | 0.23 | 0.88 | 4 |
| 14 | 0.041 | 0.036 | 0.048 | 0.020 | 0.003 | 0.04 | 0.20 | 0.24 | 0.84 | 6 |
| 15 | 0.039 | 0.042 | 0.015 | 0.029 | 0.008 | 0.02 | 0.20 | 0.23 | 0.90 | 3 |
| 16 | 0.041 | 0.038 | 0.050 | 0.027 | 0.003 | 0.04 | 0.20 | 0.24 | 0.83 | 7 |
| 17 | 0.043 | 0.041 | 0.028 | 0.019 | 0.003 | 0.02 | 0.21 | 0.23 | 0.92 | 1 |
| 18 | 0.042 | 0.038 | 0.019 | 0.012 | 0.014 | 0.02 | 0.21 | 0.23 | 0.91 | 2 |

CCC score values obtained via CRITIC – TOPSIS based Taguchi methodology were also used to calculate the main effects plots for SNR and main effect plots for means, as shown in Figure 11.

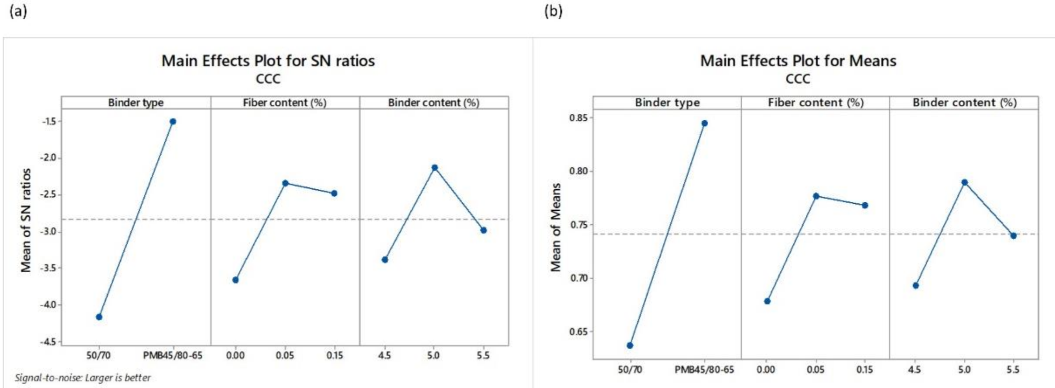



*Figure 11. Main effects plots of (a) SNR and (b) means of the CCC values*

The type of binder seems to have the greatest impact on the SNR and means values. As can be observed in the ranking, the first seven experimental designs were about mixtures using PMB. On the other hand, good results were observed in terms of functionality and durability for the mixtures using 50/70 penetration grade binder. For example, mixtures corresponding to design number 5, with 0.05% fiber content and a 5.0% binder content, exhibited particle loss values in dry and wet conditions of 7.90% and 15.71%, respectively. According to the scientific literature, values lower than 20% and 35% are recommend in $PL_{DRY}$ and $PL_{WET}$ tests [1,3,30]. This mixture also shows a proper air void content of approximately 20% and does not present binder drainage problems, as it obtained a drain down value lower than 0.3%, the limit recommended in the literature [16].

When analyzing the CCC score values, trends indicate that low values of binder content and high values of fiber content clearly affect the overall performance of mixtures using 50/70 penetration grade bitumen, as can be observed in Figure 12. Likewise, all CCC values were below 0.8 in the case of mixtures using 50/70 conventional binder with the exception of design number 9 which obtained a value of 0.82. Moreover, design 5 scored higher, with a value of 0.76. This experimental design exhibited lower values of particle loss in dry and wet conditions while maintaining admissible values of total and interconnected air voids. Besides binder drainage in this mixture was not observed. Therefore, it could be considered a proper mixture design. Finally, based on SNR, the TOPSIS approach suggests that the optimum conditions were identified for a binder type factor equal to PMB, fiber content factor of 0.05% and binder content factor of 5.0%.

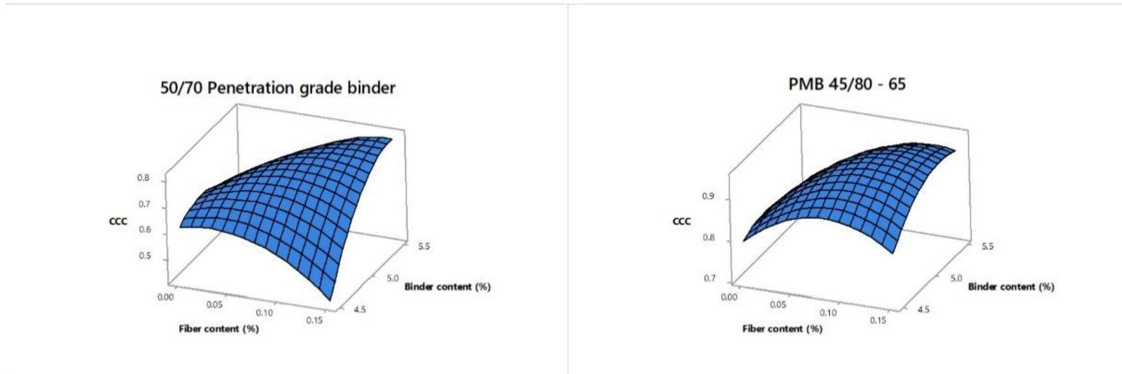



*Figure 12. Interaction effect of fiber content and binder content as a function of the CCC score value*

As with the individual responses, a regression analysis was applied for the modeling of the CCC values and the analysis of the interaction effects between input parameters and the overall CCC response. A linear plus interaction predictive equation with a p-value of 0.004 significant effect was selected. The equation for CCC are given as follows.

$$CCC = 1.128 + 0.2089 * BT - 10.84 * FC\,(\%) - 0.1049 * BC(\%) + 2.268 * FC(\%) * BC(\%) \qquad (29)$$

The graph given in Figure 13 shows the comparison between the CCC response obtained through the CRITIC-TOPSIS methodology and the CCC values from the regression model developed. The $R^2$ for the model obtained was 66.43% and the mean error between the CCC values calculated via CRITIC-TOPSIS and the model developed was of 11.78%. According to the analysis of variance (Table 12), the type of binder has a significant effect as well was the fiber-binder interaction. In other words, the overall performance of a PA mixture is linked to the proper quantities of fiber and binder depending on the type of binder.

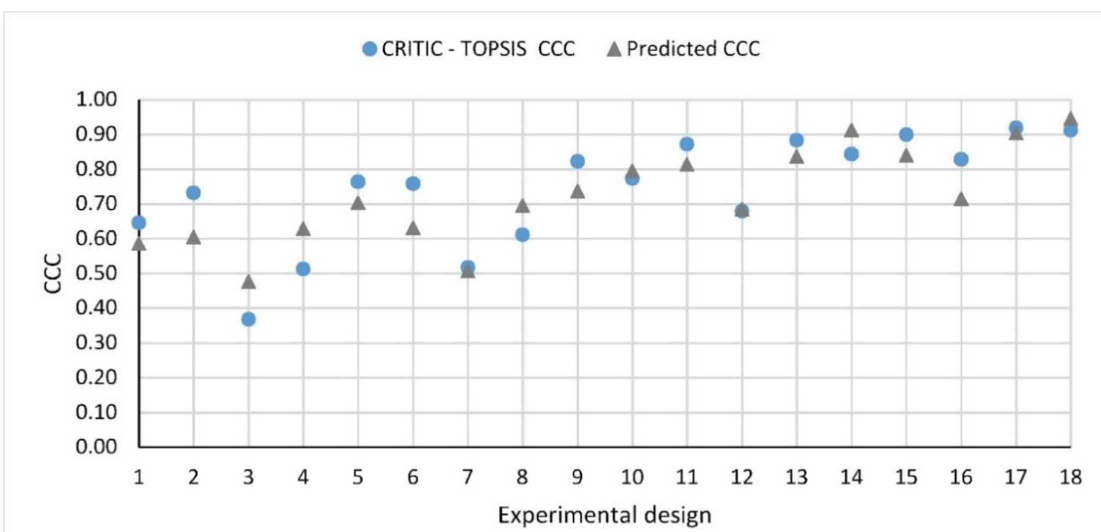



*Figure 13. Comparison between the calculated CCC response and the predicted model*

*Table 12. Analysis of variance of the regression model developed for CCC*

| Source | DF | Adj SS | Adj MS | *F*-Value | *P*-Value | Significance |
|---|---|---|---|---|---|---|
| Model | 4 | 0.280 | 0.070 | 6.430 | 0.004 | Significant |
| Linear | 3 | 0.226 | 0.075 | 6.930 | 0.005 | Significant |
| Binder type | 1 | 0.196 | 0.196 | 18.020 | 0.001 | Significant |
| Fiber content (%) | 1 | 0.018 | 0.018 | 1.610 | 0.227 | |
| Binder content (%) | 1 | 0.013 | 0.013 | 1.150 | 0.303 | |
| 2-Way Interaction | 1 | 0.060 | 0.060 | 5.510 | 0.035 | Significant |
| Fiber content (%) *Binder content (%) | 1 | 0.060 | 0.060 | 5.510 | 0.035 | Significant |
| Error | 13 | 0.142 | 0.011 | | | |
| Total | 17 | 0.422 | | | | |

## 5. Conclusions

This study presented the CRITIC-TOPSIS based on the Taguchi methodology aimed at investigating the impact of different parameters on the mechanical and functional performance of fiber reinforced porous asphalt mixtures with aramid and polyolefin fibers. A series of experiments were carried out based on the L18 Taguchi orthogonal array, and the optimal responses were identified for the total air voids, interconnected air voids, particle loss in dry conditions, particle loss in wet conditions, and binder drainage. Signal to Noise Ratio values obtained from the Taguchi design made it possible to determine the optimal levels of the control factors for the different response variables. In addition, regression models were performed with the different responses in order to evaluate the binder-fiber interaction effects as a function of the type of bitumen. Since multiple responses were obtained, a multi objective optimization was performed through the CRITIC-TOPSIS methodology. Unlike other studies that assign equal weights to the different responses, the CRITIC approach was employed in this study to find the objective criteria weights. With TOPSIS, the criteria weights were taken into account to provide a preference ranking for all the designs of experiments. Based on the results obtained, the following conclusions can be drawn:

- In terms of functionality, the binder content is the most influential factor on the total and interconnected air voids of the mixture.
- Concerning the durability of the mixture, the optimum $PL_{dry}$ response based on Signal to Noise Ratio values is obtained when employing a polymer modified binder, a 0.05% fiber content, and a 5.5% binder content. The contribution of the fiber content is less significant when a polymer-modified binder is used instead of a conventional binder.
- PA mixtures with a 50/70 penetration grade binder and 0.05% fiber content improve in a similar way to PA mixtures with a polymer-modified binder. As for the raveling resistance, the addition of fibers reduces the particle loss in dry conditions regardless of the amount of bitumen employed. However, when it comes to the particle loss in wet conditions, a higher binder content seems to be necessary to properly coat the fibers and hence to guarantee a higher durability under the action of water.

- The use of fibers in the PA mixtures not only contributed to positively mitigating the binder drainage, but also to reinforcing the mixture without compromising its functionality.
- The best alternative according to the TOPSIS method is the design number 17. This design corresponds to the use of a polymer-modified binder, 0.15% fiber content, and 5.0% binder content. Although the first few positions of the order of preference refers to experiments with mixes using polymer modified binder, good results can be also obtained using a conventional binder as long as the proper proportions of fibers are applied.
- The CRITIC-TOPSIS based Taguchi can be considered a useful tool for the evaluation of the impact of different admixtures on different responses, as well as for the optimization of multiple responses simultaneously. It is recommended to apply this novel methodology to other composites of materials.

**Author Contributions:** C.J.S.-A. and P.P.-M. designed the experiments. C.J.S.-A. and P.L.-G. carried out the experimental plan. C.J.S.-A., P.P.-M. and P.L.-G. analyzed the data. D.C.-F. supervised the experiments. C.J.S.-A., P.P.-M., P.L.-G. and D.C.-F. wrote the paper. G.C.-F. is responsible for the funding acquisition. All the authors contributed in the discussion of results and conclusions.

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# 5. DISCUSSION OF RESULTS

In this chapter, the discussion of the main results was introduced in three different sections. In the first section, the results concerning the fiber pre-selection process is presented as justification for the selection of POA and PAN fibers. In the second section, the results concerning the experimental assessment of the effectiveness of adding POA and PAN fibers in the PA mixture at porous asphalt scale and asphalt mortar scale are displayed. This phase was decisive to select the most promising fiber. Finally, once the most suitable fiber was chosen, the third section discusses the principal results regarding novel integrated DOE-MCDM analysis applied to evaluate the influence of various control factors.

## 5.1 Fiber pre-selection process

According to the analysis of results obtained from the questionnaires and by applying the FAHP, the most voted criteria were toughness and fatigue life with weights of 30% approximately (see Figure 12) while rutting resistance and indirect tensile strength had the lowest scores with values around 20%.

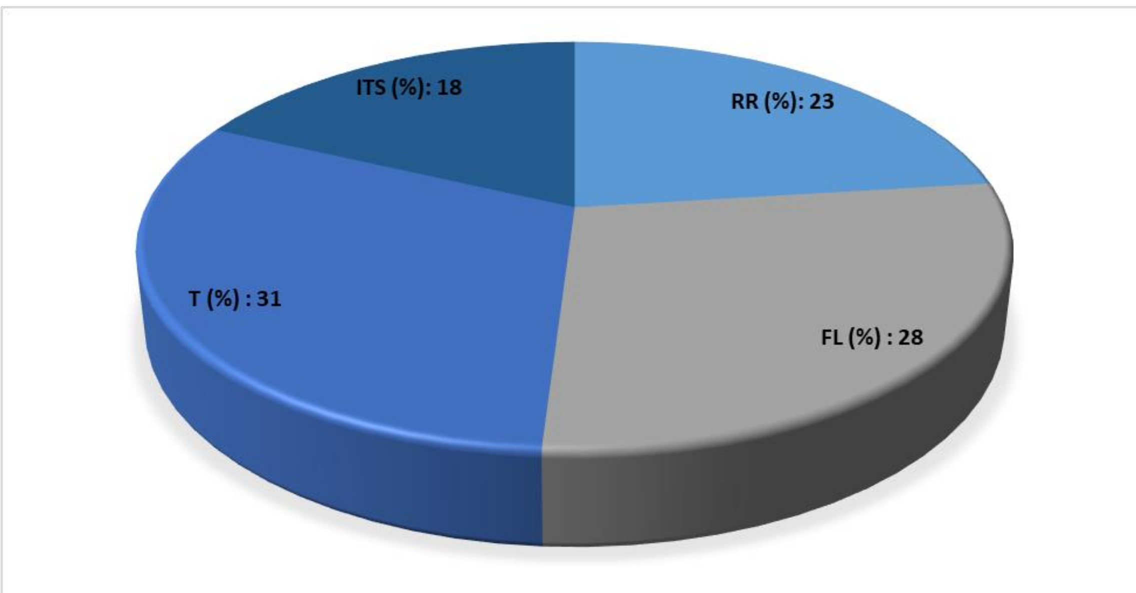



*Figure 12 Priority weights according to FAHP procedure*

The resulted ranking of fiber alternatives obtained from the WASPAS evaluation is expressed in Figure 13 in terms of Joint performance Score (JPS) values. In the WASPAS approach, JPS may range from 0 to 1. Consequently, the highest values of JPS are the most suitable alternative. In that sense, PAN and POA were the fibers best ranked to continue with the next phases of the research. It is important to mention that this analysis considers only the improvement of fibers when incorporated into asphalt dense mixture due to the lack of information related to the use of fiber reinforcement in open grade asphalt mixes. Similarly, it should be noted that other factors, such as moisture sensitivity, raveling, freezing-thaw cycles, among others, were not considered within the selection criteria, due to the lack of quantitative data.

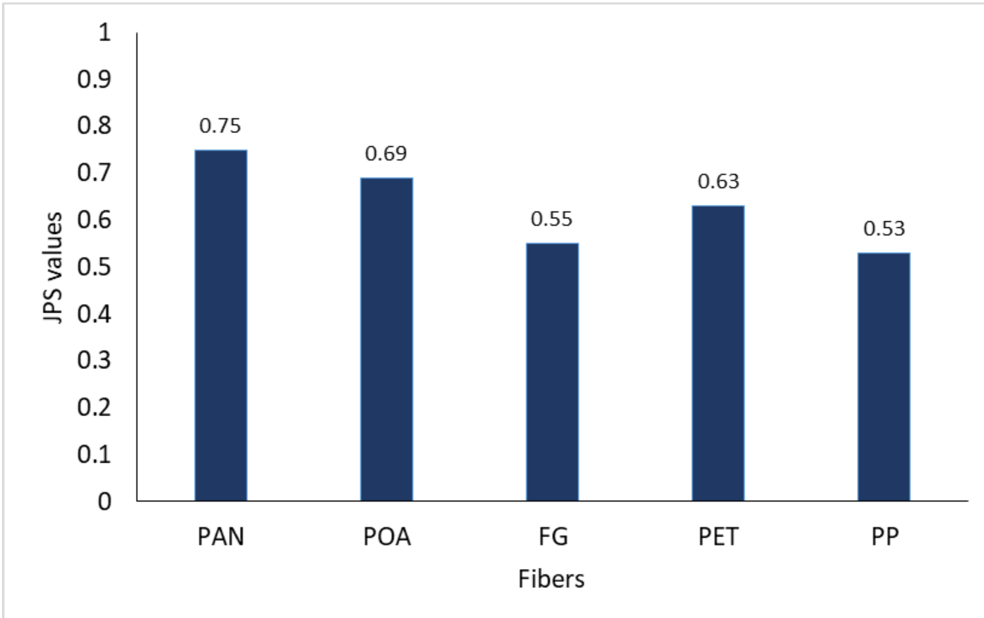



*Figure 13 Preference ranking according to WASPAS evaluation*

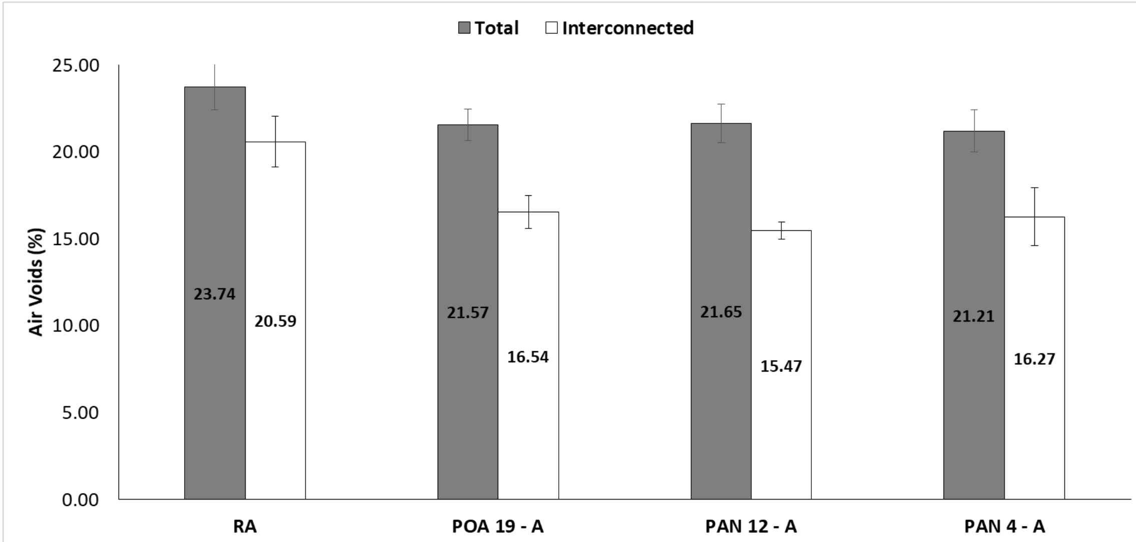
**5.2 Experimental assessment of FRPA mixtures with synthetic fibers**

*5.2.1 Experimental results at porous asphalt scale*

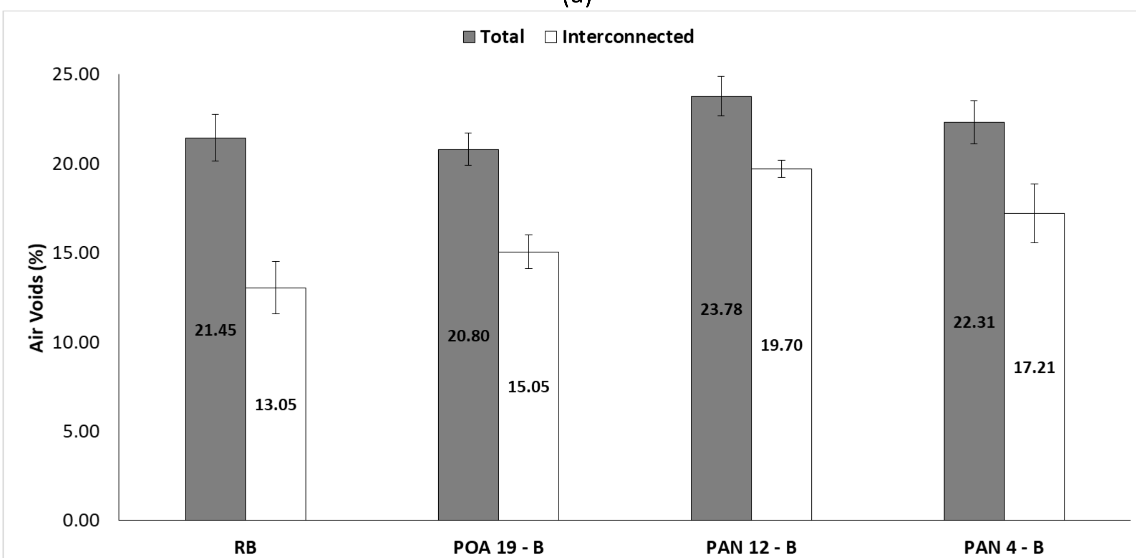
As the main objective of this phase is to select the most promising fiber, in this stage, the reinforcing effect of fibers were analyzed separately for the two filler content conditions (A & B).

*5.2.1.1 Air voids and permeability results*

The results concerning air voids and permeability of the studied PA mixtures for the two filler conditions are summarized in Figure 14 and Figure 15, respectively. As the air voids results were normally distributed and presented homogeneity of variance, parametric tests were done to check statistical differences. For the high filler condition, a slight reduction in the total and interconnected air voids was noted between the reference mixtures (RA) and the FRPA mixtures being statistically significant. However, no statistical differences were presented among the fiber-reinforced mixtures. For the low filler condition, the trend suggests that the addition of fiber increases the voids in the mix, observing statistical differences. These results allowed us to suppose that fibers help to retain some of the bitumen, permitting an increase in both total and interconnected voids of the mixtures. In all cases, the minimum air void content established by the Spanish specifications was accomplished (20%).



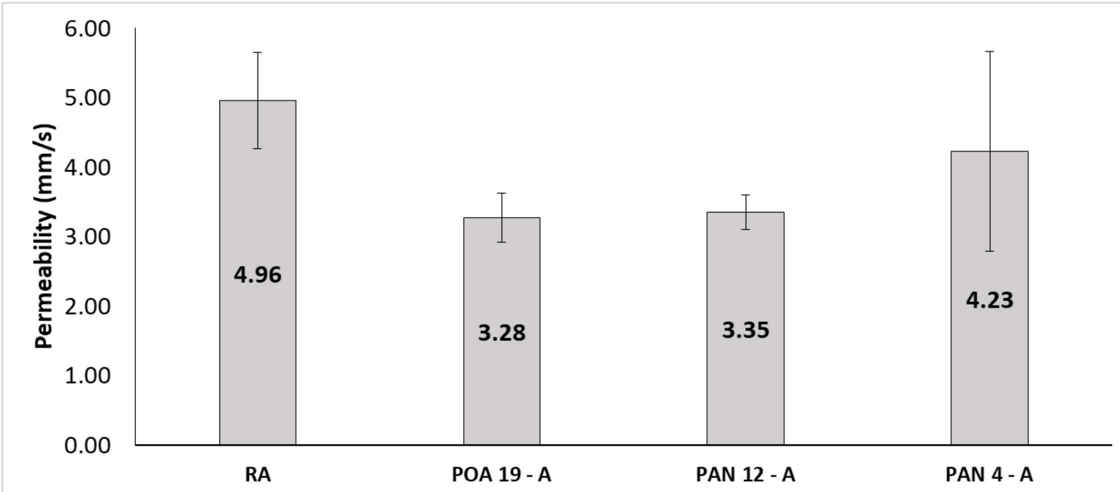

(a)



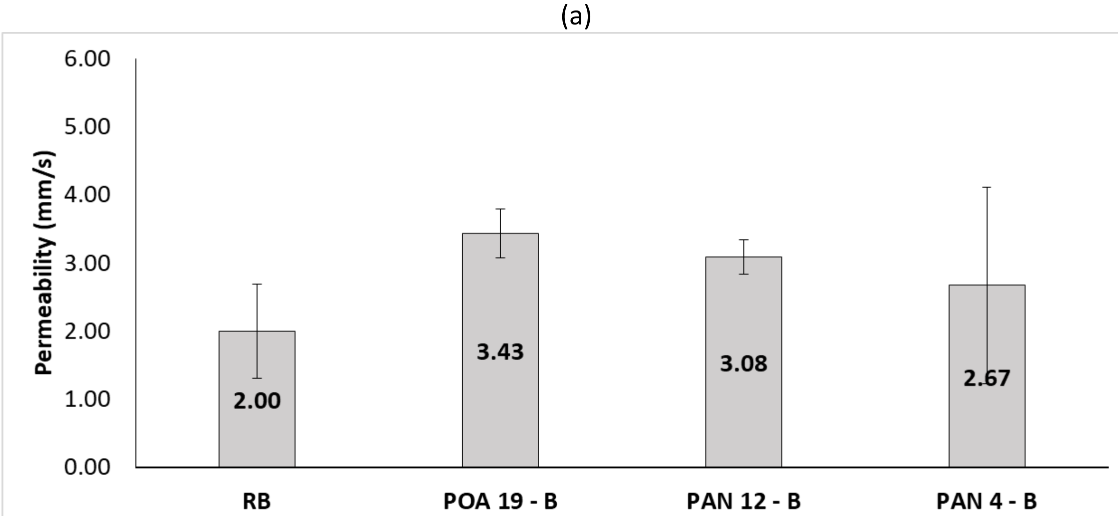

(b)

*Figure 14 Total and interconnected air voids; (a) High filler content; (b) Low filler content*

Regarding permeability values, the same phenomenon was observed. With high filler content, a slight reduction in the permeability was presented, and although no significant differences were observed between fiber-reinforced porous asphalt mixtures, the PAN 4- A showed the higher permeability rate. It is likely that the longer the fiber length, the higher the negative impact on the permeability. Focusing on the mixtures with low filler content (see Figure 15), the addition of fibers seems to increase the permeability of the PA mixture. According to the statistical analysis, this effect is significant, and the mixture that presented the biggest improvement compared to the reference mixture (RB) was the POA-B design ($p_{value}$=0.050). The observed phenomenon could be due to the fact that by decreasing the filler/binder ratio, the fibers can absorb a higher amount of the light components of the bitumen. Similarly, focusing again on the PA mixes with the lower filler content, the addition of fibers appears to increase the interconnected voids leading to a higher permeability. In general terms, although slight changes of permeability were found, the minimum recommended value in ASTM D7064-04 [1,99] was fulfilled (1.2 mm/s).




(a)



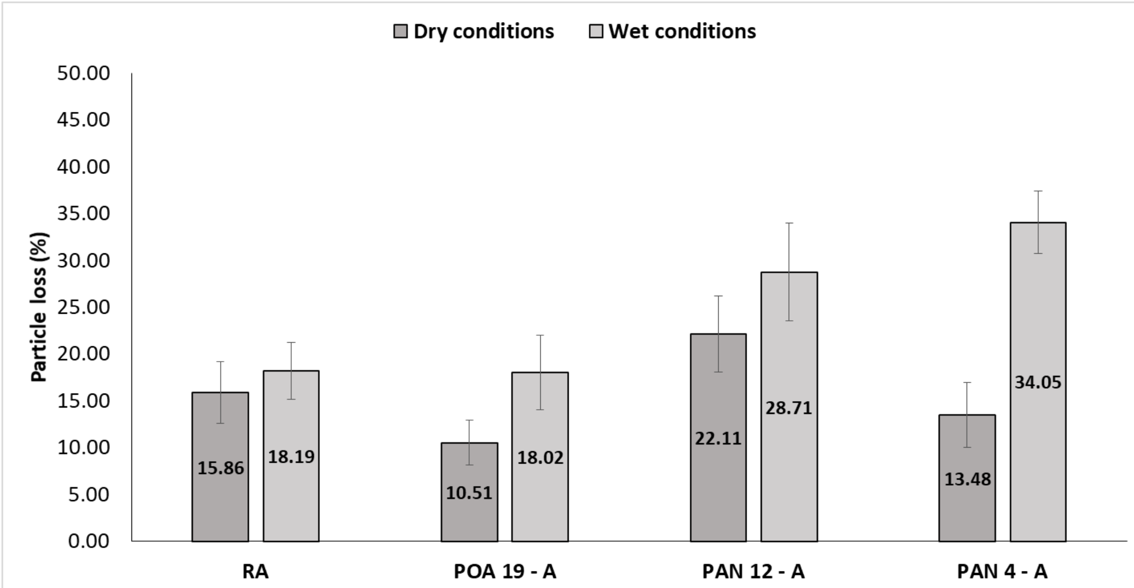

(b)

*Figure 15 Permeability results; (a) High filler content; (b) Low filler content*

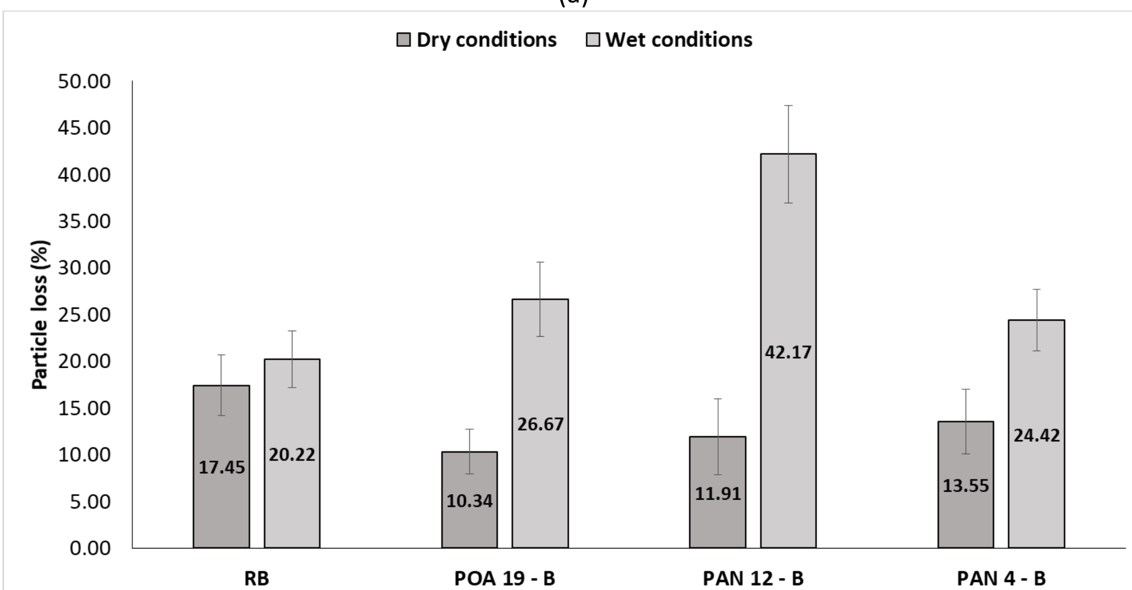
#### 5.2.1.2 Particle loss according to Cantabro *test*

The results concerning the particle loss in both dry and wet conditions for both filler contents are shown in Figure 16. According to the results, in general, the use of fibers in the PA mixture positively affected its particle loss resistance, especially in dry conditions. Concerning mixtures with high filler content, the samples POA 19-A and PAN 4-A showed particle loss improvements of 33.7% and 15%, respectively, respect the reference mixture RA. Besides, considering data dispersion, the differences among the reference mixture and the fiber-reinforced mixture with POA were found to be statistically significant ($p_{value}$= 0.047), even though the voids content was almost the same. It is worth mentioning that polyolefin fibers were fully dissolved due to the temperature of the mixing process. In this sense, Hejazi et al. [101] reported that slightly dissolved fibers provided a better bond strength with the bitumen within the hot mix asphalt. The above added to that aramid fibers have higher length and tensile properties could explain the higher impact provided by the polyolefin plus aramid fibers. In relation to mixtures manufactured with low filler contents, the addition of POA fibers to the PA mixtures with low filler content showed a higher increase in the particle loss resistance, observing a rise of 40-41% in comparison to the reference mixtures being these results statistically different ($p_{value}$=0.017). Furthermore, PAN fibers provided similar results to those provided by POA fibers. Specifically, PAN 12-B and PAN 4-B improved the resistance to particle loss by 31.7% and 22.3%, respectively, in relation to the reference mixture (RB). However, only the mixture PAN 12-B with the highest total air voids content fibers turned out to be statistically significant ($p_{value}$=0.050). As mentioned before, when the filler/binder ratio is reduced, there is a free amount of bitumen that can be absorbed by the fibers leading to a better reinforcement of the porous mixture.

The results obtained in the Cantabro test carried out in wet conditions did not turn out as promising. Actually, reference mixture RA and fiber-reinforced mixture POA 19-A presented the best results with a particle loss of 18.2 and 18.0, respectively. Overall, the addition of fibers did not provide significant improvements in the mixture in wet conditions. This could indicate that these fibers are sensitive to water absorption. Focusing on the asphalt mixes with low filler content, the initial hypothesis was that less filler content would increase the coating of the fibers by the bitumen and, therefore, increase the resistance to ravelling in wet conditions. However, similar results were obtained, and no significant differences were found. Although the fibers could be better coated by the free bitumen in the mix, decreasing the filler content affected the behaviour of the mortar making it more sensitive to the action of water. Thereby, these results suggest that the incorporation of fibers probably requires to keep an adequate filler/binder ratio and the addition of higher amounts of bitumen to coat the mortar-fiber interface completely and to prevent its exposition to the weather conditions.




(a)



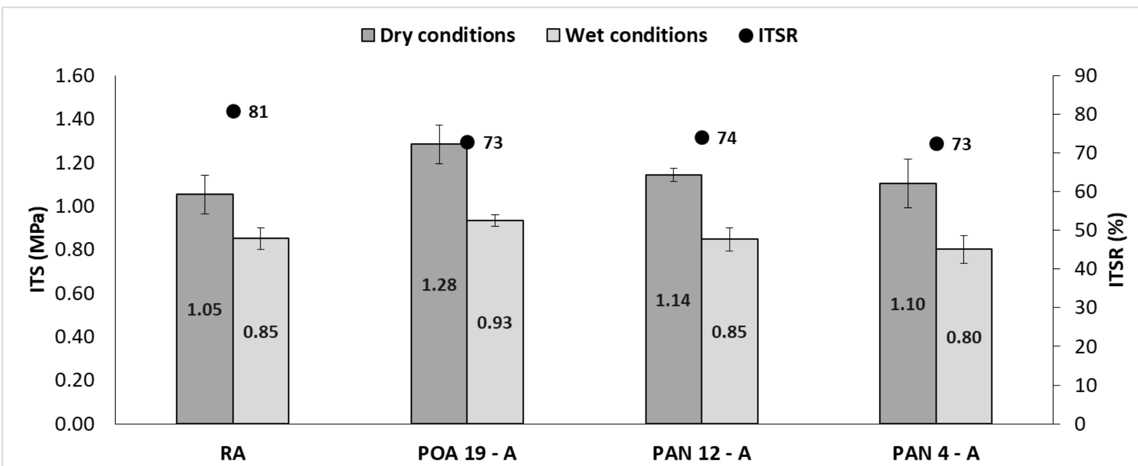

(b)

*Figure 16 Particle loss results; (a) high filler content; (b) Low filler content*

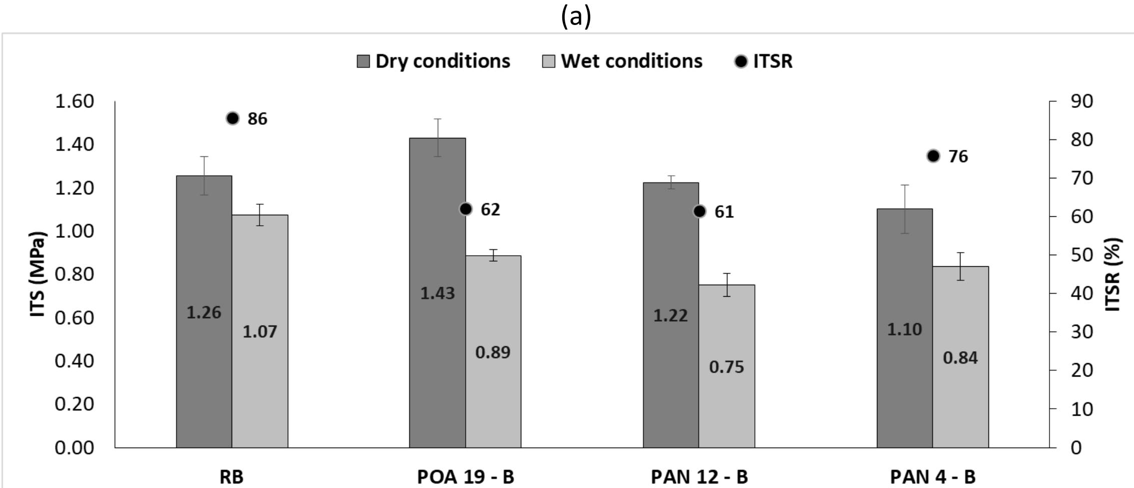
### *5.2.1.3 Indirect tensile strength and moisture sensitivity*

Figure 17 shows the ITS and moisture sensitivity results of the FRPA mixtures with respect to both filler contents. Regarding the ITS values measured in dry conditions, the increase of the tensile due to the addition of the different fibers are observed. Considering the mixtures with higher filler/binder ratio, the addition of POA fiber (19mm) increases the indirect tensile strength in 22% as compared to the reference mixture (RA), being this difference significant ($p_{value}$=0.019). However, in the case of the mixtures with low filler content, 13.5% improvement achieved by the POA fiber has turned out to be insignificant ($p_{value}$=0.060), although close to the limit of 0.05 with the 95% confidence interval. On the other hand, neither 12mm nor 4mm PAN fibers showed significant increases in the ITS values with $p_{values}$ of 0.156 and 0.530, respectively.

Concerning the ITS results in wet conditions (Figure 17), the highest strength was also obtained when POA fibers were added to the PA mixture, with an increase of 9.4% comparing to the reference mixture (RA). This is the only result significantly different ($p_{value}$=0.050). The other fiber reinforced mixtures did not show any significant improvement. Based on these results, it can be concluded that the addition of fibers to the PA mixture improves only the ITS in dry conditions. In this sense, the ITSR values confirm the aforementioned conclusions (see Figure 7). According to the results, the RB mixture showed the highest ITSR value (86%). However, it should be noted that the main reason for the observed reduction in ITSR when the fiber is added is caused by the increase of the ITS in dry conditions.




(a)




(b)

*Figure 17 Indirect tensile strength and ITSR results; (a) High filler content; (b) Low filler content*

*5.2.1.4 Toughness and cracking resistance*

In this research, typical indirect tensile stress-strain curves were recorded in dry and wet conditions for both filler conditions, as shown in Figure 18. From the graphs, it can be seen that the initial stiffness is higher in FRPA mixes as compared with the reference mixtures for high and low filler conditions in almost all the majority of cases. From the ITT test and the curves recorded, a total of 48 specimens were tested and the fracture energy (FE), post cracking energy (PE) and toughness mean values (series of three samples) were calculated as can be seen in Figure 19 and Figure 20 also in dry and wet conditions, respectively.

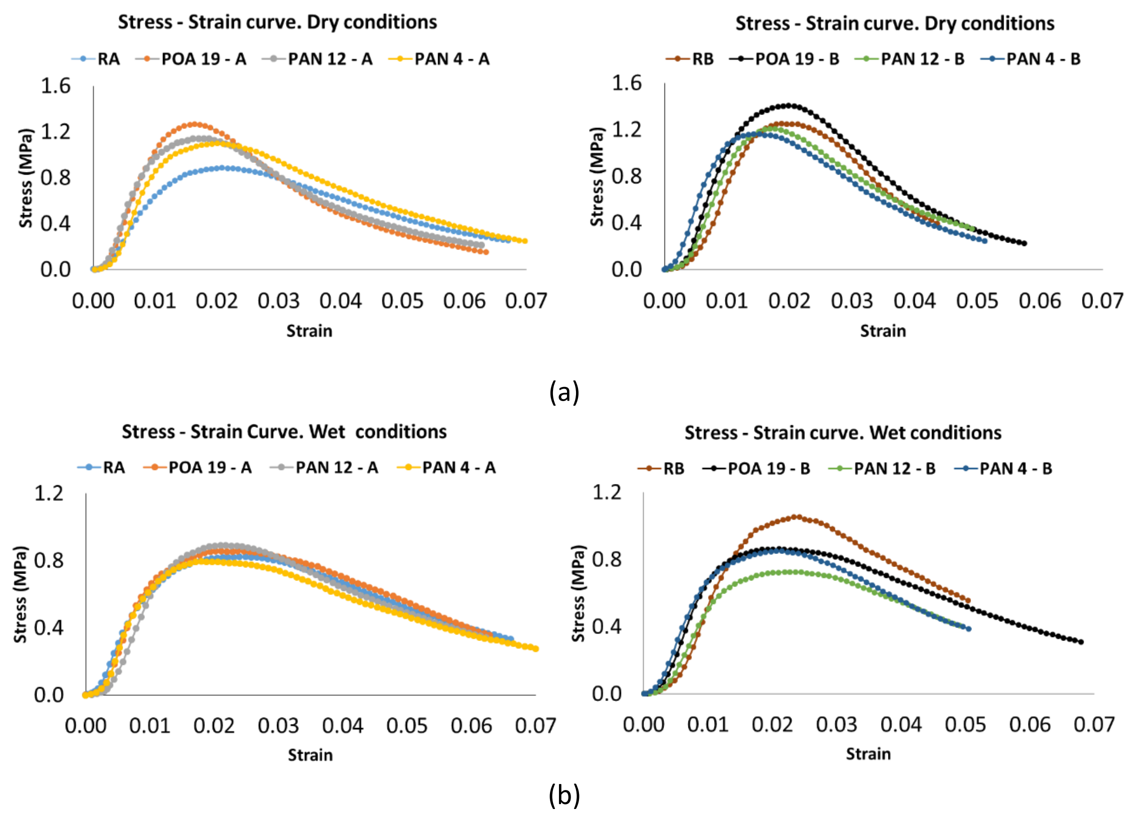
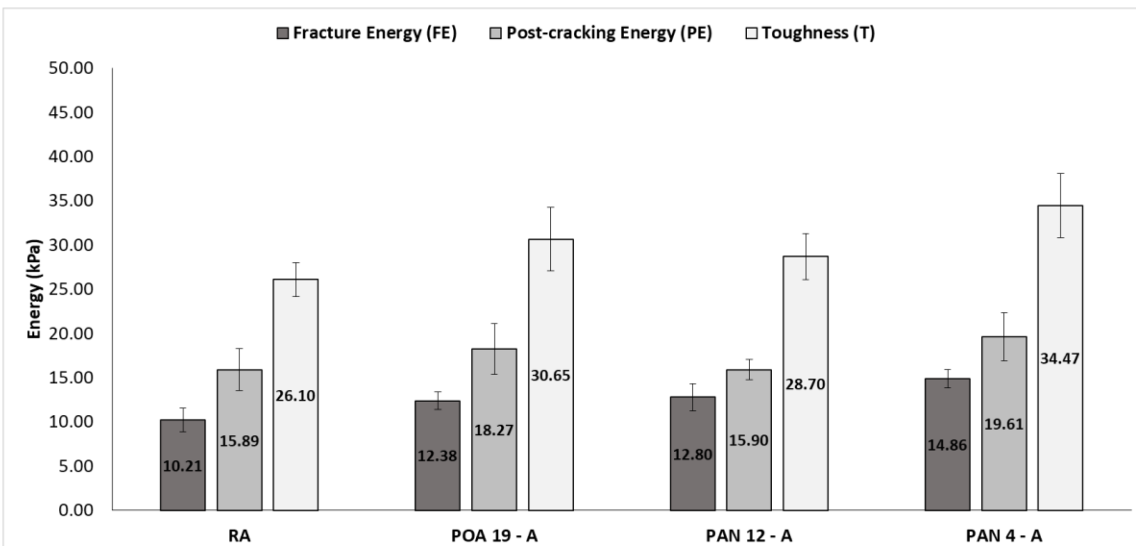


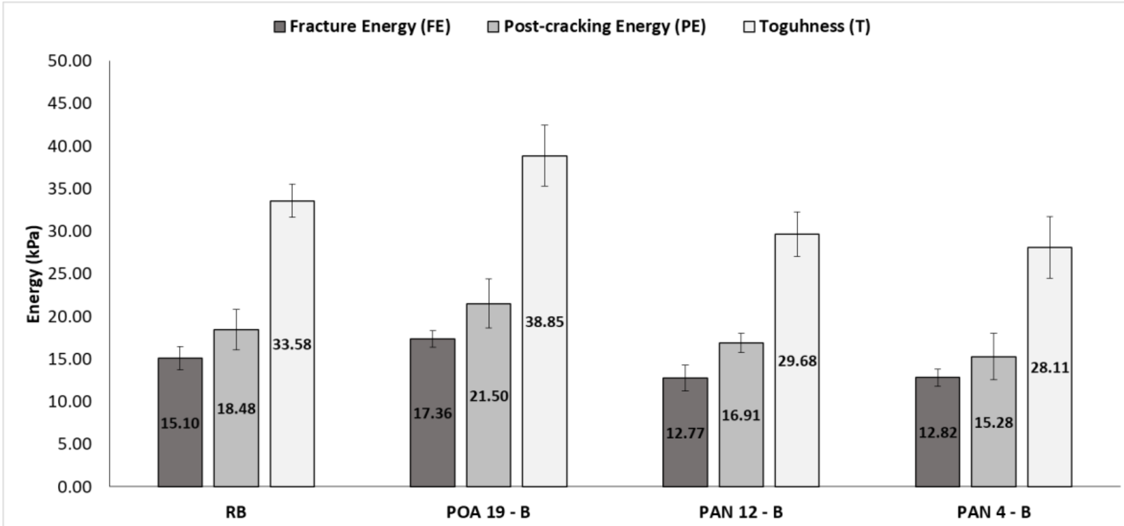

*Figure 18 Stress-strain curves of FRPA mixtures; (a) high filler content; (b) Low filler content*

Based on results obtained from fracture properties in dry conditions, the PAN 4-A mixture presented the major fracture energy with an increase of 46% comparing to the reference mixture RA being statistically significant ($p_{value}$=0.009). Similarly, this mixture also reported the highest PE and toughness with increases of 23.5% and 32.1%, respectively, compared to the reference mixture RA, being only the increase in toughness statistically significant ($p_{value}$=0.024). This is likely due to the fact that short fibers are completely embedded in the asphalt mortar of the PA mixture, forming a three-dimensional network in the mortar matrix and increasing the cohesive forces within the mortar [104].

Focusing on the samples with a lower filler content (B), the FE is slightly increased when POA fibers are added compared to the reference mixture (RB). In addition, it is interesting to note that, in dry conditions, the mixtures reinforced with PAN fibers (both 12 and 4 mm) presented similar FE for both low and high filler content and although the POA19-A mixes presented 40% higher FE than POA 19–B mixes, the result turned out to be not statistically significant ($p_{value}$=0.116). Therefore, changes in the filler content seem not to significantly affect the fracture energy of the PA mixtures. Similarly, slight increases in the post-cracking energy are generally observed in Figure 19 when using fibers. It should be noted that an increase in the post-cracking energy means a delay in the crack propagation when the pavement structure is subjected to traffic loads. Based on the results, POA fibers seem to achieve the greatest improvement in the post cracking energy. However, although PAN fibers reported improvements in relation to the reference mixture RA, lower PE results were obtained comparing to the RB mixture.



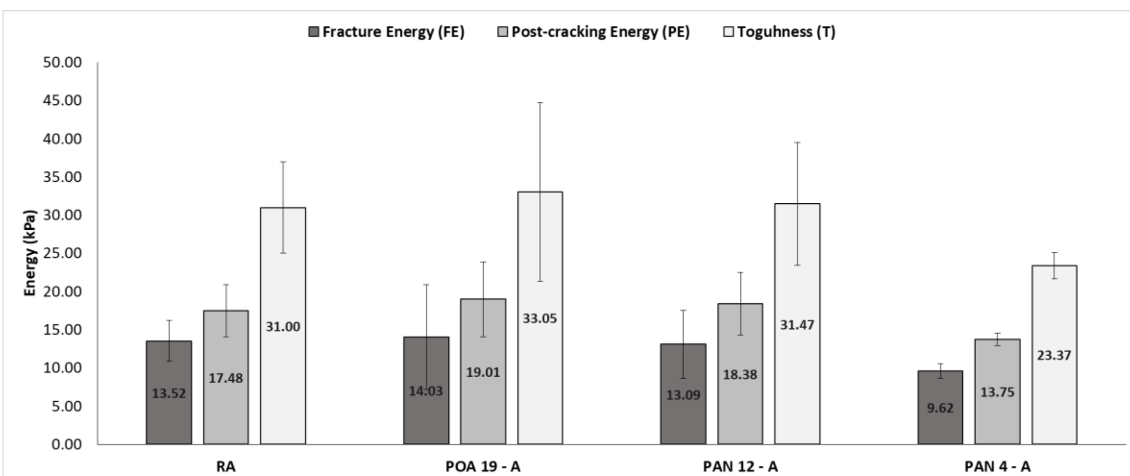

(a)



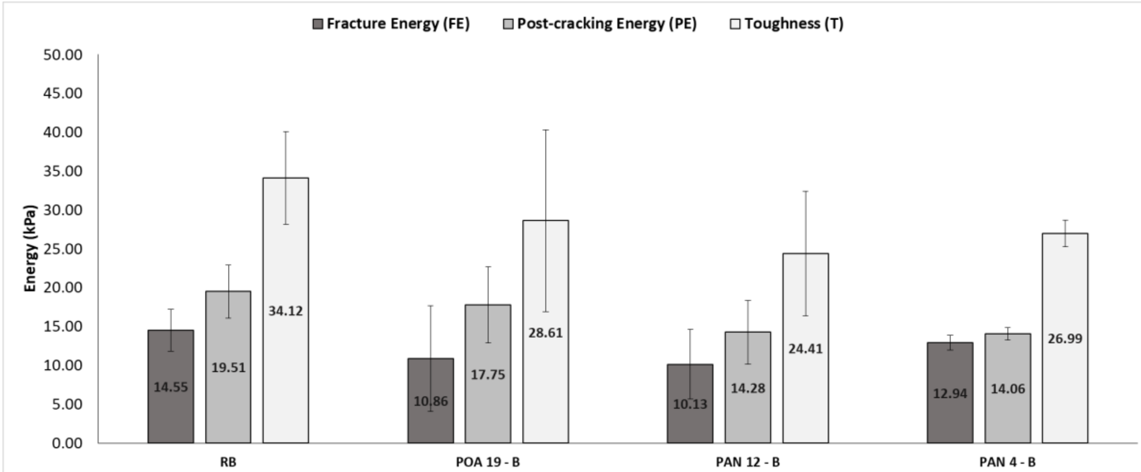

(b)

*Figure 19 Fracture properties obtained from ITT - dry conditions; (a) High filler content; (b) Low filler content*

Finally, when analyzing the results obtained in the ITT test in wet conditions, no significant improvements are observed when fibers are added to the PA mixture (Figure 20). This is probably due to a potential negative effect of water on the fiber-reinforced PA mixtures tested. In this sense, Chen and Xu [105] measured the water absorption of different types of fibers, reporting an absorption of 11% in the case of PAN fibers. According to this, the fibers are also expected to contribute to prevent bitumen drainage, so the use of higher bitumen content in these mixtures is not only possible but also highly recommended to avoid the negative water affection.




(a)




(b)

*Figure 20 Fracture properties obtained from ITT – wet conditions; (a) High filler content; (b) Low filler content*

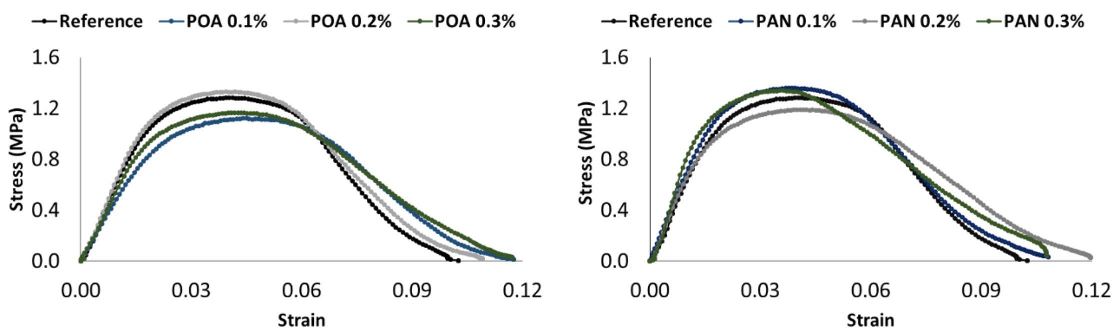
As mentioned earlier, this phase was performed to select the most promising fiber to be implemented in phase two of the research. The analysis of results discussed at this stage has allowed the selection of POA fibers and the 4 mm long PAN fibers to be used in the experimental evaluation at the asphalt mortar scale. In general, all the modified mixtures with fibers showed a very similar air voids content between them, and all of them accomplished the minimum permitted by the 20% standard. Regarding the experimental evaluation at the PA mixture scale, the addition of POA fibers improved the particle loss in dry conditions, and good results were obtained in the ITT, and slight improvements in fracture properties (dry conditions) were obtained from the stress-strain curves. On the other hand, the 4 mm long PAN fiber yielded better results than the 12 mm long PAN fiber in the particle loss in dry conditions and showed the major fracture energy being statistically significant.

### *5.2.2 Experimental results at asphalt mortar scale*

Concerning fiber-reinforced asphalt mortar mixes, the indirect tensile strength and fracture properties such as FE, PE, and toughness were calculated based on the experimental results obtained from the indirect tensile test. In this phase, 19 mm long POA fibers and 4 mm long PAN fibers were experimentally assessed in the mortar mixes. Summing up, four different fiber contents (0.0%; 0.1%; 0.2% and 0.3%) and tested at three different temperatures (15°C; 0°C and -15°C) were done in this stage. For practical purposes, since in this stage only one length of PAN fiber is used (4mm), the 4 mm long PAN fibers are now referred to as PAN.

#### *5.2.2.1 ITS and fracture property results at 15°C*

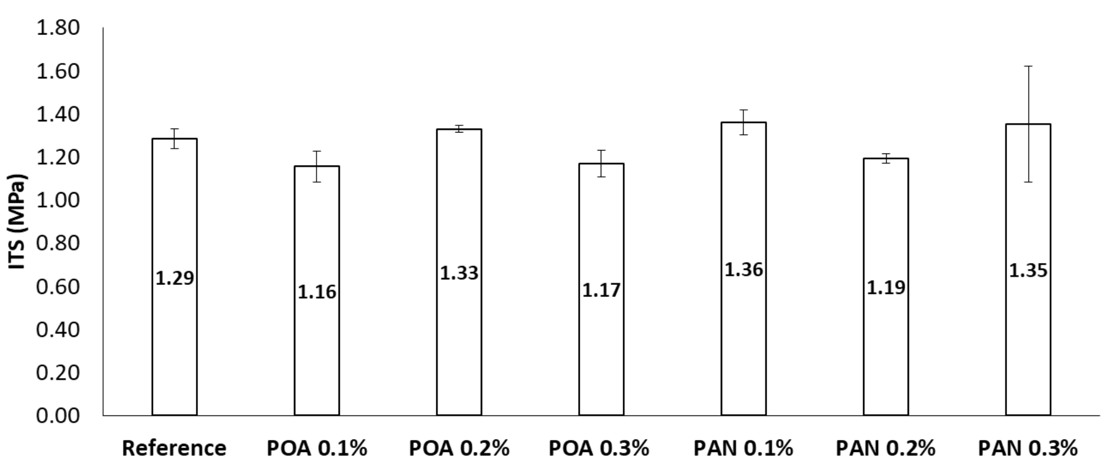
Figure 21 shows the average stress-strain curves of the fiber-reinforced asphalt mortar compared to the reference asphalt mortar without fibers at 15°C. From the graphs, it can be observed that asphalt mortar at this temperature starts with an elastic component followed by a plastic component until the peak load is reached. Although bituminous materials have a viscous component, the high loading rate contributes to minimize the potential of creep of the mortar and, therefore, behaves like an elastic-plastic material.



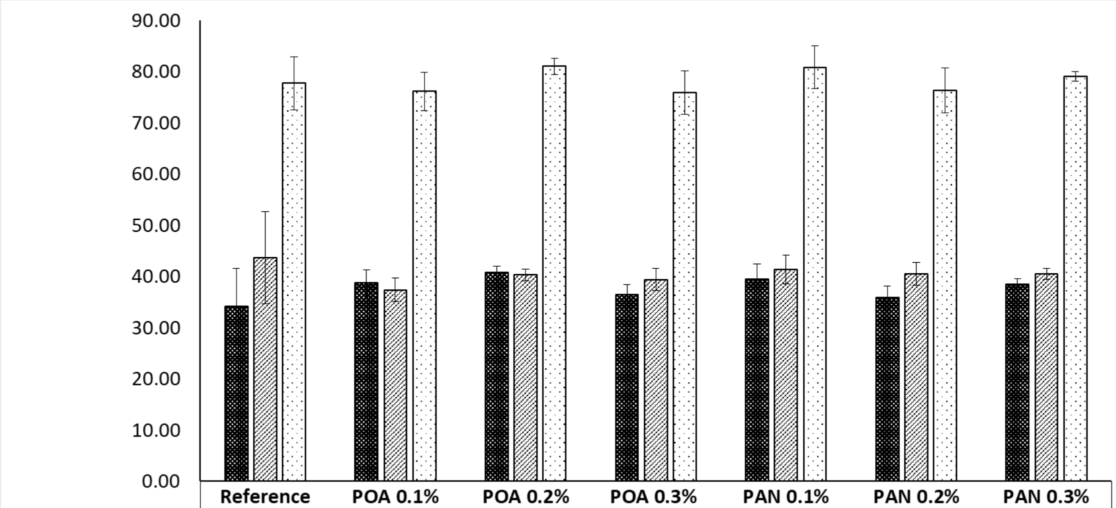

(a) (b)

*Figure 21 Stress-strain curves of bituminous mortars at 15°C; (a) POA fibers; (b) PAN fibers*

The mean results of the obtained ITS and fracture parameters of fiber-reinforced asphalt mortars at 15°C are displayed in Figure 22. The error bars indicate the standard deviation from the mean. Based on the results, the addition of fibers could improve the ITS to some extent. In order to see the statistical differences with respect to the reference mortar, two-sample t-tests were performed since all data are normally distributed and have homogeneity of variance. Despite the slight improvements, not statistical differences were seen as compared to the reference mixture. Regarding FE results, it can be observed that the amount of energy required for the initiation of the cracking increases when fibers are added. Although it did not present statistical differences, the behaviors of the fiber-reinforced asphalt mortars were different, showing a tendency to increase the FE in all cases. Similarly to FE results, statistical differences were not observed in PE and toughness results.




(a)



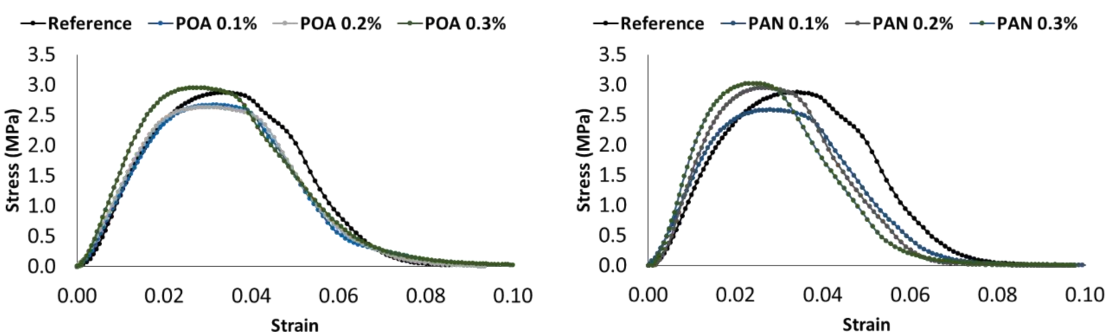
| | Reference | POA 0.1% | POA 0.2% | POA 0.3% | PAN 0.1% | PAN 0.2% | PAN 0.3% |
|---|---|---|---|---|---|---|---|
| FE (kPa) | 34.11 | 38.76 | 40.74 | 36.45 | 39.46 | 35.86 | 38.50 |
| PE (kPa) | 43.60 | 37.35 | 40.28 | 39.41 | 41.36 | 40.48 | 40.51 |
| Toughness (kPa) | 77.71 | 76.11 | 81.01 | 75.85 | 80.82 | 76.34 | 79.01 |

(b)

*Figure 22 ITS and fracture parameters results at 15°C; (a) ITS values (b) Fracture properties*

### *5.2.2.2 ITS and fracture property results at 0°C*

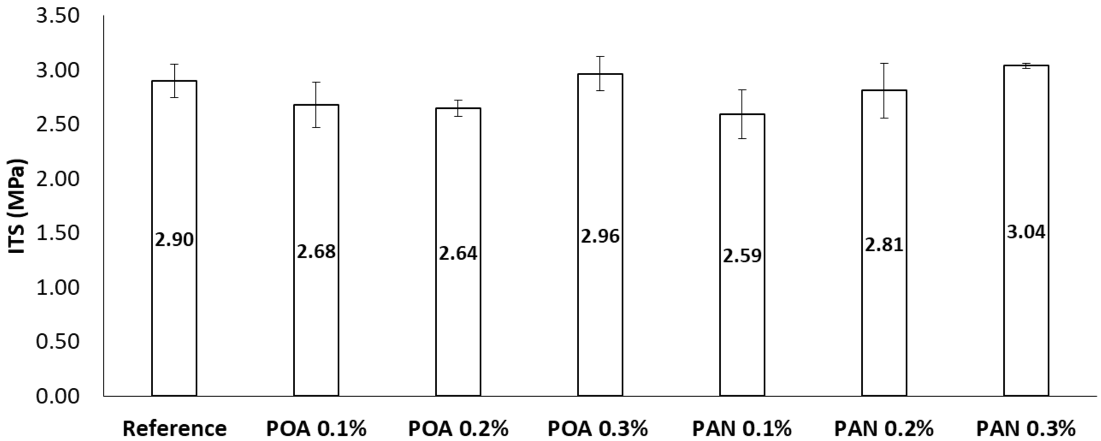
Figure 23 shows the average stress-strain curves of the fiber-reinforced asphalt mortar compared to the reference asphalt mortar without fibers at 0°C. Similar elastic-plastic behavior was identified at this temperature. However, at this low temperature, the mortar mixture becomes stiffer although retaining its ductile properties.



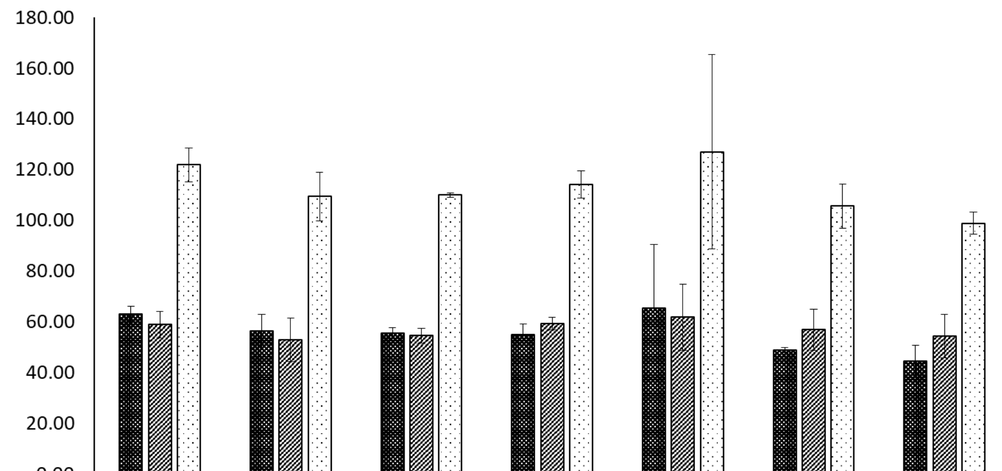

(a) (b)

*Figure 23 Stress-strain curves of bituminous mortars at 0°C; (a) POA fibers; (b) PAN fibers*

The ITS values and fracture parameters obtained from the tests carried out at 0°C are shown in Figure 24. Based on the results these were not significant with respect to the reference mortar mix. Concerning fracture parameters, an aspect to remark is that none of the types of fibers, regardless of their content, provide a significant positive impact on FE properties at this temperature.




(a)



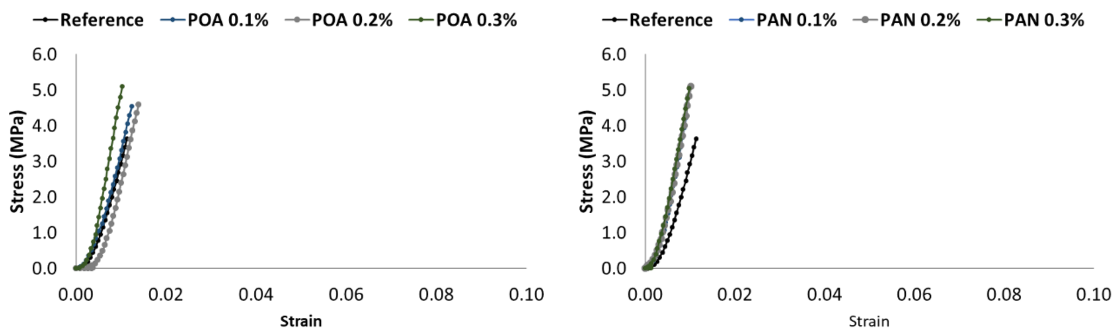

| | Reference | POA 0.1% | POA 0.2% | POA 0.3% | PAN 0.1% | PAN 0.2% | PAN 0.3% |
|---|---|---|---|---|---|---|---|
| **FE (kPa)** | **62.89** | **56.37** | **55.46** | **54.97** | **65.23** | **48.70** | **44.47** |
| **PE (kPa)** | **58.92** | **52.98** | **54.47** | **59.23** | **61.77** | **56.87** | **54.34** |
| **Toughness (kPa)** | **121.82** | **109.35** | **109.93** | **114.20** | **127.00** | **105.57** | **98.81** |

(b)

*Figure 24 ITS and fracture parameters result at 0°C (a) ITS values (b) Fracture properties*

### 5.2.2.3 ITS and fracture property results at -15°C

Figure 25 shows the average stress-strain curves obtained at the lowest temperature in this study phase. It was found that at -15°C, the behavior of the mortar mixes was observed as elastic-brittle, which means that when the tensile strength reaches its maximum value, the specimens break instantly, and the stress drops to zero after the first cracking. A similar observation was also reported by Park et al. [72], who studied the fracture properties of AC mixtures at low temperatures (-20°C). Once the specimen has achieved the maximum strength, it is broken apart in two pieces in a brittle mode. In this case, the post-cracking energy is negligible and, therefore, FE and ITS are the only parameters that can be calculated.

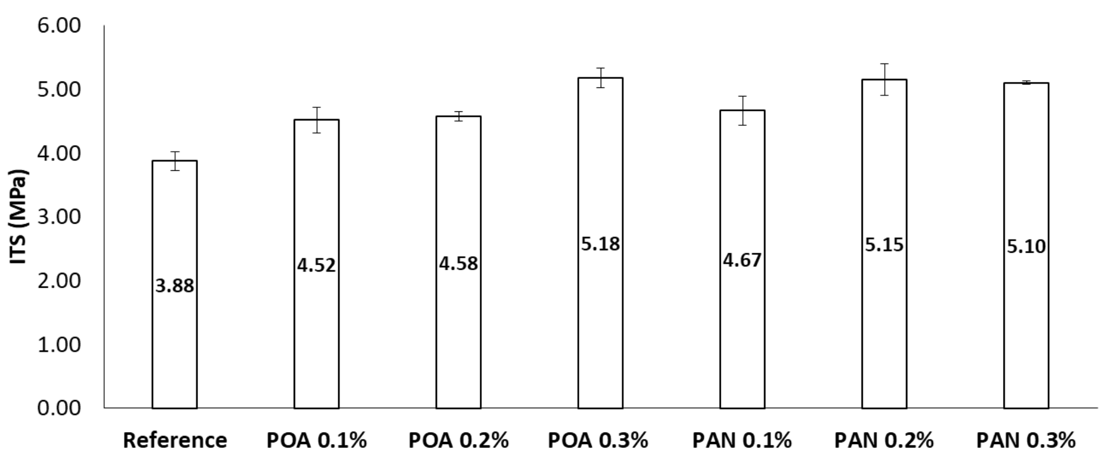



(a) (b)

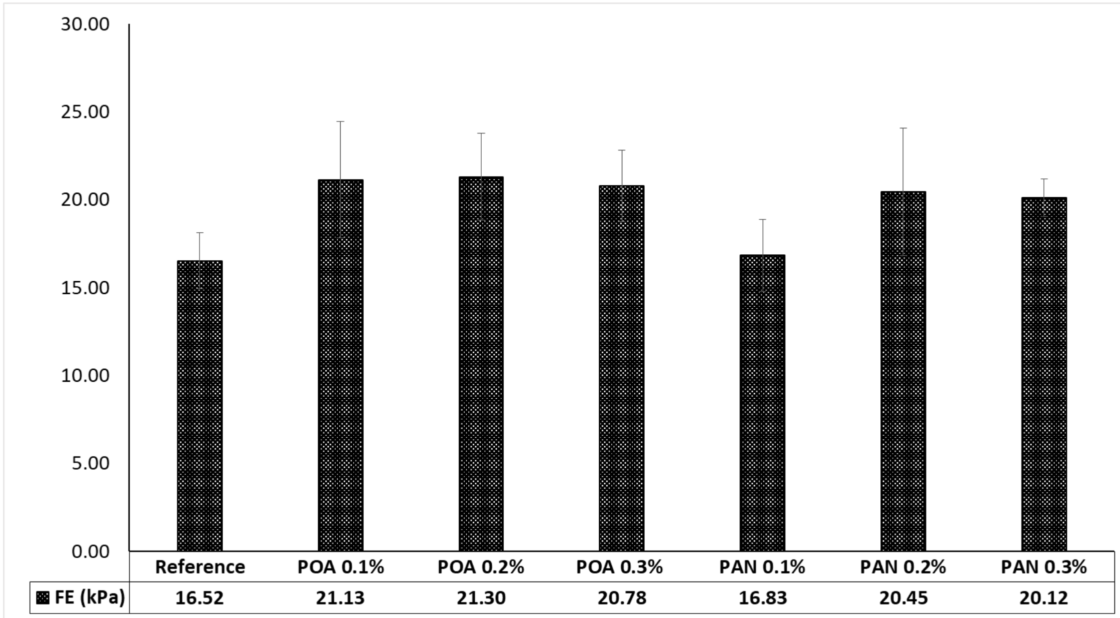
*Figure 25 Stress-strain curves of bituminous mortars at -15°C; (a) POA fibers (b) PAN fibers*

The ITS results and FE properties are displayed in Figure 26. Concerning fiber reinforcement, at -15 °C, adding fibers to the mortar increases ITS values in comparison to the samples without fibers (reference). Analyzing the influence of fiber content on the results, it can be observed that as the fiber content increases, the ITS values also increase. Concerning POA fibers, the best improvement was observed in the samples that incorporate 0.3% of POA fibers. This improvement is statistically significant in relation to the reference mortar ($p_{value} = 0.042$). Moreover, improvements of 16.50% and 18.04% were obtained by adding 0.1% and 0.2% of POA fibers. However, these differences proved not to be statistically significant. With regards to PAN fibers, mortars reinforced with 0.2% and 0.3% of PAN fibers exhibited an improvement of 32.73%, and 31.44%, respectively, respect the reference mortar. However, only the addition of 0.3% of PAN fibers proved to be statistically significant ($p_{value} = 0.021$).

The FE properties were also influenced by the fiber dosing. In this sense, improvements of 25.76% and 21.79% were obtained, adding 0.3% of POA and PAN fibers, respectively. These results were also found statistically significant with $p_{values}$ of 0.045 and 0.048, respectively. In the other cases, although there were no significant differences, there is a clear tendency where the higher fiber content, the better the fracture energy properties observed.




(a)




(b)

*Figure 26 ITS and fracture property results at -15°C; (a) ITS values (b) Fracture parameters*

Summing up the experimental tests at the asphalt mortar scale, the significant differences were noted at a low temperature suggesting that both fibers worked properly as reinforcement at the bituminous mortar scale. However, the improvements were slightly greater with the POA fibers in comparison to the PAN fibers. Moreover, considering that better results in terms of raveling and tensile strength in dry conditions were reached with FRPA manufactured with POA fibers. This set of fibers was selected as the most promising one, and the current research proceeded to work with only this fiber type in the second phase.

### 5.3 Results of the novel integrated DoE-MCDM analysis considering the influence of various control factors

As mentioned in the methodology section, in this second phase, the impact of various control factors in the functional and mechanical performance of the PA mixture is studied. Binder type, fiber content, and binder content were the main control factors to analyze it in order to be able to evaluate the reinforcing effect of fibers. Multiple responses, including total and interconnected air voids, particle loss in dry and wet conditions, and binder drain down, were assessed experimentally. The Taguchi approach was selected to design the experiments in this phase. The main effects plot for means and $SN$ ratio were calculated to determine the optimal parametric levels for each control factor in each one of the experimental responses. It is important to highlight that *SN* ratio is an indicator of the variance of the characteristics of their desired values. Thus, the *smaller-the-better* was calculated for durability (particle loss in dry and wet conditions) and binder drain down test whereas the *larger-the-better* for functional tests (air and interconnected air voids). In this phase, a low variance was found between the main effects plot for means and *SN* ratio. In other words, the

*SN* ratio matches very well with the main effects of means. Thereby, to simplify, only the main effects plot for means are presented in this section. More details can be found in article three of this thesis (section 4.3). As more than one response was calculated, this study proposed a novel MCDM analysis to transform the multiple-response optimization problem into a single-unique optimization problem and to elaborate a preference ranking among all the mixture designs. More specifically, the CRITIC approach served to determine the objective weights of the different responses, whereas TOPSIS was selected in order to transform the multiple responses into single responses and to rank all the experimental designs among the responses defined. In the first stage, the results of each of the individual responses are analyzed and discussed individually, to then, in the second stage, move on the MCDM analysis.

### *5.3.1 Analysis of individual responses*

The different response values obtained by way of the Taguchi L18 orthogonal array can be observed in Table 9. Total and interconnected air voids are considered important responses to assess the functionality of the mixture in terms of permeability, noise properties, and macrotexture. As for the results, the mean values of $T_{AV}$ and $I_{AV}$ ranged from 17.50% to 23.20% and 11.20% to 17.26%, respectively (see Table 9). Similarly, it is worth highlighting that a direct relationship exists between both responses, with a Pearson correlation coefficient of 0.89. Therefore, considering the relationship which exists between these two response values, a linear regression model with a confidence interval of 95% was developed, as it can be observed in Figure 27. Based on the data results, the model fits very well with a $R^2$ of 0.80 and $p_{value}$ < 0.0001 indicating a suitable prediction and, as a result, showing that higher values of total air voids imply higher values of interconnected air voids. The particle size distribution curve was sought to provide high total air voids. Although a minimum value of 20% of total air voids is required in order to guarantee proper hydraulic performance, skid resistance, and safety driving in Spain, other authors argued that PA mixtures with $T_{AV}$ higher than 18% are considered acceptable [3]. Overall, all the mixture designs fulfill the requirement of voids higher than 18% except for the PA9 mixture design that had an air void content of 17.50%.

*Table 9 Experimental results of the individual responses*

| Design Number | Experimental ID | $T_{AV}$ (%) | | $I_{AV}$ (%) | | $PL_{dry}$ (%) | | $PL_{wet}$ (%) | | BD (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean |
| 1 | 50/70-FC:0.00-BC:4.50 | 21.39 | 0.75 | 14.59 | 1.32 | 14.96 | 1.99 | 19.12 | 5.51 | 0.01 |
| 2 | 50/70-FC:0.00-BC:5.00 | 18.85 | 0.14 | 12.45 | 0.70 | 6.76 | 2.65 | 15.32 | 3.20 | 0.40 |
| 3 | 50/70-FC:0.00-BC:5.50 | 18.68 | 1.12 | 11.94 | 1.48 | 9.37 | 0.75 | 8.28 | 2.03 | 2.25 |
| 4 | 50/70-FC:0.05-BC:4.50 | 21.36 | 0.35 | 15.59 | 1.01 | 12.52 | 1.99 | 39.85 | 10.23 | 0.01 |
| 5 | 50/70-FC:0.05-BC:5.00 | 19.67 | 0.40 | 13.57 | 0.61 | 7.90 | 4.27 | 15.71 | 1.89 | 0.03 |
| 6 | 50/70-FC:0.05-BC:5.50 | 18.85 | 0.14 | 12.45 | 0.70 | 4.90 | 1.68 | 10.70 | 1.40 | 0.59 |
| 7 | 50/70-FC:0.15-BC:4.50 | 23.22 | 0.22 | 17.26 | 0.38 | 19.71 | 2.01 | 35.95 | 5.05 | 0.02 |
| 8 | 50/70-FC:0.15-BC:5.00 | 20.38 | 0.88 | 14.14 | 1.06 | 15.66 | 1.86 | 22.74 | 3.15 | 0.01 |
| 9 | 50/70-FC:0.15-BC:5.50 | 17.49 | 1.30 | 11.22 | 0.99 | 7.01 | 1.39 | 9.08 | 2.15 | 0.16 |
| 10 | PMB-FC:0.00-BC:4.50 | 20.59 | 1.89 | 14.36 | 2.22 | 10.57 | 4.80 | 10.81 | 3.54 | 0.00 |
| 11 | PMB-FC:0.00-BC:5.00 | 21.12 | 0.40 | 15.16 | 0.80 | 5.16 | 2.77 | 7.19 | 1.68 | 0.28 |
| 12 | PMB-FC:0.00-BC:5.50 | 20.18 | 2.18 | 13.93 | 2.91 | 4.73 | 0.78 | 7.49 | 1.72 | 0.97 |
| 13 | PMB-FC:0.05-BC:4.50 | 20.81 | 2.14 | 14.47 | 2.66 | 5.94 | 2.20 | 7.80 | 3.52 | 0.00 |
| 14 | PMB-FC:0.05-BC:5.00 | 19.54 | 1.88 | 12.39 | 2.80 | 8.12 | 5.19 | 5.62 | 0.26 | 0.04 |
| 15 | PMB-FC:0.05-BC:5.50 | 18.42 | 2.51 | 14.39 | 3.43 | 2.52 | 0.96 | 8.25 | 2.47 | 0.12 |
| 16 | PMB-FC:0.15-BC:4.50 | 19.50 | 1.14 | 13.12 | 0.91 | 8.47 | 3.70 | 7.73 | 0.45 | 0.04 |
| 17 | PMB-FC:0.15-BC:5.00 | 20.22 | 0.17 | 14.15 | 0.11 | 4.77 | 1.02 | 5.26 | 0.76 | 0.05 |
| 18 | PMB-FC:0.15-BC:5.50 | 19.91 | 1.03 | 13.03 | 0.97 | 3.30 | 0.34 | 3.48 | 0.62 | 0.21 |

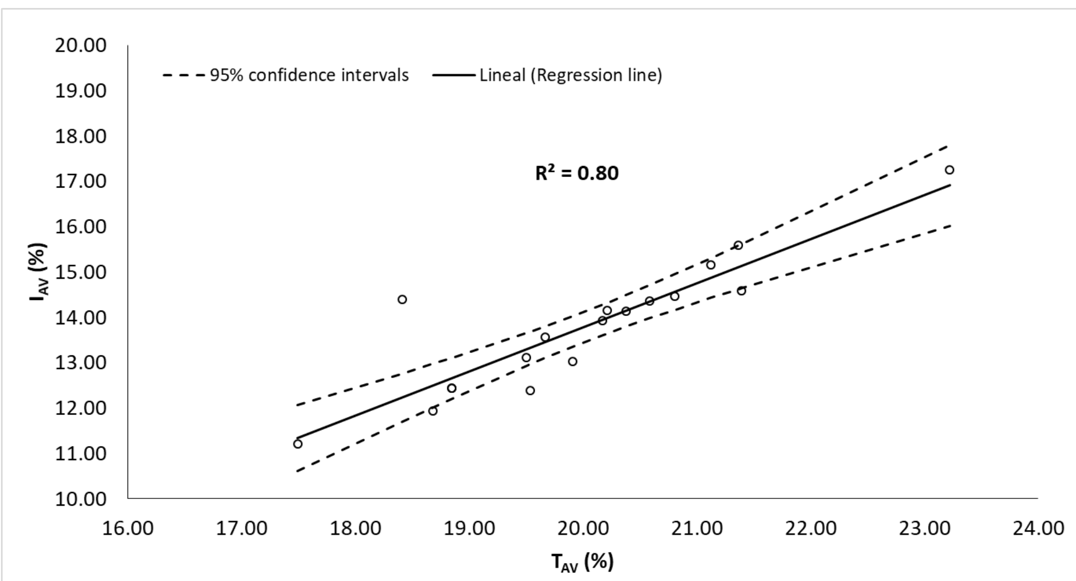
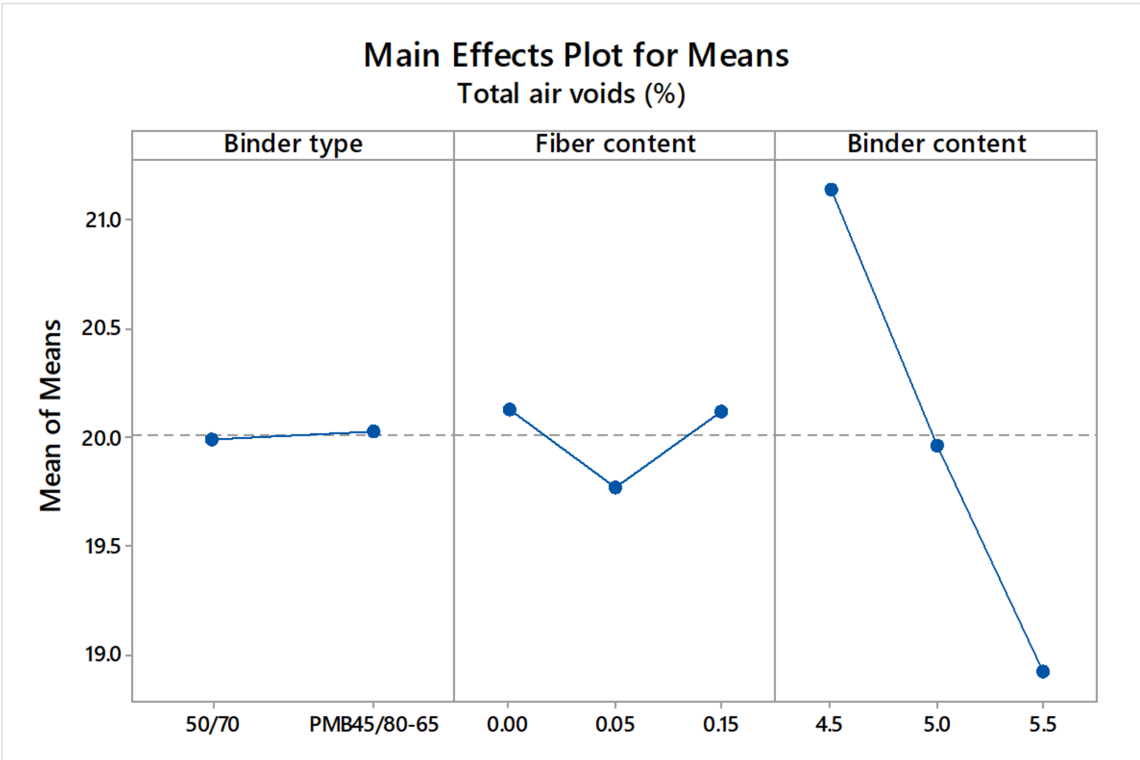
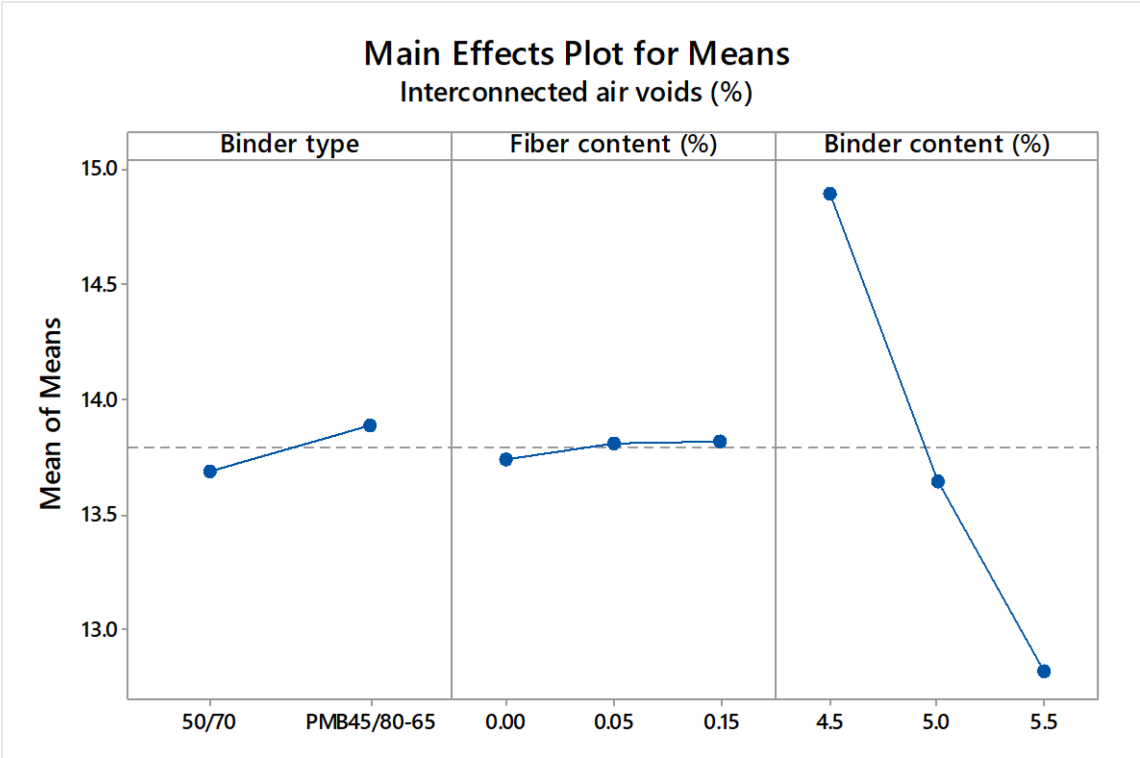



*Figure 27 Correlation between total and interconnected air voids*

The main effects plot for means of total and interconnected air voids are displayed in Figure 28. For both responses, the binder content is the most influential factor followed by the fiber content factor and binder type control factors. The trends are very similar for both air voids properties due to the stretch relation described previously. Similarly, the FC factor has a slight influence in the total air voids and a minimum influence in the interconnected air voids. Finally, the type of binder does not affect notably the voids in the mixture.



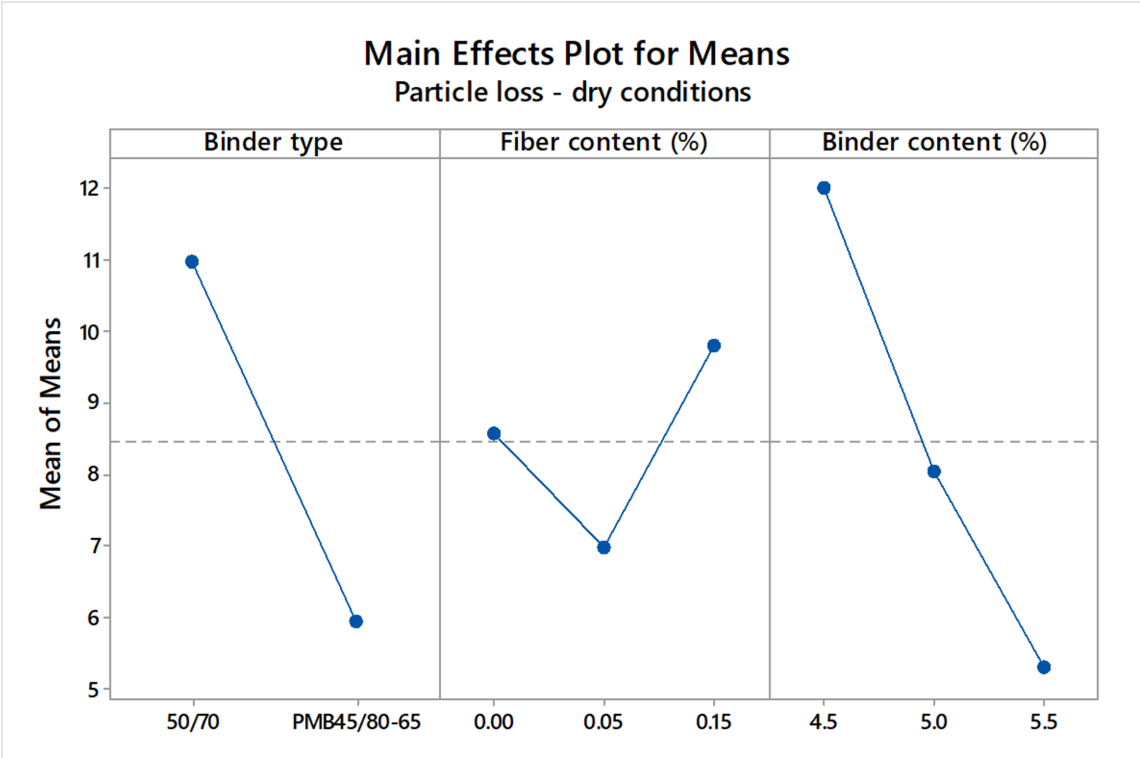

(a)



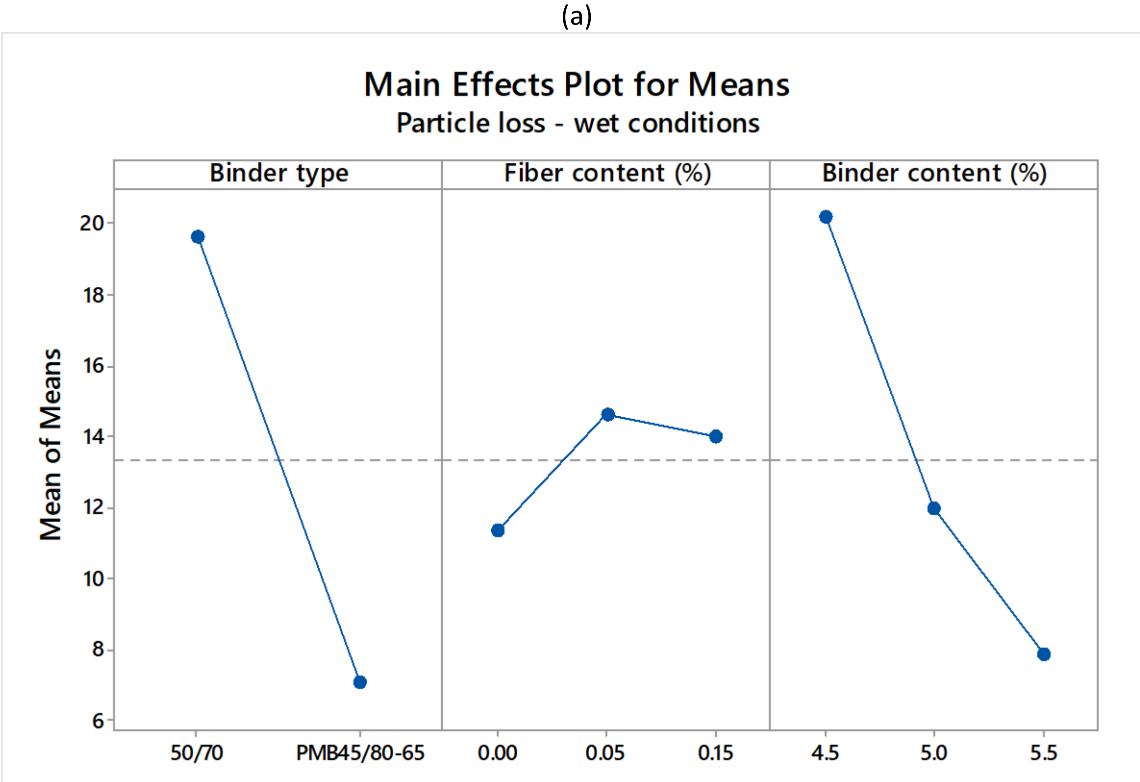

(b)

*Figure 28 Main effects plot for means; (a) Total air voids; (b) Interconnected air voids*

Due to the large number of experiments that this research involved, a significant test had to be done to evaluate the durability of the PA mixtures. Since raveling is the typical failure observed in this type of mixes, the Cantabro particle loss test in dry conditions was performed. Moreover, to measure the damage by action of water, the Cantabro particle loss test was also done in wet conditions. Figure 29 depicts the main effects plot for means for particle loss response in both dry and wet conditions. To increase the raveling resistance, lower values of particle loss are desirable. Accordingly, for $PL_{dry}$ the optimal levels were obtained when a polymer modified binder is used along with 0.05% POA fibers and 5.5% binder content. As for the $PL_{wet}$ value, the highest impact comes from the binder type and binder content. In fact, the contribution of fibers in terms of raveling resistance under water action is less appreciable when a polymer modified binder is used.




(a)




(b)

*Figure 29 Main effects plot for means; (a) particle loss - dry conditions; (b) particle loss - wet conditions*

The non-compacted PA mixtures corresponding to all designs were also subjected to evaluation of their drain down characteristics through the mesh basket drain down test following the EN 12697 – 18 standard. The main effects plot for means of Binder Drain down response are displayed in Figure 30. As well as the particle loss values, low values of binder drain down are desirable. According to the graph, the lowest binder drain down can be obtained when a conventional 50/70 penetration grade binder is used along with 0.15% POA fibers and 4.50% binder content. The reduced value of BC might suggest that fibers can absorb the free binder in the mixture as guessed in the tests carried out in the phase one of the current thesis.

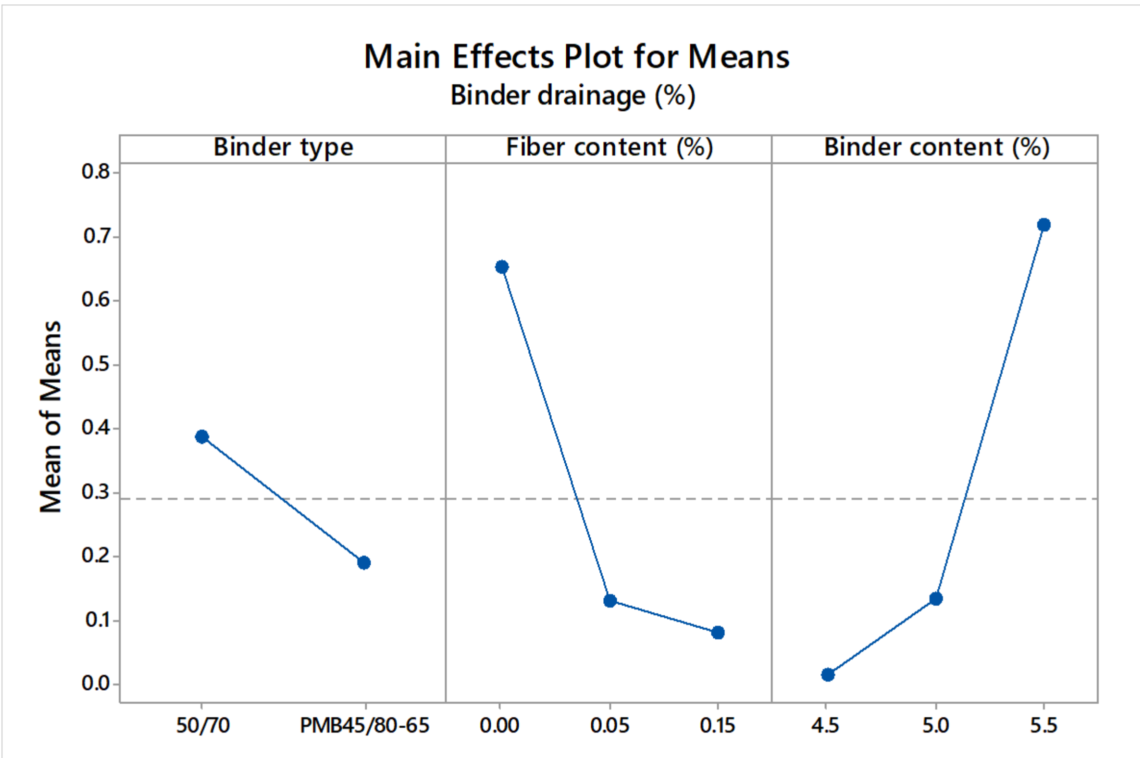



*Figure 30 Main effects plot for binder means of binder drain down*

### *5.3.2 Analysis based on MCDM analysis*

The optimal design of a PA mixture supposes the optimization of different responses. In other words, a PA mixture must fulfill different requirements from functional and mechanical points of view. Similarly, as several parameters are involved in many criteria, determining the most proper choice is a crucial task. Due to the above, the novel hybrid CRITIC-TOPSIS MCDM approach was applied to transform the multiple-response optimization problem into a single-unique response optimization problem[174]. In consequence, the CRITIC was employed in this research for the purpose of finding out the weights of each criterion. Although it is easier and quite common to assign equal weights for all criteria, using an appropriate weighting method is more beneficial in obtaining a more suitable solution. In the current work, CRITIC was chosen as an appropriate technique which takes advantage of the information provided by data. The weights assigned to each response variable are based on the contrast intensity and conflict assessment of the decision-making problem. Accordingly, Table 10 presents the amount of information and the final weights obtained from the CRITIC approach. It is worth mentioning that the greater quantity of information disposed in each criterion, the greater final weight of each response. Similarly, responses with high variance and lower correlation coefficient with other criteria have a higher amount of information. The graphical correlation matrix essential for calculating the relative weights is illustrated in Figure 31. The diagonal plots indicate the Q-Q plot, which compares the probability distribution of the data against the theoretical normal distribution function. As it can be seen, functional and mechanical responses have a stretch relation, but regarding BD response, a strict correlation was not found. The above was checked by determining the correlation coefficient Pearson among the normalized response variables (see Table 11), whose values in bold are statistically significant with a confidence interval of 95%.

As it can be seen in Table 10, total air voids and interconnected air voids have similar weights, which is due to the high correlation that exists between these two variables. On the other hand, particle loss in dry and wet conditions have the highest weights, with values of 0.24 and 0.25, respectively, suggesting that raveling resistance have a notable incidence in the overall performance of the PA mixture. Finally, the weight assigned to binder drainage was equal to 0.17, almost equal to $T_{AV}$ and $I_{AV}$ weights.

*Table 10 Amount of information and final weights obtained according to CRITIC*

| Criteria | *Amount of information* | *Final weights* |
|---|---|---|
| $T_{AV}$ (%) | 0.93 | 0.18 |
| $I_{AV}$ (%) | 0.92 | 0.17 |
| $PL_{DRY}$ (%) | 1.25 | 0.24 |
| $PL_{WET}$ (%) | 1.31 | 0.25 |
| $BD$ (%) | 0.90 | 0.17 |

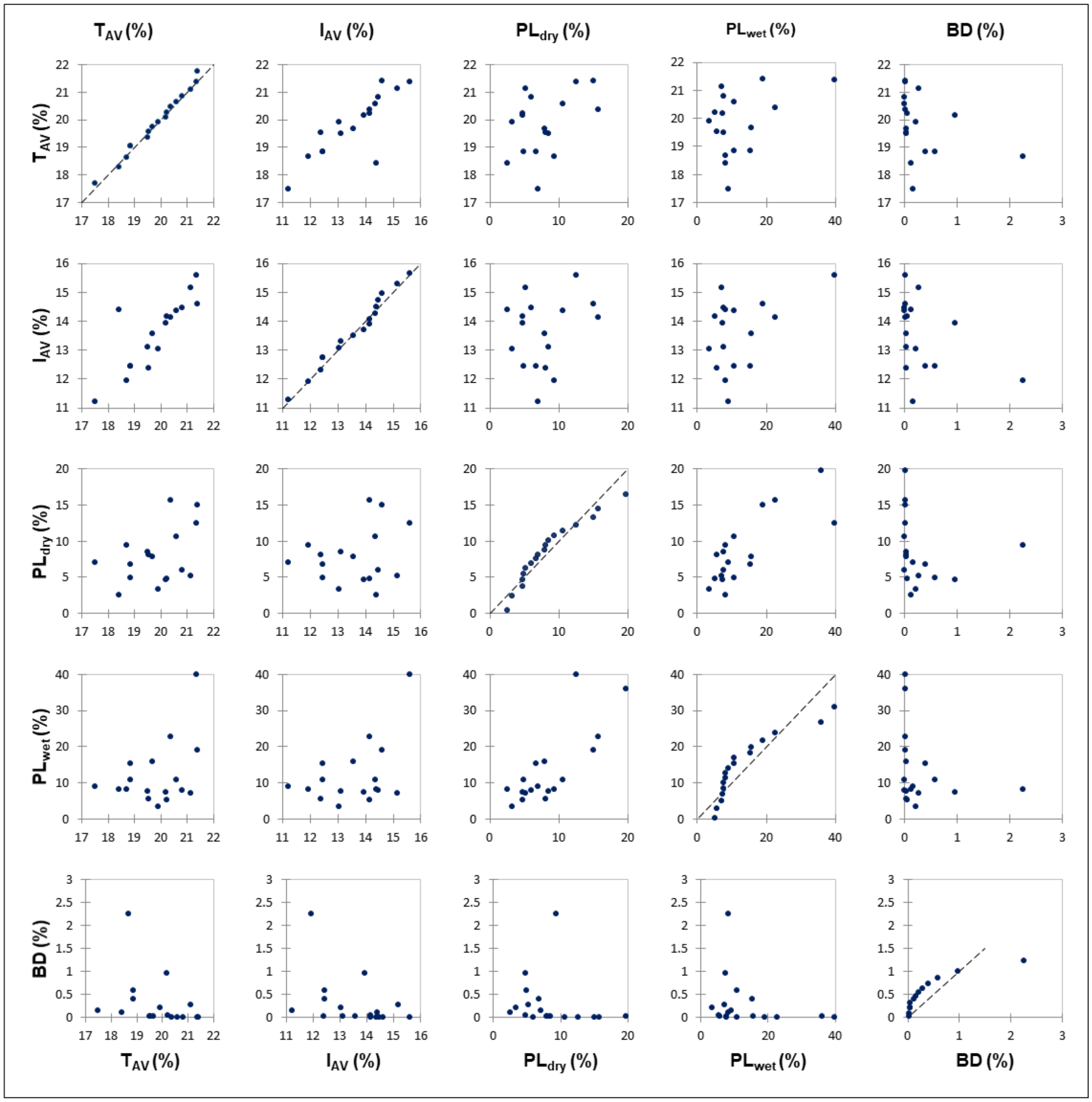



*Figure 31 Graphical correlation matrix among the different criteria*

*Table 11 Pearson correlation coefficient of normalized response variables*

| Criteria | $T_{AV}$ (%) | $I_{AV}$ (%) | $PL_{dry}$ (%) | PLwet (%) | BD (%) |
|---|---|---|---|---|---|
| $T_{AV}$ (%) | **1.00** | **0.89** | **-0.63** | **-0.59** | 0.34 |
| $I_{AV}$ (%) | **0.89** | **1.00** | **-0.50** | **-0.62** | 0.40 |
| $PL_{dry}$ (%) | **-0.63** | **-0.50** | **1.00** | **0.79** | -0.16 |
| $PL_{wet}$ (%) | **-0.59** | **-0.62** | **0.79** | **1.00** | -0.24 |
| BD (%) | 0.34 | 0.40 | -0.16 | -0.24 | **1.00** |

Once the weights of the different response variables were calculated by applying the CRITIC approach, the comparative closeness coefficient (CCC) for each design of experiments was determined employing TOPSIS methodology. In consequence, the CCC and the preference ranking for all experimental designs are presented in Table 12. It is important to point out that the higher value of CCC indicates the most proper choice among the set of alternatives. The experimental design number 17 resulted the best design, with response values of 20.22%; 14.15%; 4.77%; 5.26% and 0.05% for $T_{AV}$, $I_{AV}$, $PL_{DRY}$, $PL_{WET}$ and *BD*, respectively. This design involves the use of a polymer modified binder with 0.15% fiber content and 5.0% binder content. On the other hand, experimental design number 3 was found to be the design with the lowest CCC value and hence, the last potential choice.

*Table 12 CCC values and preference ranking according to the TOPSIS method*

| **Number** | **Experimental ID** | **$T_{AV}$ (%)** | **$I_{AV}$ (%)** | **$PL_{dry}$ (%)** | **$PL_{wet}$ (%)** | **BD (%)** | **CCC** | **Rank** |
|---|---|---|---|---|---|---|---|---|
| 17 | PMB-FC:0.15-BC:5.00 | 20.22 | 14.15 | 4.77 | 5.26 | 0.05 | 0.92 | 1 |
| 18 | PMB-FC:0.15-BC:5.50 | 19.91 | 13.03 | 3.30 | 3.48 | 0.21 | 0.91 | 2 |
| 15 | PMB-FC:0.05-BC:5.50 | 18.42 | 14.39 | 2.52 | 8.25 | 0.12 | 0.90 | 3 |
| 13 | PMB-FC:0.05-BC:4.50 | 20.81 | 14.47 | 5.94 | 7.80 | 0.00 | 0.88 | 4 |
| 11 | PMB-FC:0.00-BC:5.00 | 21.12 | 15.16 | 5.16 | 7.19 | 0.28 | 0.87 | 5 |
| 14 | PMB-FC:0.05-BC:5.00 | 19.54 | 12.39 | 8.12 | 5.62 | 0.04 | 0.84 | 6 |
| 16 | PMB-FC:0.15-BC:4.50 | 19.50 | 13.12 | 8.47 | 7.73 | 0.04 | 0.83 | 7 |
| 9 | 50/70-FC:0.15-BC:5.50 | 17.49 | 11.22 | 7.01 | 9.08 | 0.16 | 0.82 | 8 |
| 10 | PMB-FC:0.00-BC:4.50 | 20.59 | 14.36 | 10.57 | 10.81 | 0.00 | 0.77 | 9 |
| 5 | 50/70-FC:0.05-BC:5.00 | 19.67 | 13.57 | 7.90 | 15.71 | 0.03 | 0.76 | 10 |
| 6 | 50/70-FC:0.05-BC:5.50 | 18.85 | 12.45 | 4.90 | 10.70 | 0.59 | 0.76 | 11 |
| 2 | 50/70-FC:0.00-BC:5.00 | 18.85 | 12.45 | 6.76 | 15.32 | 0.40 | 0.73 | 12 |
| 12 | PMB-FC:0.00-BC:5.50 | 20.18 | 13.93 | 4.73 | 7.49 | 0.97 | 0.68 | 13 |
| 1 | 50/70-FC:0.00-BC:4.50 | 21.39 | 14.59 | 14.96 | 19.12 | 0.01 | 0.65 | 14 |
| 8 | 50/70-FC:0.15-BC:5.00 | 20.38 | 14.14 | 15.66 | 22.74 | 0.01 | 0.61 | 15 |
| 7 | 50/70-FC:0.15-BC:4.50 | 23.22 | 17.26 | 19.71 | 35.95 | 0.02 | 0.52 | 16 |
| 4 | 50/70-FC:0.05-BC:4.50 | 21.36 | 15.59 | 12.52 | 39.85 | 0.01 | 0.51 | 17 |
| 3 | 50/70-FC:0.00-BC:5.50 | 18.68 | 11.94 | 9.37 | 8.28 | 2.25 | 0.37 | 18 |

CCC score values obtained via CRITIC – TOPSIS based Taguchi methodology were also used to calculate the main effects plots for means, as shown in Figure 32.

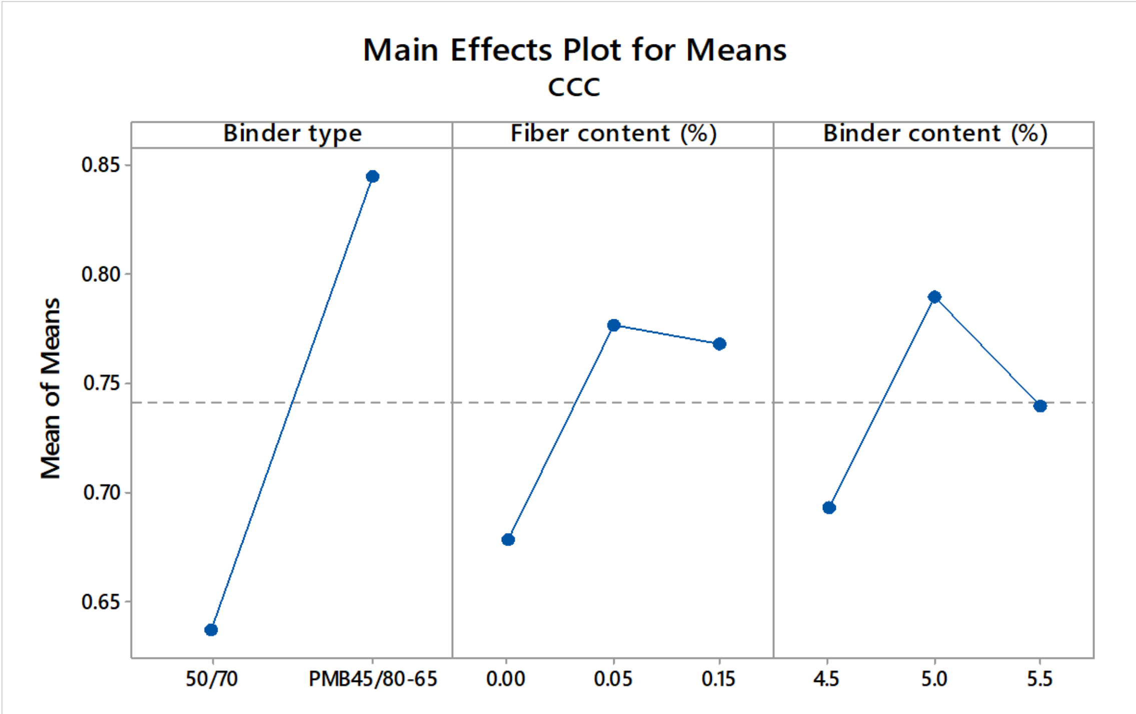
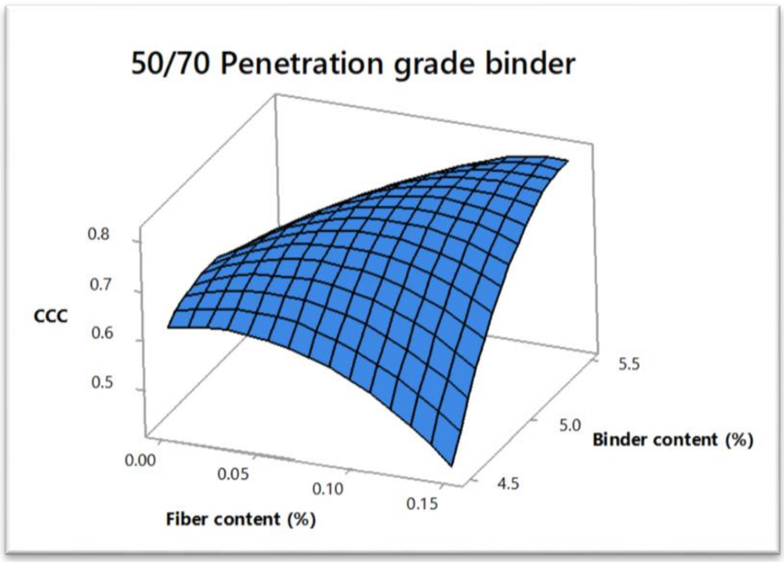



*Figure 32 Main effects plot for means of CCC values*

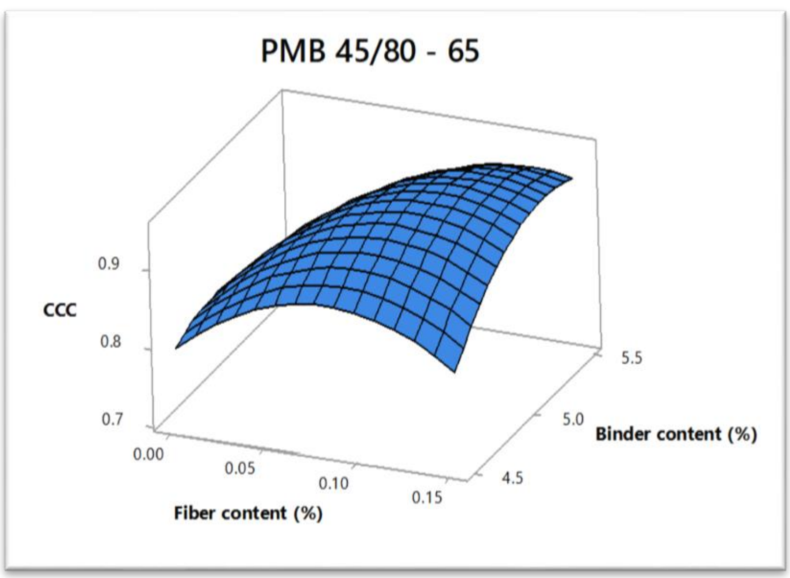
The type of binder seems to have the greatest impact on the mean values. As it can be observed in the ranking, the first seven experimental designs were about mixtures using PMB. On the other hand, good results were observed in terms of functionality and durability for the mixtures using a 50/70 penetration grade binder. For example, mixtures corresponding to design number 5, with 0.05% fiber content and a 5.0% binder content, exhibited particle loss values in dry and wet conditions of 7.90% and 15.71%, respectively. According to the scientific literature, values lower than 20% and 35% are recommended in $PL_{DRY}$ and $PL_{WET}$ tests [1,3,30]. This mixture also shows a proper air void content of approximately 20% and does not present binder drainage problems, as it obtained a drain down value lower than 0.3%, the limit recommended in the literature [16].

When analyzing the CCC score values, trends indicate that low values of binder content and high values of fiber content clearly affect the overall performance of mixtures using 50/70 penetration grade bitumen, as it can be observed in Figure 33. In other words, in mixtures manufactured with conventional binder, the inclusion of fibers entails an increment in the bitumen content to work properly. Meanwhile, in those mixtures manufactured with polymer modified binder, the reinforcement impact of adding fibers is less noticeable. However, the inclusion of fibers has no detrimental effect independently of the bitumen content and in some cases the overall performance is increased.

Likewise, all CCC values were below 0.8 in the case of mixtures using a 50/70 conventional binder with the exception of design number 9, which obtained a value of 0.82. Moreover, design 5 scored higher, with a value of 0.76. This experimental design exhibited lower values of particle loss in dry and wet conditions while maintaining admissible values of total and interconnected air voids. Besides, binder drainage in this mixture was not observed. Therefore it could be considered a proper mixture design. Finally, based on mean values, the TOPSIS approach suggests that the optimum conditions were identified for a binder type factor equal to PMB, fiber content factor of 0.05%, and binder content factor of 5.0%.




(a)




(b)

*Figure 33 Interaction effect of fiber content and binder content as a function of the CCC score value; (a) 50/70 penetration grade; (b) PMB 45/80-65*

One of the main advantages of this novel DOE-MCDM method is the development of regression analysis for the modeling of the CCC values and the analysis of the interaction effects between input parameters and the overall CCC response. A linear plus interaction predictive equation with a p-value of 0.004 significant effect was selected for that purpose. The equation for CCC is given as follows:

$$CCC = 1.128 + 0.2089 \cdot BT - 10.84 \cdot FC\,(\%) - 0.1049 \cdot BC(\%) + 2.268 \cdot FC(\%) \cdot BC(\%) \tag{9}$$

The graph given in Figure 34 shows the comparison between the CCC response obtained through the CRITIC-TOPSIS methodology and the CCC values from the regression model developed. The $R^2$ for the model obtained was 66.43% and the mean error between the CCC values calculated via CRITIC-TOPSIS and the model developed was 11.78%. According to the analysis of variance (Table 13), the type of binder has a significant effect as well was the fiber-binder interaction. In other words, the overall performance of a PA mixture is linked to the proper quantities of fiber and binder depending on the type of binder.

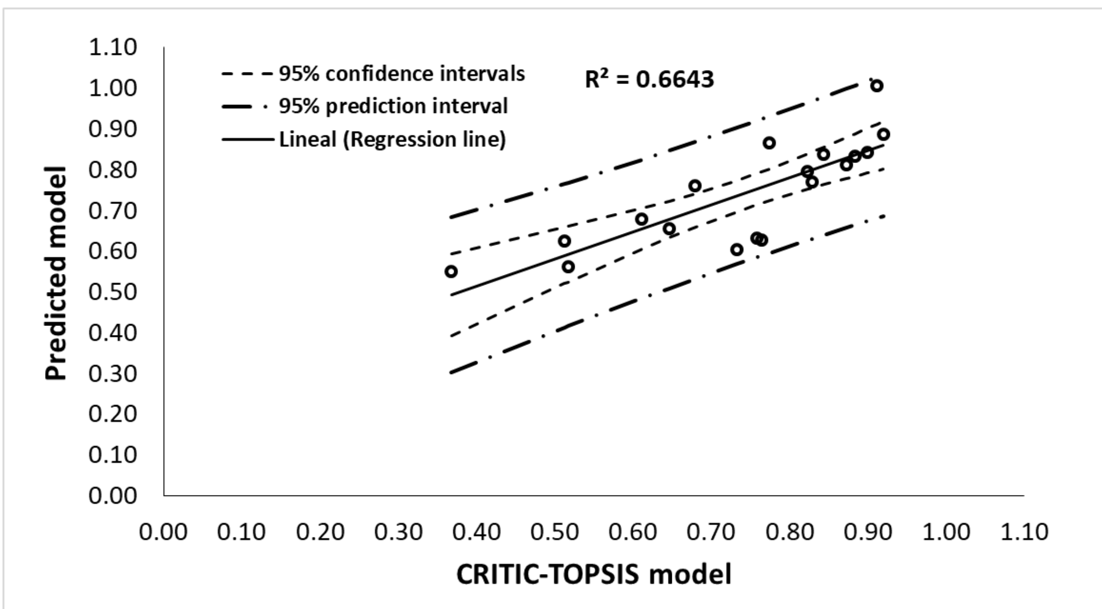



*Figure 34 Comparison between the calculated CCC response and the predicted model*

*Table 13 Analysis of variance of the regression model developed for CCC*

| Source | DF | Adj SS | Adj MS | *F*-Value | *P*-Value | Significance |
|---|---|---|---|---|---|---|
| Model | 4 | 0.280 | 0.070 | 6.430 | 0.004 | Significant |
| Linear | 3 | 0.226 | 0.075 | 6.930 | 0.005 | Significant |
| Binder type | 1 | 0.196 | 0.196 | 18.020 | 0.001 | Significant |
| Fiber content (%) | 1 | 0.018 | 0.018 | 1.610 | 0.227 | |
| Binder content (%) | 1 | 0.013 | 0.013 | 1.150 | 0.303 | |
| 2-Way Interaction | 1 | 0.060 | 0.060 | 5.510 | 0.035 | Significant |
| Fiber content (%) *Binder content (%) | 1 | 0.060 | 0.060 | 5.510 | 0.035 | Significant |
| Error | 13 | 0.142 | 0.011 | | | |
| Total | 17 | 0.422 | | | | |

TOPSIS technique was chosen as the reference method to establish the unified index and rank the alternatives. Nevertheless, other MCDM methods can be done to that purpose. Accordingly, the joint performance score (JPS) from WASPAS and appraisal score (AS) from EDAS were also selected as MCDM methods to compare with TOPSIS. EDAS method was chosen because it shares similarities with TOPSIS since both rely on the measurements of distances from a specific solution. While TOPSIS relies on the calculation of distances from the ideal solutions, in EDAS, the distance is calculated from the average solution among the alternatives. On the other hand, WASPAS was also deemed because it differs from TOPSIS as it relies on both additive and multiplicative utility functions.

Figure 35 presents the CCC, JPS, and AS values obtained from TOPSIS, WASPAS, and EDAS, respectively. Results for the EDAS method were similar to those obtained for the TOPSIS. In the case of EDAS, design 17 (PMB-FC:0.15-BC:5.00) and 18 (PMB-FC:0.15-BC:5.50) were ranked as the most desirable alternatives, whereas design 3 (50/70-FC:0.00-BC:5.50) was the least preferred choice matching well with results thrown by TOPSIS. As regards to WASPAS, the results are substantially different in terms of the ranking but with some similitudes. For example, it ranks design 13 (PMB-FC:0.05-BC:4.50) as the most appealing option, which also gave good results in terms of particle loss and air voids without risk of binder drain down. In the same way, design 3 was assigned with the lowest score value.

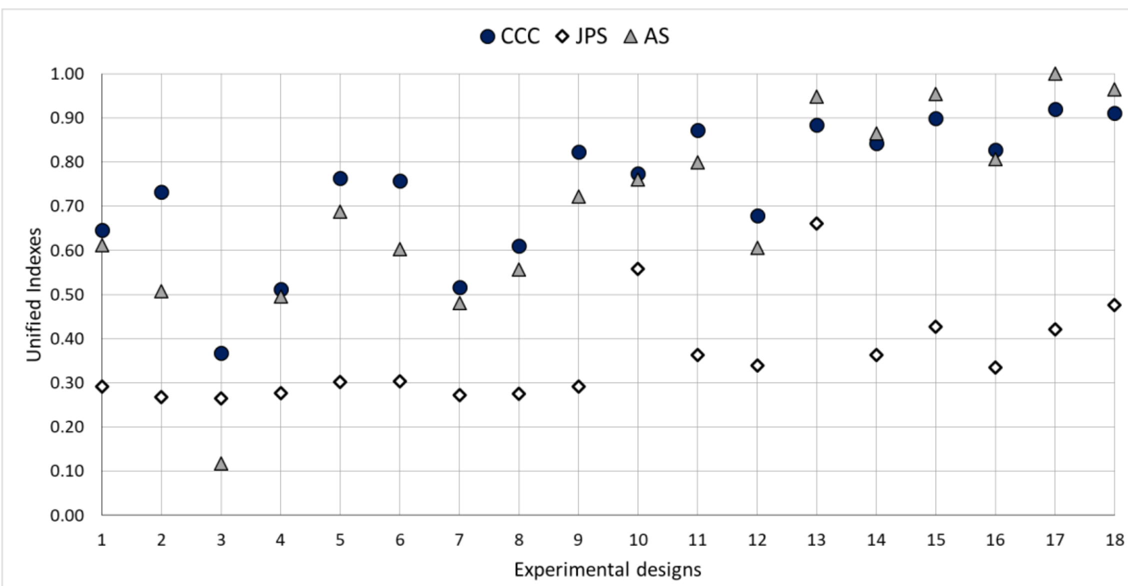



*Figure 35 CCC, JPS and AS values calculated from TOPSIS, WASPAS, and EDAS*

Another point of discussion is the close values between TOPSIS and EDAS and inferior scores achieved with the WASPAS method. However, these variations depend on the aggregation rules, which relies on each one of the methods. Figure 36 shows the relation which exists between CCC values in relation to JPS and AS values, respectively. It was expected that EDAS had the strongest association with TOPSIS ($R^2$ of 0.76) due to the similarities in the algorithm. Meanwhile, the correspondence with WASPAS is lower because of the variant in the principles of aggregation.

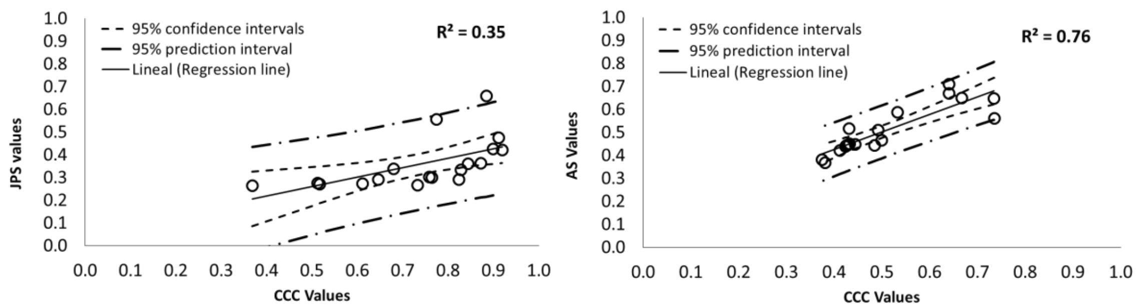
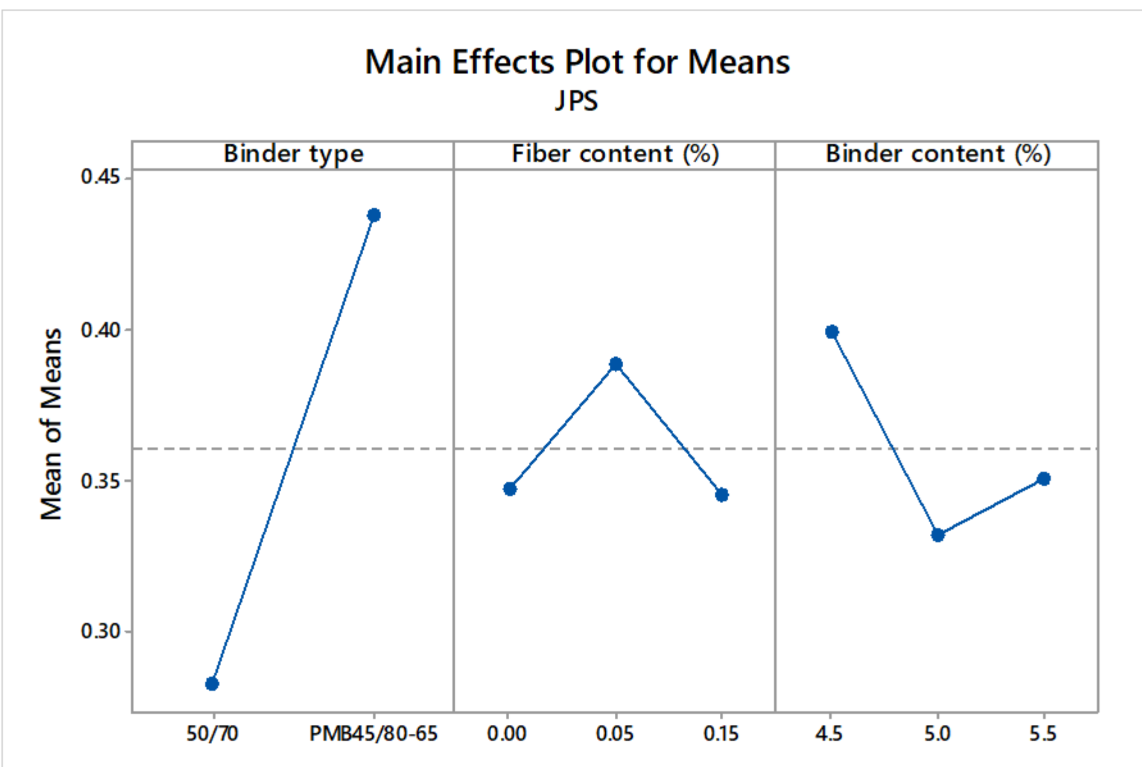
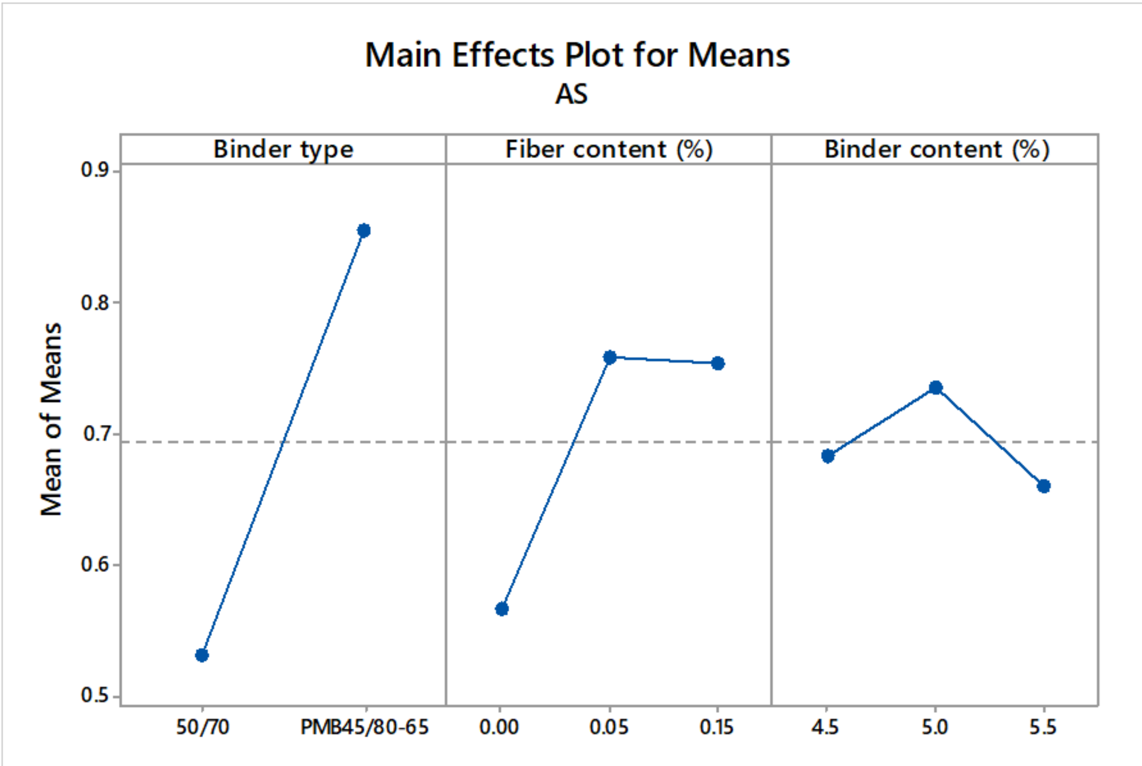



*Figure 36 Relation between CCC values in relation to JPS values (left) and AS values (right)*

Apart from the preference ranking, another point of interest is to obtain the main effects plot for means employing these other MCDM methods, as shown in Figure 37. Once again, the optimal parametric levels according to AS values match equally those obtained by TOPSIS. Consequently, PMB as binder type with 0.05% of POA fibers and 5.00% binder content was found as the optimal solution. Regarding the WASPAS method, for the first two control factors (i.e. BT and FC) the optimal values were the same. However, in the case of binder content, 4.50% is preferred over 5.00% of binder content. It is also important to highlight that these optimal parametric levels agree with the first positions of the preference ranking for both methodologies.



(a)




(b)

*Figure 37 Main effects plot for means; (a) WASPAS method; (b) EDAS method*

These results reveal that the different application of MCDM techniques displays different ranking profiles depending on the underlying aggregation principles. Based on results, the EDAS technique rendered similar to the TOPSIS method, possibly because of the similitudes which exist between both methods in the utility functions. Therefore, either of the two methods could be used indistinctly. On the other hand, some differences were found between TOPSIS and WASPAS methods. As mentioned before, WASPAS relies on additive and multiplicative utility functions, while TOPSIS entails the measurement of distances to positive and negative ideal solutions. Concerning the main effects plot for means, the results were closer except for the binder content control factor. The application of more than one MCDM analysis could also be suitable, relying on distinct variant principles of aggregation to ensure a better understanding of the results obtained.

# 6. CONCLUSIONS

This section presents the most relevant specific conclusions, the general conclusions of the research, and the future research lines.

## 6.1 Most relevant specific conclusions

The specific conclusions are divided in three stages, similar to the discussion of the results section, presenting the most relevant contributions of each section.

*6.1.1 Specific conclusions of the fiber-preselection process*

- PAN and the POA fibers were selected as the suitable choices to be used as reinforcement in the PA mixture based on a MCDM analysis, which combined the FAHP and the WASPAS method. The opinion of experts, as well as quantitative data from scientific review of mechanical performance of fibers in hot mix asphalt, served as main references to be employed in the MCDM analysis.

*6.1.2 Specific conclusions of the fiber-reinforced PA mixtures with synthetic fibers*

- The incorporation of POA and 4 mm long PAN fibers improved the particle loss resistance in dry conditions for both filler contents. Concerning the particle loss in wet conditions, no significant improvement was observed for any type of fiber.
- The addition of fibers to the PA mixture resulted in an increase in the indirect tensile strength (ITS) of the dry conditioned specimens. The best results were obtained with POA fibers. On the other hand, similar or lower strengths than the reference were found when wet conditioned specimens of fiber-reinforced PA mixtures were tested.
- The addition of PAN 4 - A and POA 19 – B type of fibers to the PA mixture showed the greatest improvements in terms of the fracture energy, post cracking energy and toughness of the dry conditioned specimens comparing to the reference mixtures. No improvements were observed concerning toughness for the fiber-reinforced wet conditioned specimens.
- At 15°C and 0°C No significant effects were observed in fiber-reinforced asphalt mortar mixes in any of the parameters measured.
- At -15°C, due to changes in the behavior of mortar, only ITS and FE property could be measured. Regarding ITS, statistical differences were observed by adding 0.3% POA fibers and 0.3% PAN fibers. Moreover, the addition of fibers contributed to increase the FE with a greater influence in the case of POA fibers.

*6.1.3 Specific conclusions of the novel DOE-MCDM analysis considering the influence of various control factors.*

- Concerning the air voids properties of the mixture, the binder content was the most influential factor whereas the fiber content did not have high impact on the functional performance of the mixture.
- Concerning the raveling resistance of the mixture, adding 0.05% of POA fibers with 5.50% of PMB were the best parametric solutions for particle loss in dry conditions. Meanwhile, for particle loss in wet conditions, least influence is shown by the addition of fibers.

- Polyolefin-aramid fibers acted very well as stabilizer agent since they allowed to retain more asphalt binder.
- Regarding criteria elicitation, the CRITIC objective weighting approach was contemplated. Consequently, the particle loss criteria were assigned with a weighting of approximately 50%, while air void properties and binder drain down responses were assigned the remaining 50%.
- The best alternative, according to the CRITIC-TOPSIS method, was design number 17. This design corresponds to the use of a polymer modified binder, 0.15% fiber content, and 5.0% binder content. Although the first few positions of the order of preference refer to experiments with mixes using polymer modified binder, good results can also be obtained using a conventional binder as long as the proper proportions of fibers are applied.
- Different applications of MCDM techniques could display differences in the preference ranking because of the algorithm and utility functions employed. EDAS rendered similar to TOPSIS method, whereas some variations were found in WASPAS as compared to TOPSIS.

### 6.2 General conclusions

- Selecting an appropriate fiber based on the mechanical performance of the fiber-reinforced bituminous mixtures is a crucial and complex task that requires delimiting complex decision variables with an integrated decision-making process. This research demonstrates that multi-criteria decision-making analysis can be used as an attractive way to do a pre-selection of suitable alternatives for use in asphalt mixtures.
- In relation to the experimental results of fiber-reinforced PA mixtures with POA and PAN fibers, it was evidenced that the highest mechanical performance of the PA mixtures was provided by the addition of POA fibers. The most clearly improvements were observed in particle loss conditions, indirect tensile strength, and fracture parameters, all in dry conditions.
- Concerning the experimental work of fiber-reinforced asphalt mortar mixes, it was evidenced that statistical improvements were observed only at -15°C, when the behavior of the mortar turned out to be elastic-brittle. The greater influence was observed in the case of POA fibers.
- Regarding the control factors comparison in PA mixture through the integrated DoE-MCDM analysis, the use of polymer modified binder could be preferred in comparison to fibers in terms of voids, raveling, and binder drain down. However, the use of fibers with a proper amount of bitumen can also be an attractive alternative to be implemented as reinforcement in porous asphalt mixture to increase the durability without compromising the functionality and without the risk of binder drain down.
- This study presented the novel DoE-MCDM analysis as a powerful tool for experimental evaluation of fiber-reinforced PA mixtures. On the one hand, the DoE technique helped to take into account multiple parameters defined in different control factors to be analyzed

simultaneously in various individual responses. On the other hand, as multiple responses are involved, the integration of MCDM techniques allow to convert the multi-response optimization problem into a single-response optimization problem. To be more precise, the CRITIC served as an automated decision-making tool for criteria elicitation, whereas CCC score values from TOPSIS method were effective for establishing a unified index and to perform the preference ranking among alternatives.

### 6.3 Future research lines

Based on the results obtained from this study, and the analysis carried out during the development of it, the following research lines are proposed:

- To evaluate other types of fibers in PA mixtures, considering other properties such as length, diameter, and shape of the fiber (e.g. monofilament, staple, twisted, crimped, pellet). This is because these other properties have a great influence on the overall performance of PA mixtures.
- To evaluate the potential recyclability of fiber-reinforced PA mixtures. In the future, roads will be built with these novel materials, and hence greater amounts of reclaimed asphalt pavement will be needed. With this study, it could contribute to the development of pavement structures that generate less environmental impact.
- To implement waste fibers for the reinforcement of PA mixtures. Several industries, during their manufacturing process, generate waste fibers that are usually dumped in landfills. However, these waste fibers can be used for the design of new fiber-reinforced PA mixtures.
- To analyze the influence of more than one fiber simultaneously in the PA mixture. Possibly, the incorporation of more than one fiber could reinforce better the PA mixture. Changing the fiber content of both fibers in the mixture is necessary to optimize the overall performance of the porous asphalt.
- To evaluate other control factors at asphalt mortar scales such as binder content, voids content and the monotonic loading speed is also recommended in fiber-reinforced asphalt mortars. The application of dynamic tests such as fatigue cracking could also be considered.
- In the multi-criteria decision-making analysis, to consider taking into account other criteria such as economic and environmental impact. These additional criteria are also convenient to do a decision-making analysis.
- To maximize the functionality of the PA mixture with higher infiltration capabilities. To that purpose, changes in the particle size distribution are necessary, and the employment of other additives are necessary to increase the air voids content while keeping the same durability than conventional PA mixtures.
- To study the fiber-reinforced PA mixtures under other additional testing and conditioning methods such as freeze-thaw cycles and man-made threads (e.g. fuel spills).
- To include other MCDM tools for criteria elicitation (FAHP, BWM, and ENTROPY) and for establishing a unified index which allows the preference ranking among alternatives (e.g.

WASPAS, EDAS, VIKOR). The Monte-Carlo stochastic simulation can also be added to deal with the uncertainty in the decision-making process. Unsupervised exploratory statistical tools are also recommended when large datasets are involved.

- To apply the novel integrated DoE-MCDM analysis to other study cases. Bituminous mixtures, soils, and Portland concrete are composites prepared with various materials and where different responses must be analyzed. In this sense, DoE-MCDM analysis appears as a very useful tool to be used in the optimization of multiple experimental studies.

# 7. RESUMEN EXTENDIDO

**TÍTULO DE LA TESIS**

**EVALUACIÓN EXPERIMENTAL DE MEZCLAS ASFÁLTICAS POROSAS REFORZADAS CON FIBRAS A TRAVÉS DEL DISEÑO DE EXPERIMENTOS INTEGRADO CON ANÁLISIS DE TOMA DE DECISIONES DE CRITERIOS MÚLTIPLES**

## 7.1 Introducción

### *7.1.1 Antecedentes*

Es frecuente observar el empleo de mezclas asfálticas densas en caliente como capa de rodadura en carreteras. Sin embargo, otro tipo de mezclas bituminosas como las de gradación abierta son una atractiva opción para la construcción de nuevas estructuras de pavimento. Esta mezcla, comúnmente conocida como asfalto poroso (PA) en Europa [1,2], capa de fricción de gradación abierta (OGFC) o capa de fricción porosa (PFC) en los Estados Unidos [3,4] y hormigón asfáltico poroso (PAC) en China [5], es considerada una solución eco-amigable debido a los múltiples beneficios que ofrece [3]. Entre sus ventajas, destaca su capacidad de drenar el agua y mejor manejo del agua de escorrentía debido al alto contenido de huecos (generalmente en el rango entre 18-22%) [6,7]. Del mismo modo, las mezclas porosas ayudan a mitigar el ruido generado por el paso de los vehículos y a disminuir el riesgo de hidroplaneo y deslizamiento en condiciones húmedas [3]. Otras ventajas incluyen la reducción del efecto de isla de calor [8] y la mejora de la visibilidad al reducir los reflejos en condiciones húmedas. Todas estas propiedades finalmente redundan en una disminución de la tasa de accidentes.

A pesar de los múltiples beneficios, la durabilidad de la mezcla es sustancialmente más pequeña que las mezclas de asfalto densas convencionales. No obstante, el contacto árido sobre árido formado por el esqueleto estructural de los áridos gruesos proporciona una alta resistencia a la deformación permanente. La abrasión que se puede definir como la pérdida de partículas de la superficie del pavimento debido a los esfuerzos cortantes generados por el tráfico es el tipo de falla más común observado en este tipo de mezclas [10]. Por lo anterior, algunas agencias gubernamentales de América y Europa han incluido en sus especificaciones el uso de betunes modificados con polímeros dada su mayor elasticidad, especialmente a temperaturas más bajas y con la idea de que el envejecimiento de este betún es menor que el betún convencional [11].

Por otro lado, las fibras aparecen como una alternativa innovadora para implementarse en mezclas de asfalto poroso. En muchos materiales de construcción, como el hormigón y los suelos, las fibras se utilizan principalmente como refuerzo y se agregan con el fin de aumentar la resistencia a la tracción y aportar ductilidad a los materiales compuestos [12]. En mezclas bituminosas, también se ha estudiado el uso de diferentes tipos de fibras, incluyendo minerales, orgánicas, de acero y sintéticas [13]. Ha habido una gran cantidad de mezclas bituminosas modificadas con fibras en las que las fibras se han utilizado para tratar los principales problemas de las mezclas densas de los pavimentos flexibles como la deformación permanente, el agrietamiento por fatiga y el agrietamiento térmico [14]. Mientras tanto, en las mezclas PA, las fibras orgánicas como la celulosa se emplean generalmente para reducir el escurrimiento del ligante. Hasta la fecha, se han encontrado pocos esfuerzos de investigación y muy poca información relacionado con el uso de otros tipos de fibras en mezclas PA en la literatura científica. Dadas las mejoras en las propiedades mecánicas de otros compuestos, analizar el efecto de las fibras en las mezclas de PA es el objetivo que esta investigación tomó en consideración.

Como una contribución novedosa de este estudio, el concepto de diseño de experimentos (DOE) combinado con el análisis de toma de decisiones de criterios múltiples (MCDM) se ha aplicado como herramienta estadística para abordar los objetivos cruciales en esta investigación. Por un lado, se ha aplicado un DOE basado en la matriz ortogonal de Taguchi, ya que permite analizar la interacción de diferentes factores de control con un número reducido de experimentos. Del mismo modo, el DOE permite manejar varias variables simultáneamente e identificar los factores más relevantes y los niveles óptimos que influyen en cada una de las respuestas.

Por otro lado, el análisis MCDM es una alternativa adecuada para organizar y resolver problemas que involucran múltiples criterios [15]. En la presente investigación, un análisis MCDM ayudó en la preselección de las fibras más adecuadas que podrían reforzar la mezcla de PA. Además, dado que se obtuvo más de una respuesta experimentalmente, se propuso el análisis MCDM para transformar el problema de optimización de respuesta múltiple en un problema de optimización de respuesta individual.

*7.1.2 Normativa para la elaboración de la tesis*

La presente tesis doctoral se presenta bajo la modalidad de tesis por compendio de artículos científicos previamente publicados y se rige según las disposiciones relativas a los estudios de Doctorado y la obtención del título de doctor en la Universidad de Cantabria que se mencionan a continuación:

- Regulaciones académicas del manejo de estudios de doctorado regulado por Real Decreto 99/2011 aprobado por el Consejo de Gobierno de la Universidad de Cantabria en marzo 4 de 2015, en su título IX. “Preparación de tesis como compendio de artículos”.
- Regulaciones para la elaboración de la tesis como compendio de artículos dentro del Programa de Doctorado en Ingeniería Civil de la Escuela de Doctorado de la Universidad de Cantabria.

El compendio de artículos de investigación que soportan la presente tesis doctoral se muestra a continuación:

- **Artículo 1**. Laboratory assessment of porous asphalt mixtures reinforced with synthetic fibers. (DOI: 10.1016/j.conbuildmat.2019.117224). Aceptado para publicación en octubre 11 de 2019.
- **Artículo 2.** An experimental laboratory study of fiber reinforced asphalt mortars with polyolefin-aramid and polyacrylonitrile fibers. (DOI: 10.1016/j.conbuildmat.2020.118622). Aceptado para publicación en febrero 28 de 2020.

- **Artículo 3.** Multi-Response Optimization of Porous Asphalt Mixtures Reinforced with Aramid and Polyolefin fibers employing the CRITIC-TOPSIS Based on Taguchi Methodology. (DOI: 10.3390/ma12223789). Aceptado para publicación en noviembre 8 de 2019.

*7.1.3 Proyectos asociados con la tesis*

La investigación actual presenta los resultados llevados a cabo en la línea de investigación "Construcción de nuevas estructuras de firme" desarrollados por el Grupo de Investigación de la Tecnología de la Construcción (GITECO) de la Universidad de Cantabria. La tesis doctoral está enmarcada en dos proyectos europeos:

- Proyecto FIBRA: *Fostering the implementation of fiber-reinforced asphalt mixtures by ensuring its safe, optimized and cost-efficient use.* Este proyecto ha recibido financiación de la Comisión Europea del Departamento de Carreteras (CEDR) bajo el programa de investigación transnacional de carreteras llamado 2017 bajo contrato número N. 867481. El proyecto FIBRA tiene como objetivo superar las barreras técnicas para la implementación segura y rentable de mezclas de asfalto reforzado con fibra (FRAM) por parte de las Autoridades Nacionales de Carreteras (NRADS). El grupo de investigación GITECO de la Universidad de Cantabria (España) coordina este proyecto y lleva a cabo la investigación junto con las siguientes instituciones: EMPA, Laboratorio Federal Suizo de Ciencia y Tecnología de Materiales (Suiza); ISBS, Instituto für Straßenwesen de la Technishche Universität Braunschweig (Alemania), BAM Infra bv (Países Bajos), SINTEF AS (Noruega) y Veidekke Industri AS (Noruega).

- Proyecto FORESEE: *Future proofing strategies FOr Resilient transport networks against Extreme Events*. Este proyecto ha recibido financiación del programa de investigación e innovación Horizon 2020 de la Unión Europea en virtud del acuerdo de subvención nº 769373. El objetivo general del proyecto es proporcionar herramientas rentables y confiables para mejorar la resiliencia de la infraestructura de transporte como la capacidad de reducir la magnitud y / o eventos disruptivos. La presente tesis doctoral está vinculada al paquete de trabajo tres cuyo objetivo principal es desarrollar mezclas de asfalto poroso con capacidades de infiltración mejoradas con durabilidad y capacidad estructural similares a las mezclas permeables convencionales.

*7.1.4 Objetivos de la investigación y alcance*

El objetivo principal de este estudio fue analizar el efecto de refuerzo de fibras innovadoras en las mezclas porosas utilizando una metodología novedosa que combina el diseño de experimentos con el análisis de toma de decisiones de criterios múltiples. La presente investigación analizó experimentalmente los efectos de la adición de fibras sintéticas en el comportamiento funcional y mecánico de la mezcla PA y a escala del mortero bituminoso. Además, se comparó el efecto de refuerzo de las fibras sobre la mezcla PA teniendo en cuenta otros factores de control, tales como el tipo de betún, el contenido de fibra y el contenido de asfalto. Con ese fin, se desarrolló un estudio paramétrico basado en la metodología de Taguchi. Como se obtuvo más de una respuesta experimental, se aplicó un análisis MCDM para convertir el problema de optimización de respuesta múltiple en un único problema de optimización de respuesta. Para lograr este objetivo se completaron las siguientes tareas:

- Una evaluación experimental en laboratorio de mezclas asfálticas porosas reforzadas con fibras sintéticas.
- Un estudio de laboratorio experimental de morteros bituminosos reforzados con fibras sintéticas.
- Una combinación de análisis DOE-MCDM aplicada a analizar el efecto de refuerzo de las fibras considerando otros factores de control.

## 7.2 Síntesis del estado del arte

### *7.2.1 Mezcla asfáltica porosa*

La mezcla PA como es comúnmente conocida en Europa es un tipo especial de mezcla bituminosa caracterizada por tener un alto contenido de huecos con aire fabricados con áridos de alta calidad y un número reducido de finos [3]. En general, se recomienda un contenido mínimo de huecos de aire del 20% para este tipo de mezcla. Sin embargo, en los Estados Unidos también es apropiado un valor mínimo del 18% [6]. Dada la alta porosidad, esta mezcla es altamente permeable permitiendo el paso del agua a través de su estructura. Otros efectos como el hidroplaneo, los efectos de salpicadura, el ruido en rodadura y la reflectividad de la superficie también se reducen con la incorporación de mezclas PA. Un incremento en la resistencia al deslizamiento especialmente en condiciones húmedas y un mejor manejo del agua de escorrentía también son otras ventajas reportadas en la literatura [16].

En los Estados Unidos se usa desde 1950, mientras que en Europa esta mezcla comenzó a usarse desde 1970 [11,16]. Sin embargo, debido a la poca durabilidad, algunos países y estados de los EE. UU. han dejado de usarla. La estructura abierta de la mezcla está altamente expuesta al aire y el agua, debilitando la cohesión dentro del mortero y la adhesión generada en la interfaz ligante-árido [17].

Entre los aditivos más comunes que se utilizan se encuentran los polímeros, la cal hidratada (HL), los agentes anti-stripping y las fibras de celulosa. Países como España, Colombia, Alemania y algunos estados de EE.UU. emplean PMB en su normativa estándar, mientras que otros países como Holanda emplean mezcla porosa con betún convencional incorporando fibras de celulosa como agente estabilizador para aumentar el contenido de ligante sin el riesgo de que este escurra [20].

Cada país dentro de sus propias especificaciones tiene diferentes criterios para la fabricación de mezclas PA. Según las normas españolas [29], los requisitos mínimos que debe cumplir una mezcla porosa son:

- Los huecos de aire en la mezcla deben ser de al menos del 20%.
- La pérdida de partículas en la prueba de Cántabro debe ser inferior al 20% en condiciones secas y al 35% en condiciones húmedas considerando los valores más restrictivos.

- La resistencia conservada a la tracción indirecta (ITSR) debe ser superior al 85%.
- Las mezclas de PA no deben presentar problemas de escurrimiento del ligante. Se toma como valor tradicional un límite del 0.3%.

La Tabla 1 muestra la distribución del tamaño de partícula especificada en las especificaciones españolas.

*Tabla 1 Distribución típica del tamaño de partícula, mezcla PA*

| Tamiz (mm) | Inferior | Centro huso | Superior |
|---|---|---|---|
| 22 | 100.0 | 100.0 | 100.0 |
| 16 | 90.0 | 95.0 | 100.0 |
| 8 | 40.0 | 50.0 | 60.0 |
| 4 | 13.0 | 20.0 | 27.0 |
| 2 | 10.0 | 13.5 | 17.0 |
| 0.5 | 5.0 | 8.5 | 12.0 |
| 0.063 | 3.0 | 4.5 | 6.0 |

### *7.2.2 Fibras en mezclas bituminosas*

Las mezclas bituminosas reforzadas con fibras (FRAM) se comportan como un compuesto en el que las fibras están distribuidas homogéneamente en la matriz de asfalto-árido para aumentar las propiedades mecánicas. Varios tipos de fibras (Figura 1) incluyendo minerales (basalto, asbesto); orgánicas (celulosa, lignina, fibra de coco); metálicas y sintéticas (poliéster, poliacrilonitrilo, poliolefina, aramida, nylon, polipropileno) se han agregado a la mezcla asfáltica densa como refuerzo. En general, el objetivo principal de la inclusión de fibras es aportar ductilidad a la mezcla y proporcionar resistencia a la tracción. Del mismo modo, las fibras actúan como una barrera que previene la formación y propagación de grietas. En las mezclas SMA y las mezclas porosas, la inclusión de fibras de celulosa permiten evitar el escurrimiento de ligante [30].


*Figura 1 Fibras comúnmente usadas como refuerzo en mezclas asfálticas en caliente*

Las fibras se pueden agregar a la mezcla asfáltica mediante el proceso por vía seca o húmeda. En el primer proceso (vía seca), las fibras se mezclan directamente en el tambor mezclador. En el proceso por vía húmeda, las fibras se incorporan al betún que luego se usará para fabricar la mezcla. En ambos casos, existe la necesidad de una distribución homogénea de las fibras dentro de la mezcla. Generalmente, el proceso por vía seca se prefiere sobre el proceso por vía húmeda debido a que las fibras tienden a dispersarse mejor evitando la formación de "clústeres". Otra ventaja es que no requiere equipos especializados.

### *7.2.3 Diseño de experimentos*

El diseño de experimento (DOE) fue introducido por Ronald A. Fischer en la primera mitad del siglo XX en el Reino Unido. Este método se ha utilizado ampliamente en diferentes campos de la industria, tales como el proceso de mecanizado, la optimización de materiales y la ingeniería de construcción. Una de las grandes ventajas del DOE es la posibilidad de investigar un amplio espectro de parámetros y obtener respuestas a diferentes tipos de criterios. Dentro de los métodos más conocidos existe el diseño factorial completo de experimentos, el método de superficie de respuesta (RSM) y el método Taguchi.

El método Taguchi es un tipo de DOE, propuesto por Genichi Taguchi en Japón durante los años 80, aplicado con éxito en la industria japonesa para la optimización de diversos procesos y desarrollo de materiales. En ingeniería civil se ha utilizado en diferentes campos, como el hormigón a base de geopolímero [52], el hormigón mezclado con polímeros [53], el pavimento permeable de hormigón Portland [54] y el mortero auto-compactante [55]. Las principales preguntas que se pueden resolver utilizando el enfoque de Taguchi son las siguientes:

- Comparar varios aditivos en un compuesto para seleccionar el mejor en una respuesta dada.
- Comparar dos o más materiales con respecto a un criterio específico.
- Identificar las variables de control más relevantes que influyen en una o más características de un producto final.
- Identificar los principales factores o condiciones operativas que afectan un proceso determinado.
- Apoyar el diseño y rediseño de nuevos productos y procesos.

Diferentes factores de control y niveles paramétricos se pueden examinar a través del concepto de matrices ortogonales propuesto en el método Taguchi. El uso de matrices ortogonales contribuye a reducir el número de experimentos que facilitan el diseño de los experimentos. Además, la relación señal-ruido (*SN*) típica del método Taguchi es una medida que permite la determinación de parámetros de entrada significativos mediante la evaluación de la varianza mínima [56]. En otras palabras, los valores más altos de la relación *SN* sugieren una mayor relevancia de los parámetros de entrada en las respuestas. En general, la relación *SN* se puede especificar en tres escenarios diferentes, conocidos como *Menor es mejor, Mayor es mejor* y *el Nominal es mejor*. La Figura 2 muestra el diagrama de flujo típico para llevar a cabo el diseño de experimentos siguiendo la metodología Taguchi.

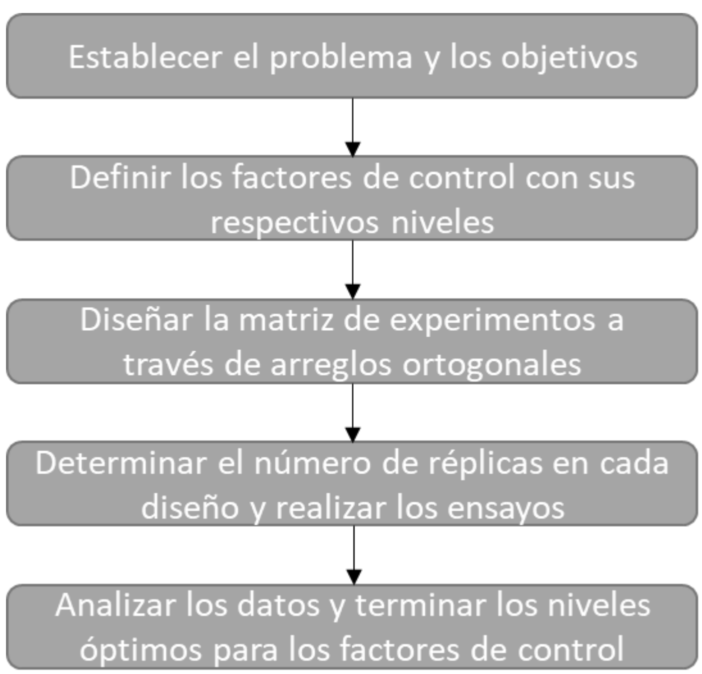



*Figura 2 Diagrama de flujo de la metodología Taguchi*

### *7.2.4 Análisis de toma de decisiones con criterios múltiples (MCDM)*

Dados los grandes avances en la construcción e implementación de nuevos materiales, productos y procesos en la industria, las decisiones complejas que involucran una serie de alternativas y criterios se convierten en una tarea que consume bastante tiempo. Los métodos de toma de decisiones con criterios múltiples (*MCDM*) ayudan a identificar las opciones más prometedoras contenidas en un conjunto de alternativas basadas en criterios previamente establecidos [57]. Estas metodologías contribuyen a facilitar el proceso de toma de decisiones y establecer una clasificación de preferencias. Por mencionar algunos ejemplos, ponderación aditiva simple (*SAW*), modelo de producto ponderado (*WPM*), eliminación y elección que expresa la realidad (*ELECTRE*), análisis relacional gris (*GRA*), técnica de ordenar preferencias por similitud con la solución ideal (*TOPSIS*), evaluación de productos de suma agregados ponderados (*WASPAS*), la solución de compromiso y la optimización de criterios múltiples (*VIKOR*) y la solución de distancia desde el promedio (*EDAS*) se han aplicado en diversos campos, como la selección de materiales, la ubicación militar, la calidad del servicio, la construcción y los procesos de fabricación [58,59].

Para superar los inconvenientes de la ponderación de criterios, los responsables de la toma de decisiones también han aplicado otros enfoques de MCDM. Los primeros incluyen enfoques de ponderación subjetiva que involucran la participación humana para determinar el peso de los criterios. Los más conocidos son el Proceso de jerarquía analítica (*AHP*), el Proceso de jerarquía analítica en un entorno difuso (*FAHP*) y el Método más rentable (*BWM*). No obstante, dado que estos métodos dependen de las preferencias humanas, los enfoques objetivos también son atractivos, ya que los pesos se establecen directamente al extraer la información contenida en los datos originales. La importancia de los criterios a través del Método de correlación entre criterios (*CRITIC*), se conoce como un enfoque de ponderación objetivo que facilita la toma de decisiones automatizada [60].

La combinación de metodologías *MCDM* permite un modelo mucho más robusto en el proceso de toma de decisiones. Por un lado, algunas técnicas se utilizan para determinar los pesos de los atributos, mientras que otros métodos se centran en establecer un índice unificado de los cuales se puede elegir la mejor alternativa. En la industria de la construcción, el análisis *MCDM* híbrido *AHP-TOPSIS* destaca como una de las alternativas preferidas para llevar a cabo un proceso de toma de decisiones, probablemente porque involucra la participación de expertos y emplea un algoritmo matemático estructurado directo con bajos esfuerzos computacionales [61]. En los últimos años, algunos autores [62] han argumentado que la metodología *WASPAS* funciona con mayor precisión que otras. De hecho, Zavadskas et al. [62] sugirió que *WASPAS* es más robusta que los enfoques *WSM* y *WPM*. Además, conceptos como la incertidumbre y la vaguedad están presentes en el proceso de evaluación y, por lo tanto, la incorporación de conjuntos difusos es una herramienta valiosa para abordar este tipo de problema. El problema asociado con los parámetros de entrada imprecisos se maneja empleando simulaciones estocásticas de Monte-Carlo (*MC*). Esta herramienta sirve principalmente para considerar las variables cuantitativas no como números únicos sino como distribuciones de probabilidad.

## 7.3 Metodología

Esta investigación comprende dos grandes fases. En una primera fase, la efectividad de añadir fibras sintéticas en la mezcla porosa es analizada en términos de comportamiento mecánico y funcional. Un conjunto de fibras de poliolefina-aramida (POA) y de poliacrilonitrilo (PAN) fueron preseleccionadas para ser usadas durante toda la investigación en base a un análisis multi-criterio previo entre varios miembros del proyecto FIBRA. Continuando con la explicación de la primera fase, un completo plan experimental fue llevado a cabo no sólo a la escala de la mezcla porosa sino también a la escala del mortero bituminoso. En esta fase, se permitió seleccionar la fibra más prometedora y así dar continuidad a la segunda fase, la cual consistió en evaluar varios factores de control de manera simultánea. El tipo de betún (BT), el contenido de fibra (FC), y el contenido de betún (BC) fueron los principales factores de control para ser analizados experimentalmente. Un novedoso método que combina el diseño de experimentos y el análisis multi-criterio fue propuesto para transformar el problema de múltiple respuesta en un problema de respuesta singular para luego poder seleccionar los niveles óptimos por cada factor de control y el ranking de preferencia entre las alternativas. De esta forma se obtiene el impacto real de la fibra seleccionada considerando todas las variables del análisis. A continuación, se describe brevemente la metodología en cinco secciones incluyendo el proceso de preselección de las fibras de POA y PAN, los materiales y preparación de especímenes, los ensayos experimentales realizados, los diseños experimentales llevados a cabo en la fase uno y los diseños experimentales llevados a cabo en la fase dos.

### *7.3.1 Proceso de preselección de las fibras de POA y PAN*

El proceso de preselección de las fibras se puede dividir en tres etapas. La primera consiste en la definición del análisis de toma de decisiones, la segunda corresponde a la ponderación de pesos y la tercera comprende la evaluación de las alternativas. Este análisis se limitó al comportamiento mecánico, basado en información suministrada por la literatura acerca del uso de fibras como refuerzo en mezclas asfálticas densas. Las principales propiedades consideradas fueron: resistencia a la rodadura (RR), resistencia a fatiga (FL), tenacidad (T) y tracción indirecta (ITS). Como alternativas, las fibras preseleccionadas fueron polyester (PET), polipropileno (PP), fibra de vidrio (fiber glass), poliacrilonitrilo (PAN), y el conjunto de fibras de poliolefina y aramida (POA).

Para la asignación de pesos se empleó el proceso de análisis jerárquico combinado con conjuntos difusos (FAHP) ya que involucra la participación de expertos lo cual es apropiado en esta fase preliminar. Para tal fin una serie de cuestionarios fueron preparados y completados por 25 expertos de distintos sectores incluyendo el académico, la industria y la administración pública. Con respecto a la evaluación de alternativas el modelo de pesos ponderados de sumas y productos (WASPAS) fue el seleccionado.

### *7.3.2 Materiales empleados y preparación de muestras*

En esta investigación dos tipos betunes fueron empleados, un betún convencional 50/70 y un betún modificado con polímeros PMB 45/80 – 65. Con respecto a los áridos, la ofita fue empleada como árido grueso mientras que la caliza se empleó como árido fino y filler. La Figura 3 muestra las fibras utilizadas en la investigación. Por un lado, el conjunto de fibras poliolefina-aramida (POA), ambas con una longitud de 19 mm. La proporción de este conjunto de fibras corresponde a 87% aramida y un 13% poliolefina. El segundo tipo de fibras empleado fueron las de poliacrilonitrilo (PAN). Para este tipo de fibra dos diferentes tamaños 2 y 4 mm fueron considerados.

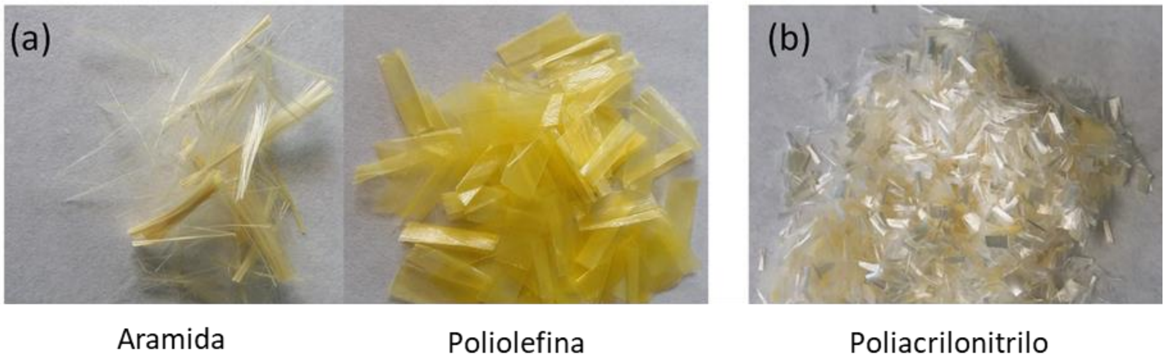



*Figura 3 Fibras usadas en la investigación; (a) fibras POA; (b) fibras PAN*

En esta investigación las probetas fueron preparadas siguiendo la normativa española [29]. La granulometría empleada es de gradación porosa como lo especifica el PG3 (Figura 4). La compactación de las probetas se hizo utilizando el martillo Marshall y aplicando 50 golpes por cara como lo especifica la norma EN 12-697 – 30. De la misma manera, especímenes de mortero cilíndricos de 100 mm de diámetro y 61 mm de altura aproximadamente fueron fabricados empleando el compactador giratorio. Las probetas de mortero se diseñaron con un contenido objetivo de huecos objetivo de 2.50%. La granulometría empleada correspondió a la parte fina utilizada en la mezcla porosa (Figura 5). El contenido de betún fue de 9.30% por peso de mezcla, el cual fue calculado de manera teórica en base a un método propuesto de la superficie específica de la distribución del tamaño de partículas [74].

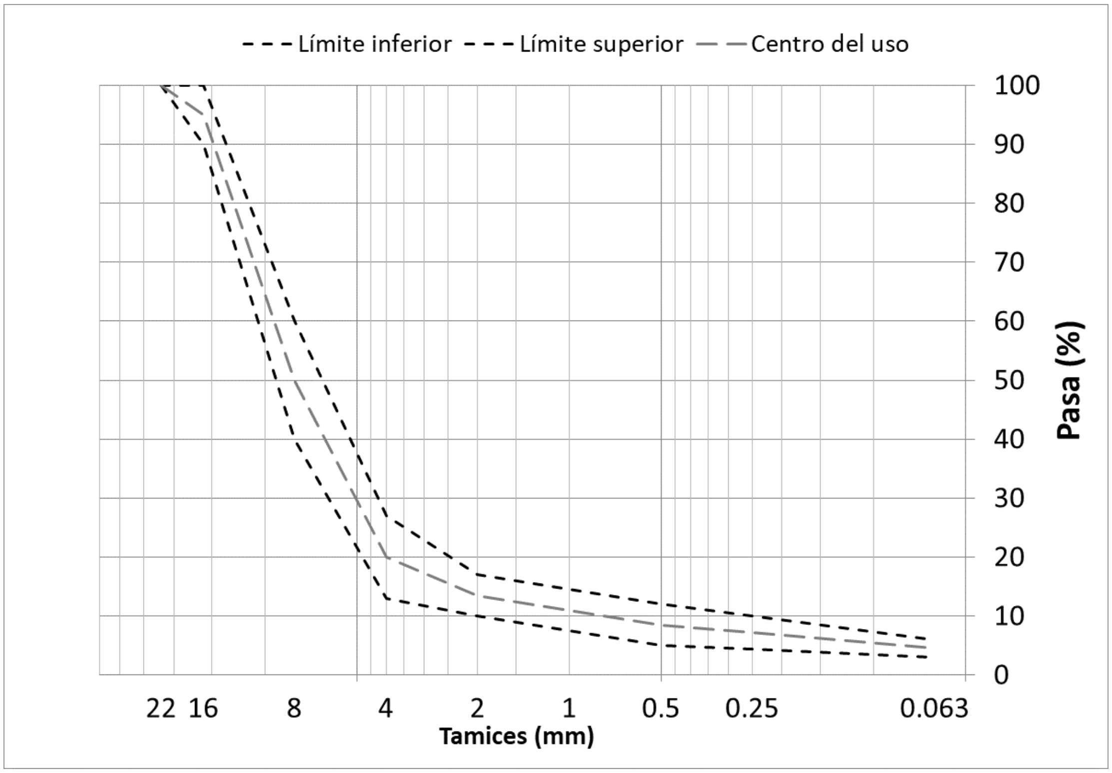



*Figura 4 Granulometría de la mezcla PA*

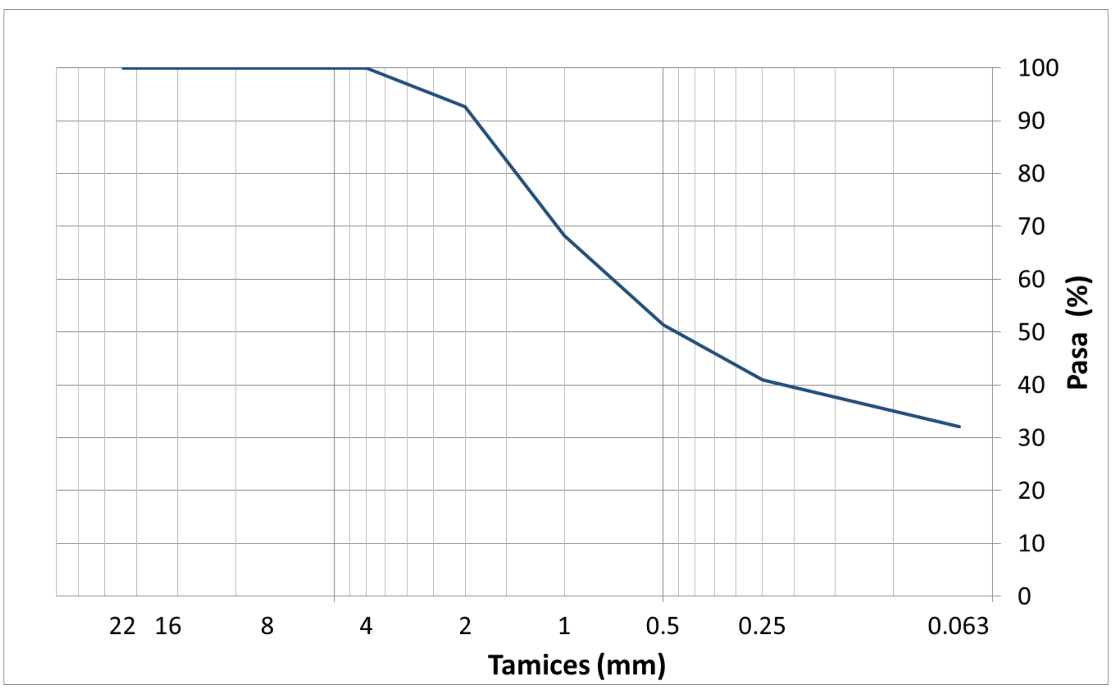



*Figura 5 Granulometría del mortero*

### *7.3.3 Configuración de ensayos experimentales*

La configuración de ensayos experimentales de esta investigación está resumida en la Tabla 2. Como respuestas funcionales los huecos totales, interconectados y la permeabilidad fueron calculados.

Por otro lado, la pérdida de partículas y la resistencia a la tracción indirecta fueron respuestas obtenidas desde el punto de vista mecánico tenidas en cuenta para evaluar la durabilidad de la mezcla asfáltica. Cabe añadir que las curvas de tracción indirecta fueron obtenidas y a partir de ahí, se calcularon tres importantes parámetros de fractura denominados, Energía de fractura (*FE*), Energía post-fractura (*PE*) y Tenacidad (ver Figura 6). Por un lado, la energía de fractura fue calculada como el área de la curva esfuerzo-deformación desde la parte inicial de la curva hasta la deformación alcanzada $\varepsilon_p$ en la carga máxima. Por otro lado, *PE* se calculó como el área de la curva esfuerzo-deformación, desde $\varepsilon_p$ hasta dos veces $\varepsilon_p$. Finalmente, la tenacidad se obtuvo como la suma de los parámetros *PE* y *FE*. Finalmente, dado el bajo contenido de finos que tiene la mezcla PA, ésta es propensa a presentar problemas de escurrimiento del ligante. Por ende, el ensayo de escurrimiento fue realizado empleando el método de la cesta.

*Tabla 2 Configuración de ensayos experimentales*

| Respuesta | Símbolo | Unidades | Procedimiento |
|---|---|---|---|
| Huecos de aire totales | $T_{AV}$ | (%) | EN 12697 - 8 |
| Huecos de aire interconectados | $I_{AV}$ | (%) | Literatura científica |
| Permeabilidad | *k* | mm/s | Permeámetro |
| Pérdida de partículas - condiciones secas | $PL_{dry}$ | (%) | EN 12697 - 17 |
| Pérdida de partículas - condiciones húmedas | $PL_{wet}$ | (%) | NLT 362/92 |
| Resistencia a tracción indirecta - condiciones secas | $ITS_{dry}$ | (MPa) | EN 12697 - 23 |
| Resistencia a tracción indirecta - condiciones húmedas | $ITS_{wet}$ | (MPa) | EN 12697 - 23 |
| Sensibilidad al agua | ITSR | (%) | EN 12697 - 12 |
| Escurrimiento | BD | (%) | EN 12697 - 18 |

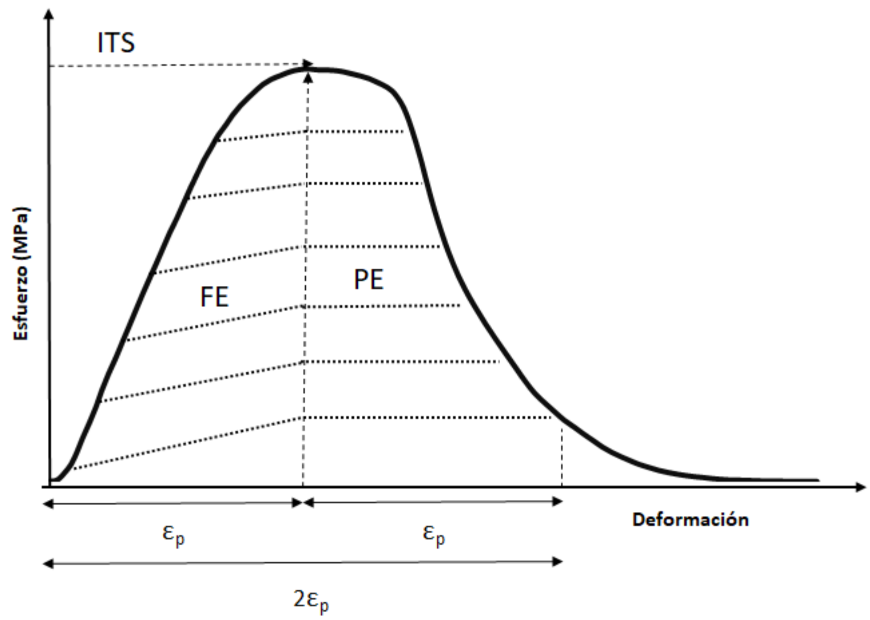



*Figura 6 Curva esfuerzo-deformación*

### *7.3.4 Ensayos experimentales llevados a cabo en la fase uno de la investigación*

Para evaluar el efecto de refuerzo de las fibras de POA y PAN en mezclas PA, se produjeron un total de ocho diseños experimentales (Tabla 3) diferentes y catorce réplicas por cada diseño de mezcla variando el tipo de fibra (sin fibra, POA 19 mm, PAN 4 mm y PAN 12 mm) y la cantidad de filler empleado (4.9% y 4.3% en peso de la fracción agregada). Se fabricaron un total de 112 muestras. En todas las muestras, la cantidad de betún utilizada fue del 4.3% por peso en la mezcla.

*Tabla 3 Diseños de mezclas porosas reforzadas con fibras*

| ID. Nº | Diseño de mezcla | Betún | | Fibras | | | Filler |
|---|---|---|---|---|---|---|---|
| | | Tipo | Dosificación (%) | Tipo | Longitud | Dosificación (%) | Dosificación (%) |
| 1 | RA | 50/70 | 4.3 | - | - | - | 4.9 |
| 2 | POA 19 - A | 50/70 | 4.3 | POA | 19 | 0.05 | 4.9 |
| 3 | PAN 12 - A | 50/70 | 4.3 | PAN | 12 | 0.05 | 4.9 |
| 4 | PAN 4 - A | 50/70 | 4.3 | PAN | 4 | 0.05 | 4.9 |
| 5 | RB | 50/70 | 4.3 | - | - | - | 4.3 |
| 6 | POA 19 - B | 50/70 | 4.3 | POA | 19 | 0.05 | 4.3 |
| 7 | PAN 12 - B | 50/70 | 4.3 | PAN | 12 | 0.05 | 4.3 |
| 8 | PAN 4 - B | 50/70 | 4.3 | PAN | 4 | 0.05 | 4.3 |

Para evaluar el efecto de refuerzo de las fibras de POA y PAN a escala del mortero asfáltico, se prepararon un total de 21 mezclas y tres réplicas por cada diseño con diferentes tipos de fibras (sin fibra, fibras de POA de 19 mm de largo y PAN de 4 mm de largo fibras) con diferentes contenidos de fibra (0.0%, 0.1%, 0.2% 0.3%) y evaluados a tres temperaturas diferentes (15°C, 0 °C, -15 °C). En esta etapa, se prepararon un total de 63 mezclas de mortero asfáltico.

Tanto las mezclas porosas como las de mortero asfáltico fueron analizadas estadísticamente a través del software MINITAB. Ensayos paramétricos y no paramétricos según correspondiese fueron realizados para ver si existían diferencias significativas entre los diseños experimentales. Todos los ensayos fueron llevados a cabo con un nivel de confianza del 95%.

### *7.3.5 Diseños experimentales llevados a cabo en la fase dos de la investigación*

El modelo Taguchi fue empleado en esta investigación para la modelación del diseño de experimentos. Por ende, un robusto arreglo ortogonal $L_{18}$ fue planeado para el diseño de experimentos. El tipo de betún (BT), el contenido de fibra seleccionada (FC) y el contenido de betún (BC) fueron los principales factores de control considerados, mientras que los huecos totales de aire, los huecos de aire interconectados, la pérdida de partículas en condiciones secas y húmedas y el escurrimiento de betún fueron las principales respuestas obtenidas y analizadas individualmente en esta segunda fase. La combinación de los distintos niveles para cada uno de los diseños experimentales de acuerdo al método Taguchi se muestran en la Tabla 4. Detalles de los 18 diseño experimentales realizados se muestran en Tabla 5 .

*Tabla 4 Factores de control con sus respectivos niveles paramétricos*

| Parámetro de entrada | Notación | Nivel 1 | Nivel 2 | Nivel 3 |
|---|---|---|---|---|
| Tipo de ligante | BT | 50/70 | PMB | - |
| Contenido de fibra (%) | FC | 0 | 0.05 | 0.15 |
| Contenido de betún (%) | BC | 4.5 | 5.0 | 5.5 |

*Tabla 5 configuración experimental de acuerdo método Taguchi*

| Número | Código | BT | FC (%) | BC (%) |
|---|---|---|---|---|
| 1 | 50/70-FC:0.00-BC:4.50 | 50/70 | 0.00 | 4.50 |
| 2 | 50/70-FC:0.00-BC:5.00 | 50/70 | 0.00 | 5.00 |
| 3 | 50/70-FC:0.00-BC:5.50 | 50/70 | 0.00 | 5.50 |
| 4 | 50/70-FC:0.05-BC:4.50 | 50/70 | 0.05 | 4.50 |
| 5 | 50/70-FC:0.05-BC:5.00 | 50/70 | 0.05 | 5.00 |
| 6 | 50/70-FC:0.05-BC:5.50 | 50/70 | 0.05 | 5.50 |
| 7 | 50/70-FC:0.15-BC:4.50 | 50/70 | 0.15 | 4.50 |
| 8 | 50/70-FC:0.15-BC:5.00 | 50/70 | 0.15 | 5.00 |
| 9 | 50/70-FC:0.15-BC:5.50 | 50/70 | 0.15 | 5.50 |
| 10 | PMB-FC:0.00-BC:4.50 | PMB45/80-65 | 0.00 | 4.50 |
| 11 | PMB-FC:0.00-BC:5.00 | PMB45/80-65 | 0.00 | 5.00 |
| 12 | PMB-FC:0.00-BC:5.50 | PMB45/80-65 | 0.00 | 5.50 |
| 13 | PMB-FC:0.05-BC:4.50 | PMB45/80-65 | 0.05 | 4.50 |
| 14 | PMB-FC:0.05-BC:5.00 | PMB45/80-65 | 0.05 | 5.00 |
| 15 | PMB-FC:0.05-BC:5.50 | PMB45/80-65 | 0.05 | 5.50 |
| 16 | PMB-FC:0.15-BC:4.50 | PMB45/80-65 | 0.15 | 4.50 |
| 17 | PMB-FC:0.15-BC:5.00 | PMB45/80-65 | 0.15 | 5.00 |
| 18 | PMB-FC:0.15-BC:5.50 | PMB45/80-65 | 0.15 | 5.50 |

De acuerdo con el método Taguchi las relaciones señales-ruido (SN) son un indicador de la variabilidad de una respuesta específica bajo distintas condiciones de ruido. En consecuencia, en esta investigación la condición "*menor-es-mejor*" fue aplicada a minimizar la pérdida de partículas en condiciones secas y húmedas, así como el escurrimiento de ligante. Por otro lado, la condición "*mas-es-mejor*" fue empleada para maximizar los huecos totales e interconectados.

Además, en esta investigación debido a que se obtuvo más de una respuesta, el análisis multi-criterio fue empleado para transformar el problema de múltiple respuesta en un problema de respuesta singular. En esta investigación el método TOPSIS, que basa su teoría en el cálculo de las distancias euclidianas a las soluciones ideales positivas y negativas respectivamente, fue empleado para establecer un índice unificado y establecer el ranking de preferencias. Para gestionar la asignación de pesos el método objetivo CRITIC fue empleado, dado que es un proceso objetivo que no requiere de la participación humana. El método asigna los pesos en función de la intensidad contrastada de cada una de las respuestas y la evaluación de conflictos entre los diferentes criterios.

### 7.4 Discusión de resultados

En esta sección, la discusión de resultados está introducida en tres secciones distintas. La primera sección presenta los resultados concernientes al proceso de preselección de fibras a través del análisis multi-criterio. En la segunda fase, los resultados experimentales de mezclas PA reforzados con fibras están descritos. Una vez la fibra más prometedora fue seleccionada, en una tercera fase se presentaron los resultados de la metodología integrada DoE-MCDM considerando la influencia de varios factores de control.

### *7.4.1 Proceso de preselección de fibras*

De acuerdo al análisis de resultados obtenido de los cuestionarios aplicando el método FAHP, los criterios más valorados fueron tenacidad y la vida a fatiga con unos pesos de 31% y 28%, respectivamente. Por el contrario, resistencia a la rodadura y tracción indirecta obtuvieron los pesos más bajos con valores de 23% y 18%, respectivamente. El resultado del ranking de los distintos tipos de fibra empleando la metodología WASPAS y en términos de la valoración de rendimiento conjunto (JPS) se puede ver en la Tabla 6. Los valores JPS pueden variar entre 0 y 1. En consecuencia los valores JPS más altos corresponden a la alternativa más adecuada. Vale la pena recalcar que este análisis solo consideró las mejoras de las fibras cuando se incorporaban en mezclas densas debido a la falta de información del uso de fibras como refuerzo en mezclas porosas.

*Tabla 6 Pesos asignados de acuerdo a la metodología WASPAS*

| Tipo de fibra | PAN | POA | FG | PET | PP |
|---|---|---|---|---|---|
| JPS | 0.75 | 0.69 | 0.55 | 0.63 | 0.53 |

### *7.4.2 Resultados experimentales de mezclas PA reforzadas con fibras sintéticas*

*- Resultados a la escala de la mezcla PA*

Los valores medios de huecos totales, interconectados y permeabilidad con su respectiva desviación estándar están mostrados en la Tabla 7. De los resultados se puede apreciar que la adición de fibras disminuyó ligeramente la respuesta funcional de la mezcla en el caso en que se usó un contenido de filler más alto. Para esta condición no se encontraron diferencias significativas en el tipo de fibra utilizado. Para la condición de filler más bajo, la tendencia sugiere que la adición de fibras incrementa los huecos totales e interconectados. Estos resultados podrían sugerir que las fibras absorben parcialmente el betún permitiendo un incremento en la porosidad total a interconectada. En términos de permeabilidad, las tendencias observadas fueron bastante similares. En general a pesar de la disminución de los huecos, todas las mezclas PA reportaron una funcionalidad con huecos totales superior al 20%. De igual manera con respecto a la permeabilidad, todas las mezclas PA arrojaron valores admisibles de permeabilidad superiores a 1.2 mm/s [1,99], como se sugiere en la literatura científica.

*Tabla 7 Resultados de huecos y permeabilidad*

| Mezcla PA | RA | POA 19 - A | PAN 12 - A | PAN 4 - A | RB | POA 19 - B | PAN 12 - B | PAN 4 - B |
|---|---|---|---|---|---|---|---|---|
| Huecos totales EN 12697 - 8 | | | | | | | | |
| Media | 23.74 | 21.57 | 21.65 | 21.21 | 21.45 | 20.80 | 23.78 | 22.31 |
| SD | 1.32 | 0.91 | 1.10 | 1.21 | 1.78 | 1.35 | 1.41 | 0.73 |
| Huecos interconectados (%) | | | | | | | | |
| Media | 20.59 | 16.54 | 15.47 | 16.27 | 13.05 | 15.05 | 19.70 | 17.21 |
| SD | 1.45 | 0.94 | 0.49 | 1.66 | 2.95 | 1.80 | 1.02 | 2.50 |
| Permeabilidad (mm/s) | | | | | | | | |
| Media | 4.96 | 3.28 | 3.35 | 4.23 | 2.00 | 3.43 | 3.08 | 2.67 |
| SD | 0.69 | 0.36 | 0.25 | 1.44 | 0.16 | 1.16 | 0.22 | 0.34 |

En la Tabla 8, se muestran los resultados obtenidos del ensayo cántabro. Con respecto a la pérdida de partículas en condiciones secas, mejoras significativas se pueden apreciar con la adición de fibras POA y fibras PAN de 4 mm de longitud. De la misma manera, a pesar de la reducción en el contenido de filler, notables mejoras se notaron con la adición de fibras. Sin embargo, solo se notaron diferencias significativas con la adición de fibras POA y fibras PAN de 12 mm de longitud. En la pérdida de partículas bajo la acción del agua no se notaron mejoras con la adición de fibras. Los mejores resultados de igual forma se obtuvieron con las fibras POA arrojando resultados muy similares a las mezclas de referencia.

*Tabla 8 Resultados del ensayo Cántabro*

| Mezcla PA | RA | POA 19 - A | PAN 12 - A | PAN 4 - A | RB | POA 19 - B | PAN 12 - B | PAN 4 - B |
|---|---|---|---|---|---|---|---|---|
| Pérdida de partículas - condiciones secas (%) EN 12697 - 17 | | | | | | | | |
| Media | 15.86 | 10.51 | 22.11 | 13.48 | 17.45 | 10.34 | 11.91 | 13.55 |
| SD | 3.29 | 2.40 | 4.07 | 3.48 | 3.89 | 1.95 | 3.72 | 0.66 |
| Pérdida de partículas - condiciones húmedas (%) EN 12697 - 17 | | | | | | | | |
| Media | 18.19 | 18.02 | 28.71 | 34.05 | 20.22 | 26.67 | 42.17 | 24.42 |
| SD | 3.06 | 3.98 | 5.22 | 3.31 | 9.08 | 5.88 | 7.59 | 2.95 |

En la Tabla 9 se pueden observar los resultados concernientes a tracción indirecta en condiciones secas y húmedas, al igual que la relación de sensibilidad al agua. De los resultados obtenidos, las fibras POA arrojaron mejoras significativas en el esfuerzo a tracción indirecta con respecto a la mezcla PA de referencia. Esta fue la única fibra que arrojó resultados estadísticamente significativos. En lo que respecta a la tracción indirecta en condiciones húmedas, no se presentaron mejoras notables con la adición de fibras. Ligeras mejoras significativas fueron únicamente observadas con la adición de fibras POA y en la condición de alto contenido de filler.

*Tabla 9 Resultados de tracción indirecta y sensibilidad al agua*

| Mezcla PA | RA | POA 19 - A | PAN 12 - A | PAN 4 - A | RB | POA 19 - B | PAN 12 - B | PAN 4 - B |
|---|---|---|---|---|---|---|---|---|
| Tracción indirecta - condiciones secas (MPa) EN 12697 - 23 | | | | | | | | |
| Media | 1.05 | 1.28 | 1.14 | 1.10 | 1.26 | 1.43 | 1.22 | 1.10 |
| SD | 0.09 | 0.09 | 0.03 | 0.11 | 0.06 | 0.10 | 0.16 | 0.11 |
| Tracción indirecta - condiciones húmedas (MPa) EN 12697 - 23 | | | | | | | | |
| Media | 0.85 | 0.93 | 0.85 | 0.80 | 1.07 | 0.89 | 0.75 | 0.84 |
| SD | 0.05 | 0.03 | 0.05 | 0.06 | 0.10 | 0.14 | 0.10 | 0.04 |
| Relación de tracción indirecta EN 12697 - 12 | | | | | | | | |
| Media | 81 | 73 | 74 | 73 | 86 | 62 | 61 | 76 |

- *Resultados a la escala del mortero asfáltico*

Con respecto a los morteros asfálticos reforzados con fibras, la resistencia a la tracción, y los parámetros de fractura, FE, PE y tenacidad fueron calculadas en base a los resultados experimentales obtenidos del ensayo de tracción indirecta. En esta fase, fibras de POA de 19 mm de longitud y fibras de PAN de 4 mm de longitud fueron tenidas en cuenta dado que arrojaron los mejores resultados en las mezclas PA.

El comportamiento del mortero asfáltico al romperse a 15°C y 0°C tuvo una componente elástica seguida de una componente plástica hasta el esfuerzo máximo alcanzado. Por otro lado, el comportamiento de los morteros asfálticos a -15°C fue elástico ocasionando una ruptura frágil una vez la carga pico fue alcanzada. De acuerdo a las curvas esfuerzo-deformación, se obtuvieron los parámetros de fractura para las mezclas asfálticas reforzadas con fibras a cada una de las distintas temperaturas como se puede apreciar en la Tabla 10. A pesar de todos los resultados obtenidos, únicamente diferencias significativas fueron obtenidas a -15°C. A esta temperatura el betún se tornó bastante rígido y en consecuencia la tracción indirecta y la energía de fractura fueron los únicos parámetros obtenidos. Con la adición de fibras POA se puede apreciar una tendencia clara en el incremento de la resistencia a tracción indirecta, así como en la energía de fractura.

*Tabla 10 Parámetros de fractura obtenidos a las tres distintas temperaturas*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 15°C | | | | | | | |
| Tracción indirecta (MPa) | | | | | | | |
| Mortero | Referencia | POA 0.1 | POA 0.2 | POA 0.3 | PAN 0.1 | PAN 0.2 | PAN 0.3 |
| Media | 1.29 | 1.16 | 1.33 | 1.17 | 1.36 | 1.19 | 1.35 |
| SD | 0.05 | 0.07 | 0.02 | 0.06 | 0.06 | 0.02 | 0.27 |
| Energía de fractura (kPa) | | | | | | | |
| Media | 34.11 | 38.76 | 40.74 | 36.45 | 39.46 | 35.86 | 38.50 |
| SD | 7.43 | 2.56 | 1.29 | 2.01 | 2.99 | 2.31 | 1.12 |
| Energía post - cracking (kPa) | | | | | | | |
| Media | 43.60 | 37.35 | 40.28 | 39.41 | 41.36 | 40.48 | 40.51 |
| SD | 8.99 | 2.32 | 1.11 | 2.22 | 2.78 | 2.29 | 1.08 |
| Tenacidad (kPa) | | | | | | | |
| Media | 77.71 | 76.11 | 81.01 | 75.85 | 80.82 | 76.34 | 79.01 |
| SD | 5.16 | 3.69 | 1.54 | 4.22 | 4.18 | 4.39 | 0.92 |
| 0°C | | | | | | | |
| Tracción indirecta (MPa) | | | | | | | |
| Mortero | Referencia | POA 0.1 | POA 0.2 | POA 0.3 | PAN 0.1 | PAN 0.2 | PAN 0.3 |
| Media | 2.90 | 2.68 | 2.64 | 2.96 | 2.59 | 2.81 | 3.04 |
| SD | 0.15 | 0.21 | 0.07 | 0.16 | 0.23 | 0.25 | 0.02 |
| Energía de fractura (kPa) | | | | | | | |
| Media | 62.89 | 56.37 | 55.46 | 54.97 | 65.23 | 48.70 | 44.47 |
| SD | 3.30 | 6.43 | 2.23 | 4.24 | 25.35 | 0.98 | 6.33 |
| Energía post - cracking (kPa) | | | | | | | |
| Media | 58.92 | 52.98 | 54.47 | 59.23 | 61.77 | 56.87 | 54.34 |
| SD | 5.26 | 8.56 | 3.00 | 2.59 | 13.13 | 8.14 | 8.51 |
| Tenacidad (kPa) | | | | | | | |
| Media | 121.82 | 109.35 | 109.93 | 114.20 | 127.00 | 105.57 | 98.81 |
| SD | 6.73 | 9.47 | 0.87 | 5.35 | 38.39 | 8.77 | 4.39 |
| -15°C | | | | | | | |
| Tracción indirecta (MPa) | | | | | | | |
| Mortero | Referencia | POA 0.1 | POA 0.2 | POA 0.3 | PAN 0.1 | PAN 0.2 | PAN 0.3 |
| Media | 3.88 | 4.52 | 4.58 | 5.18 | 4.67 | 5.15 | 5.10 |
| SD | 0.40 | 0.84 | 0.47 | 0.52 | 0.58 | 0.74 | 0.26 |
| Energía de fractura (kPa) | | | | | | | |
| Media | 16.52 | 21.13 | 21.30 | 20.78 | 16.83 | 20.45 | 20.12 |
| SD | 1.59 | 3.30 | 2.48 | 2.02 | 2.06 | 3.61 | 1.09 |

### *7.4.3 Resultados del integrado DOE-MCDM análisis considerando la influencia de varios factores de control*

Para esta etapa la fibra POA ha sido seleccionada como la fibra más prometedora. En esta fase el refuerzo de la fibra es evaluado considerando otros factores de control. La metodología Taguchi fue la empleada para la elaboración del arreglo ortogonal de experimentos. En esta fase también se busca mejorar la funcionalidad de la mezcla sin afectar su durabilidad, así como evitar el riesgo de escurrimiento de ligante. Los ensayos llevados en esta etapa fueron desde el punto de vista funcional el cálculo de los huecos totales e interconectados de la mezcla. Desde el punto de vista mecánico, se realizó el ensayo cántabro en condiciones secas y húmedas. De la misma forma, el escurrimiento de betún fue medido para analizar el potencial estabilizante que tienen las fibras. Las relaciones SN sirvieron de base para analizar cada una de las respuestas de manera individual. La condición *Mayor-es-mejor* fue el tipo de criterio tenido en cuenta en el cálculo de los huecos. Por otro lado, *Menor-es-mejor* fue el criterio tenido en cuenta para calcular la pérdida de partículas y el escurrimiento de betún. Vale la pena recordar que las relaciones SN son un indicador de la varianza de las características para sus valores medios. En esta fase, una baja varianza fue encontrada entre los efectos principales de las medias y las relaciones SN. Es decir, para simplificar, solo los efectos de las medias obtenidas serán presentados en esta sección.

Una vez las respuestas se analizaron de manera individual, un robusto análisis multi-criterio fue llevado a cabo para transformar el problema de múltiple respuesta en un problema de única respuesta. Las metodologías multi-criterio CRITIC y TOPSIS fueron las utilizadas para determinar los pesos de las respuestas, los factores de control más influyentes y un índice unificado que permitiese evaluar el comportamiento global de la mezcla con un único indicador.

- *Análisis de respuestas funcionales*

Los resultados experimentales de los 18 diseños están consignados en la Tabla 11. Los valores medios de porosidad total e interconectada oscilaron entre 17.50% a 23.20% y 11.20% a 17.26% para ambas respuestas, respectivamente. Hay que resaltar que se encontró una relación directa entre ambas porosidades con un coeficiente de Pearson de 0.89. Aunque un valor mínimo de huecos totales del 20% es requerido para garantizar una apropiada funcionalidad, otros estudios han revelado que un contenido de huecos superior al 18% es aceptable [3]. En general, todos los diseños cumplieron con el requerimiento de huecos superior al 18% a excepción del diseño 9 donde tuvo lugar un contenido de huecos de 17.50%.

*Tabla 11 Resultados experimentales de los 18 diseños*

| Número | Código | $T_{AV}$ (%) | | $I_{AV}$ (%) | | $PL_{dry}$ (%) | | $PL_{wet}$ (%) | | BD (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Media | SD | Media | SD | Media | SD | Media | SD | Media |
| 1 | 50/70-FC:0.00-BC:4.50 | 21.39 | 0.75 | 14.59 | 1.32 | 14.96 | 1.99 | 19.12 | 5.51 | 0.01 |
| 2 | 50/70-FC:0.00-BC:5.00 | 18.85 | 0.14 | 12.45 | 0.70 | 6.76 | 2.65 | 15.32 | 3.20 | 0.40 |
| 3 | 50/70-FC:0.00-BC:5.50 | 18.68 | 1.12 | 11.94 | 1.48 | 9.37 | 0.75 | 8.28 | 2.03 | 2.25 |
| 4 | 50/70-FC:0.05-BC:4.50 | 21.36 | 0.35 | 15.59 | 1.01 | 12.52 | 1.99 | 39.85 | 10.23 | 0.01 |
| 5 | 50/70-FC:0.05-BC:5.00 | 19.67 | 0.40 | 13.57 | 0.61 | 7.90 | 4.27 | 15.71 | 1.89 | 0.03 |
| 6 | 50/70-FC:0.05-BC:5.50 | 18.85 | 0.14 | 12.45 | 0.70 | 4.90 | 1.68 | 10.70 | 1.40 | 0.59 |
| 7 | 50/70-FC:0.15-BC:4.50 | 23.22 | 0.22 | 17.26 | 0.38 | 19.71 | 2.01 | 35.95 | 5.05 | 0.02 |
| 8 | 50/70-FC:0.15-BC:5.00 | 20.38 | 0.88 | 14.14 | 1.06 | 15.66 | 1.86 | 22.74 | 3.15 | 0.01 |
| 9 | 50/70-FC:0.15-BC:5.50 | 17.49 | 1.30 | 11.22 | 0.99 | 7.01 | 1.39 | 9.08 | 2.15 | 0.16 |
| 10 | PMB-FC:0.00-BC:4.50 | 20.59 | 1.89 | 14.36 | 2.22 | 10.57 | 4.80 | 10.81 | 3.54 | 0.00 |
| 11 | PMB-FC:0.00-BC:5.00 | 21.12 | 0.40 | 15.16 | 0.80 | 5.16 | 2.77 | 7.19 | 1.68 | 0.28 |
| 12 | PMB-FC:0.00-BC:5.50 | 20.18 | 2.18 | 13.93 | 2.91 | 4.73 | 0.78 | 7.49 | 1.72 | 0.97 |
| 13 | PMB-FC:0.05-BC:4.50 | 20.81 | 2.14 | 14.47 | 2.66 | 5.94 | 2.20 | 7.80 | 3.52 | 0.00 |
| 14 | PMB-FC:0.05-BC:5.00 | 19.54 | 1.88 | 12.39 | 2.80 | 8.12 | 5.19 | 5.62 | 0.26 | 0.04 |
| 15 | PMB-FC:0.05-BC:5.50 | 18.42 | 2.51 | 14.39 | 3.43 | 2.52 | 0.96 | 8.25 | 2.47 | 0.12 |
| 16 | PMB-FC:0.15-BC:4.50 | 19.50 | 1.14 | 13.12 | 0.91 | 8.47 | 3.70 | 7.73 | 0.45 | 0.04 |
| 17 | PMB-FC:0.15-BC:5.00 | 20.22 | 0.17 | 14.15 | 0.11 | 4.77 | 1.02 | 5.26 | 0.76 | 0.05 |
| 18 | PMB-FC:0.15-BC:5.50 | 19.91 | 1.03 | 13.03 | 0.97 | 3.30 | 0.34 | 3.48 | 0.62 | 0.21 |

En la Tabla 12 se pueden apreciar las respuestas de medias para los valores de huecos totales e interconectados. Para ambas respuestas, el contenido de betún fue el factor más influyente seguido del factor contenido de fibra y del factor tipo de betún. Las tendencias son similares para ambos contenidos de huecos dada la estrecha correlación que existe entre ambas variables. El contenido de fibra tiene una ligera influencia en los huecos interconectados mientras que el tipo de ligante no tiene un notable impacto en los huecos de la mezcla.

*Tabla 12 Respuesta de medias de valores funcionales*

| Huecos de aire totales | | | |
|---|---|---|---|
| Nivel | BT | FC | BC |
| 1 | 19.99 | 20.14 | 21.15 |
| 2 | 20.03 | 19.77 | 19.96 |
| 3 | - | 20.12 | 18.92 |
| Delta | 0.04 | 0.36 | 2.23 |
| Rank | 3.00 | 2.00 | 1.00 |
| Huecos de aire interconectados | | | |
| Nivel | BT | FC | BC |
| 1 | 13.69 | 13.74 | 14.90 |
| 2 | 13.89 | 13.81 | 13.64 |
| 3 | | 13.82 | 12.83 |
| Delta | 0.20 | 0.08 | 2.07 |
| Rank | 2.00 | 3.00 | 1.00 |

En la Tabla 13 se muestran los valores medios obtenidos del ensayo Cántabro tanto en condiciones secas como en condiciones húmedas. Los mejores niveles para la pérdida de partículas en condiciones secas fueron obtenidos empleando un betún modificado añadiendo 0.05% fibras de POA y 5.50% como contenido de ligante. En condiciones húmedas, los impactos más influyentes fueron el tipo y contenido de betún. De hecho, la contribución de las fibras en términos de pérdida de partículas en condiciones húmedas es menos apreciable cuando se usa un betún modificado.

*Tabla 13 Respuesta de medias del ensayo Cántabro*

| Pérdida de partículas - condiciones secas | | | |
|---|---|---|---|
| Nivel | BT | FC | BC |
| 1 | 10.98 | 8.59 | 12.03 |
| 2 | 5.95 | 6.98 | 8.06 |
| 3 | - | 9.82 | 5.30 |
| Delta | 5.02 | 2.84 | 6.73 |
| Rank | 2.00 | 3.00 | 1.00 |
| Pérdida de partículas - condiciones húmedas | | | |
| Nivel | BT | FC | BC |
| 1 | 19.64 | 11.37 | 20.21 |
| 2 | 7.07 | 14.66 | 11.98 |
| 3 | - | 14.04 | 7.88 |
| Delta | 12.57 | 3.29 | 12.33 |
| Rank | 1.00 | 3.00 | 2.00 |

En lo que respecta al escurrimiento, la Tabla 14 muestra los valores medios. Similar a la pérdida de partículas, valores bajos de escurrimiento de ligante son deseados. La tendencia sugiere que cuando se emplean fibras el ligante 50/70 es más adecuado que el modificado. Lo anterior supone que las fibras absorben mejor los componentes de un betún convencional en lugar de uno modificado.

*Tabla 14 Respuesta de medias del ensayo de escurrimiento*

| | Escurrimiento de ligante | | |
|---|---|---|---|
| Nivel | BT | FC | BC |
| 1 | 0.39 | 0.65 | 0.01 |
| 2 | 0.19 | 0.13 | 0.14 |
| 3 | - | 0.08 | 0.72 |
| Delta | 0.20 | 0.57 | 0.70 |
| Rank | 3.00 | 2.00 | 1.00 |

- *Análisis MCDM*

Una vez todas las respuestas fueron analizadas individualmente, el siguiente paso consistió en aplicar el análisis multi-criterio con el fin de transformar el problema de respuesta múltiple, en un problema de respuesta singular. Por un lado, la metodología CRITIC fue empleada para la ponderación de cada una de las respuestas mientras que la metodología TOPSIS fue empleada para establecer un índice unificado que juntara todas las respuestas de manera conjunta.

Como se puede apreciar en la Tabla 15 tanto los huecos totales como interconectados poseen pesos similares, lo cual es debido a la alta correlación que existe entre estas dos variables. Por otro lado, la pérdida de partículas en seco y húmedo tuvieron los pesos más altos con valores de 0.24 y 0.25 respectivamente. Finalmente, el escurrimiento de betún fue valorado con un peso bastante similar a los de los huecos.

*Tabla 15 Ponderación de pesos según método CRITIC*

| Respuestas | $T_{AV}$ (%) | $I_{AV}$ (%) | $PL_{dry}$ (%) | $PL_{wet}$ (%) | BD (%) |
|---|---|---|---|---|---|
| $W_j$ | 0.18 | 0.17 | 0.24 | 0.25 | 0.17 |

Una vez que se calcularon los pesos de las diferentes variables de respuesta aplicando el enfoque CRITIC, se determinó el coeficiente comparativo de proximidad (CCC) para cada diseño de experimentos utilizando la metodología TOPSIS. En consecuencia, el CCC y el ranking de preferencia para todos los diseños experimentales se presentan en la Tabla 16. Es importante señalar que los valores más altos de CCC indican la elección más adecuada entre el conjunto de alternativas. El diseño experimental número 17 resultó el mejor diseño, con valores de respuesta de 20.22%; 14.15%; 4.77%; 5.26% y 0.05% para $T_{AV}, I_{AV}, PL_{DRY}, PL_{WET}$ y *BD*, respectivamente. Este diseño implica el uso de betún modificado con polímeros con un contenido de fibra de 0.15% y un contenido de betún de 5.0%. Por otro lado, se determinó que el diseño experimental número 3 es el diseño con el valor CCC más bajo y, por lo tanto, la última opción preferida.

*Tabla 16 valores CCC y ranking de preferencias de acuerdo con TOPSIS*

| Número | Código | $T_{AV}$ (%) | $I_{AV}$ (%) | $PL_{dry}$ (%) | $PL_{wet}$ (%) | BD (%) | CCC | Posición |
|---|---|---|---|---|---|---|---|---|
| 17 | PMB-FC:0.15-BC:5.00 | 20.22 | 14.15 | 4.77 | 5.26 | 0.05 | 0.92 | 1 |
| 18 | PMB-FC:0.15-BC:5.50 | 19.91 | 13.03 | 3.30 | 3.48 | 0.21 | 0.91 | 2 |
| 15 | PMB-FC:0.05-BC:5.50 | 18.42 | 14.39 | 2.52 | 8.25 | 0.12 | 0.90 | 3 |
| 13 | PMB-FC:0.05-BC:4.50 | 20.81 | 14.47 | 5.94 | 7.80 | 0.00 | 0.88 | 4 |
| 11 | PMB-FC:0.00-BC:5.00 | 21.12 | 15.16 | 5.16 | 7.19 | 0.28 | 0.87 | 5 |
| 14 | PMB-FC:0.05-BC:5.00 | 19.54 | 12.39 | 8.12 | 5.62 | 0.04 | 0.84 | 6 |
| 16 | PMB-FC:0.15-BC:4.50 | 19.50 | 13.12 | 8.47 | 7.73 | 0.04 | 0.83 | 7 |
| 9 | 50/70-FC:0.15-BC:5.50 | 17.49 | 11.22 | 7.01 | 9.08 | 0.16 | 0.82 | 8 |
| 10 | PMB-FC:0.00-BC:4.50 | 20.59 | 14.36 | 10.57 | 10.81 | 0.00 | 0.77 | 9 |
| 5 | 50/70-FC:0.05-BC:5.00 | 19.67 | 13.57 | 7.90 | 15.71 | 0.03 | 0.76 | 10 |
| 6 | 50/70-FC:0.05-BC:5.50 | 18.85 | 12.45 | 4.90 | 10.70 | 0.59 | 0.76 | 11 |
| 2 | 50/70-FC:0.00-BC:5.00 | 18.85 | 12.45 | 6.76 | 15.32 | 0.40 | 0.73 | 12 |
| 12 | PMB-FC:0.00-BC:5.50 | 20.18 | 13.93 | 4.73 | 7.49 | 0.97 | 0.68 | 13 |
| 1 | 50/70-FC:0.00-BC:4.50 | 21.39 | 14.59 | 14.96 | 19.12 | 0.01 | 0.65 | 14 |
| 8 | 50/70-FC:0.15-BC:5.00 | 20.38 | 14.14 | 15.66 | 22.74 | 0.01 | 0.61 | 15 |
| 7 | 50/70-FC:0.15-BC:4.50 | 23.22 | 17.26 | 19.71 | 35.95 | 0.02 | 0.52 | 16 |
| 4 | 50/70-FC:0.05-BC:4.50 | 21.36 | 15.59 | 12.52 | 39.85 | 0.01 | 0.51 | 17 |
| 3 | 50/70-FC:0.00-BC:5.50 | 18.68 | 11.94 | 9.37 | 8.28 | 2.25 | 0.37 | 18 |

Los valores de CCC obtenidos a través de la metodología CRITIC-TOPSIS basado en Taguchi también se usaron para calcular los valores medios de efectos principales, como se muestra en la Tabla 17.

*Tabla 17 Respuesta unificada de medias según la metodología TOPSIS*

| Nivel | Valores CCC - Método TOPSIS | | |
|---|---|---|---|
| | BT | FC | BC |
| 1 | 0.64 | 0.68 | 0.69 |
| 2 | 0.85 | 0.78 | 0.79 |
| 3 | - | 0.77 | 0.74 |
| Delta | 0.21 | 0.10 | 0.10 |
| Rank | 1.00 | 2.00 | 3.00 |

El tipo de betún parece tener el mayor impacto en los valores medios. Como se puede observar en la clasificación, los primeros siete diseños experimentales fueron sobre mezclas usando PMB. Por otro lado, se observaron buenos resultados en términos de funcionalidad y durabilidad para las mezclas que usaron un betún 50/70. Por ejemplo, las mezclas correspondientes al diseño número 5, con un contenido de fibra de 0.05% y un contenido de betún de 5.0%, exhibieron valores de pérdida de partículas en condiciones secas y húmedas de 7.90% y 15.71%, respectivamente. Esta mezcla también mostró un contenido adecuado de huecos de aire de aproximadamente 20% y no presentó problemas de escurrimiento, ya que obtuvo un valor inferior a 0.3%, el límite recomendado en la literatura [16].

El método TOPSIS sirvió de referencia para establecer un índice unificado y clasificar las alternativas. Sin embargo, otros métodos multi-criterio pueden ser empleados para tal fin. En consecuencia, la valoración de rendimiento conjunto (JPS) del método WASPAS y el peso de evaluación (AS) de la técnica EDAS también se seleccionaron como métodos multi-criterio para comparar con TOPSIS. El método EDAS comparte similitudes con TOPSIS ya que ambos se basan en las mediciones de distancias para una solución específica. Por otro lado, WASPAS difiere con TOPSIS ya que basa su algoritmo en funciones de utilidad aditiva y multiplicativa.

*Tabla 18 Valores CCC, JPS, y AS de acuerdo a TOPSIS, WASPAS y EDAS respectivamente*

| Diseño | Código | CCC | Posición | JPS | Posición | AS | Posición |
|---|---|---|---|---|---|---|---|
| 1 | 50/70-FC:0.00-BC:4.50 | 0.65 | 14.00 | 0.29 | 12.00 | 0.61 | 11.00 |
| 2 | 50/70-FC:0.00-BC:5.00 | 0.73 | 12.00 | 0.27 | 17.00 | 0.51 | 15.00 |
| 3 | 50/70-FC:0.00-BC:5.50 | 0.37 | 18.00 | 0.26 | 18.00 | 0.12 | 18.00 |
| 4 | 50/70-FC:0.05-BC:4.50 | 0.51 | 17.00 | 0.28 | 14.00 | 0.50 | 16.00 |
| 5 | 50/70-FC:0.05-BC:5.00 | 0.76 | 10.00 | 0.30 | 11.00 | 0.69 | 10.00 |
| 6 | 50/70-FC:0.05-BC:5.50 | 0.76 | 11.00 | 0.30 | 10.00 | 0.60 | 13.00 |
| 7 | 50/70-FC:0.15-BC:4.50 | 0.52 | 16.00 | 0.27 | 16.00 | 0.48 | 17.00 |
| 8 | 50/70-FC:0.15-BC:5.00 | 0.61 | 15.00 | 0.28 | 15.00 | 0.56 | 14.00 |
| 9 | 50/70-FC:0.15-BC:5.50 | 0.82 | 8.00 | 0.29 | 13.00 | 0.72 | 9.00 |
| 10 | PMB-FC:0.00-BC:4.50 | 0.77 | 9.00 | 0.56 | 2.00 | 0.76 | 8.00 |
| 11 | PMB-FC:0.00-BC:5.00 | 0.87 | 5.00 | 0.36 | 6.00 | 0.80 | 7.00 |
| 12 | PMB-FC:0.00-BC:5.50 | 0.68 | 13.00 | 0.34 | 8.00 | 0.61 | 12.00 |
| 13 | PMB-FC:0.05-BC:4.50 | 0.88 | 4.00 | 0.66 | 1.00 | 0.95 | 4.00 |
| 14 | PMB-FC:0.05-BC:5.00 | 0.84 | 6.00 | 0.36 | 7.00 | 0.86 | 5.00 |
| 15 | PMB-FC:0.05-BC:5.50 | 0.90 | 3.00 | 0.43 | 4.00 | 0.95 | 3.00 |
| 16 | PMB-FC:0.15-BC:4.50 | 0.83 | 7.00 | 0.33 | 9.00 | 0.81 | 6.00 |
| 17 | PMB-FC:0.15-BC:5.00 | 0.92 | 1.00 | 0.42 | 5.00 | 1.00 | 1.00 |
| 18 | PMB-FC:0.15-BC:5.50 | 0.91 | 2.00 | 0.48 | 3.00 | 0.96 | 2.00 |

La Tabla 18 presenta los valores CCC, JPS y AS obtenidos de TOPSIS, WASPAS y EDAS, respectivamente. Los resultados por el método EDAS fueron similares a los obtenidos por TOPSIS. De acuerdo a EDAS, el diseño 17 (PMB-FC: 0.15-BC:5.00) y 18 (PMB-FC: 0.15-BC:5.50) se clasificaron como las alternativas más adecuadas mientras que el diseño 3 (50/70-FC: 0.00-BC:5.50) resultó la opción menos preferida, lo cual coincide bien con los resultados arrojados por TOPSIS. En cuanto a WASPAS, los resultados son sustancialmente diferentes en términos de clasificación, pero con algunas similitudes en cuanto a la valoración de las variables. Por ejemplo, clasifica el diseño 13 (PMB-FC: 0.05-BC: 4.50) como la opción más atractiva que también dio buenos resultados en términos de pérdida de partículas y huecos de aire sin riesgo de escurrimiento. Del mismo modo, el diseño 3 fue asignado con la valoración más baja.

## 7.5 Conclusiones

En esta sección se presentan las conclusiones específicas de mayor relevancia, las conclusiones generales de toda la investigación y las futuras líneas de investigación.

### *7.5.1 Conclusiones específicas de mayor relevancia*

Las conclusiones específicas se dividen en tres secciones, de manera similar a la sección de resultados presentando las contribuciones más relevantes de cada fase.

- *Conclusiones específicas del proceso de preselección de fibras*

- Las fibras de poliacrilonitrilo y el conjunto de fibras de poliolefina-aramida fueron seleccionadas como las opciones más adecuadas para ser usadas como refuezo en mezclas PA. Su selección se basó en un análisis multi-criterio que combinó los métodos FAHP y WASPAS. La opinión de expertos, así como datos cuantitativos de la literatura científica sobre el rendimiento mecánico de las fibras en mezclas bituminosas sirvieron como referencias principales para ser empleadas en el análisis multi-criterio.

- *Análisis experimental de las mezclas PA reforzadas con fibras sintéticas*

- La incorporación de fibras POA y PAN de 4 mm de largo mejoró la resistencia a la pérdida de partículas en condiciones secas para ambos contenidos de filler. Con respecto a la pérdida de partículas en condiciones húmedas, no se observaron mejoras significativas para ningún tipo de fibra.
- La adición de fibras a la mezcla PA resultó en un aumento de la resistencia a la tracción indirecta (ITS) de las muestras acondicionadas en seco. Los mejores resultados se obtuvieron con fibras POA. Por otro lado, se encontraron resistencias similares o menores que la referencia cuando se analizaron muestras acondicionadas en húmedo de mezclas PA reforzadas con fibra.
- La adición de fibras de tipo PAN 4 - A y POA 19 - B a la mezcla de PA mostraron las mayores mejoras en términos de energía de fractura, energía post-fractura y tenacidad de las muestras acondicionadas en seco en comparación con las mezclas de referencia RA y RB, respectivamente. No se observaron mejoras con respecto a la tenacidad de las muestras reforzadas con fibra acondicionadas en húmedo.
- A 15°C y 0°C no se observaron efectos significativos en ninguno de los parámetros medidos para los morteros bituminosos reforzados con fibras.
- A -15 ° C, debido a cambios en el comportamiento del mortero, solo se pudieron medir las propiedades ITS y FE. Con respecto a ITS, se observaron diferencias estadísticas al agregar 0.3% de fibras POA y 0.3% de fibras PAN. Además, la adición de fibras contribuyó a aumentar la FE con una mayor influencia en el caso de las fibras POA.

- *Metodología integrada DOE-MCDM análisis considerando la influencia de varios factores de control*

- Con respecto a las propiedades de huecos de aire, el contenido de betún fue el factor de control más influyente, por encima del contenido de fibras que no tuvo un alto impacto en la funcionalidad de la mezcla.
- En cuanto a la resistencia a la abrasión de la mezcla, agregar 0.05% de fibras POA junto con 5.50% de betún PMB fueron las mejores soluciones paramétricas para las condiciones secas. Mientras tanto, para la pérdida de partículas en condiciones húmedas, se corroboró que la adición de fibras mostró la menor influencia.
- Las fibras de poliolefina-aramida mostraron una alta capacidad como agente estabilizador ya que permitieron retener el ligante asfáltico.
- Con respecto a la ponderación de criterios, se contempló el método de ponderación objetiva CRITIC. Los criterios de pérdida de partículas se asignaron con un peso de aproximadamente el 50%, mientras que a las propiedades de huecos de aire y escurrimiento de ligante se le asignaron el 50% restante.
- La mejor alternativa según el método CRITIC-TOPSIS correspondió al diseño 17. Este diseño corresponde al uso de un betún modificado con polímeros, un contenido de fibra de 0.15% y un contenido de betún de 5.0%. Aunque las primeras posiciones del orden de preferencia se refieren a experimentos con mezclas que usan ligante modificado con polímeros, también se pueden obtener buenos resultados usando un betún convencional siempre que se apliquen las proporciones adecuadas de fibras.
- La aplicación de distintas técnicas multi-criterio podría mostrar diferencias en la clasificación de preferencias debido al algoritmo y las funciones de utilidad empleadas. EDAS mostró resultados similares al método TOPSIS, mientras que algunas variaciones fueron encontradas en WASPAS en comparación con TOPSIS.

### *7.5.2 Conclusiones generales*

- Seleccionar una fibra adecuada basada en el rendimiento mecánico de las mezclas bituminosas reforzadas con fibra es una tarea crucial y compleja que requiere delimitar variables de decisión mediante un proceso integrado de toma de decisiones. Esta investigación demostró que el análisis de toma de decisiones con criterios múltiples se puede utilizar como una forma atractiva de hacer una preselección de las alternativas adecuadas para su uso en mezclas de asfalto.
- En relación a los resultados experimentales de las mezclas PA reforzados con fibras de POA y PAN, se evidenció que el mayor comportamiento mecánico de las mezclas se obtuvo mediante la adición de fibras POA. Las mejoras más claras se observaron en condiciones de pérdida de partículas, resistencia indirecta a la tracción y parámetros de fractura, todo en condiciones secas.
- Con respecto al trabajo experimental de los morteros bituminosos reforzados con fibras, se evidenció que las diferencias estadísticas se observaron solo a -15 °C. La adición de fibras

de POA y PAN aumentaron tanto el ITS como el FE. Sin embargo, se observó una mayor influencia en el caso de las fibras POA.

- Con respecto a la comparación de factores de control en la mezcla PA a través del análisis DOE-MCDM integrado, se podría preferir el uso de betún modificado con polímeros en comparación con las fibras en términos de huecos, desgaste y escurrimiento. Sin embargo, el uso de fibras con una cantidad adecuada de betún también puede ser una alternativa atractiva para implementarse como refuerzo en la mezcla de asfalto poroso para aumentar la durabilidad sin comprometer la funcionalidad y sin el riesgo de que escurra ligante.
- Este estudio presentó el novedoso análisis DOE-MCDM como una herramienta útil y eficiente para la evaluación experimental de mezclas PA reforzadas con fibras. Por un lado, la técnica DOE ayudó a tener en cuenta múltiples parámetros definidos en diferentes factores de control para ser analizados simultáneamente en varias respuestas individuales. Por otro lado, a medida que intervinieron múltiples respuestas, la integración de las técnicas multi-criterio permitió convertir el problema de optimización de respuesta múltiple en un problema de optimización de respuesta única. Para ser más precisos, CRITIC sirvió como herramienta automatizada de toma de decisiones para la ponderación de pesos, mientras que los valores de CCC del método TOPSIS fueron efectivos para establecer un índice unificado y realizar la clasificación de preferencias entre las alternativas.

### *7.5.3 Futuras líneas de investigación*

Con base en los resultados obtenidos de este estudio, y el análisis realizado durante el desarrollo del mismo, se proponen las siguientes líneas de investigación:

- Evaluar otro tipo de fibras en mezclas PA teniendo en cuenta otras propiedades como la longitud, el diámetro y la forma de la fibra (por ejemplo, monofilamento, grapa, retorcida, ondulada, granulada). Dado que estas propiedades pueden presentar influencia en el rendimiento general de las mezclas de PA.
- Evaluar el potencial de reciclaje de las mezclas PA reforzadas con fibra. En el futuro, se construirán carreteras con estos nuevos materiales y, por lo tanto, se dispondrá de mayores cantidades de pavimento residual. Con este estudio, se podría contribuir al desarrollo de estructuras de pavimento que generen menos impacto ambiental.
- Utilizar fibras residuales como alternativa de refuerzo en mezclas PA. Varias industrias durante su proceso de fabricación generan fibras de desecho que generalmente se arrojan a los vertederos. Sin embargo, estas fibras pueden usarse para el diseño de nuevas mezclas de PA reforzadas con fibra.
- Analizar la influencia de más de una fibra simultáneamente en la mezcla PA. Posiblemente, la incorporación de más de una fibra podría reforzar mejor la mezcla porosa. Para tal fin, es necesario adaptar el diseño para optimizar el comportamiento general del asfalto poroso.
- Evaluar otros factores de control a la escala del mortero asfáltico, como el contenido de ligante, el contenido de huecos de aire y/o variar la velocidad de carga monotónica.

Igualmente se podría considerar la aplicación de pruebas dinámicas como agrietamiento por fatiga.

- En el análisis de toma de decisiones de criterios múltiples, se sugiere tener en cuenta otros criterios, como el impacto económico y ambiental. Estos criterios adicionales también son convenientes para hacer un mejor análisis de toma de decisiones.
- Maximizar la funcionalidad de la mezcla PA con mayores capacidades de infiltración. Para dicho propósito, son necesarios cambios en la distribución del tamaño de partícula, y valorar el empleo de otros aditivos para aumentar el contenido de huecos de aire manteniendo siempre la misma durabilidad que las mezclas porosas convencionales.
- Estudiar las mezclas porosas reforzadas con fibra bajo otros métodos de prueba y acondicionamiento adicionales, tales como ciclos de hielo y deshielo, así como evaluar la durabilidad frente amenazas causadas por el ser humano (por ejemplo, derrames de combustible).
- Incluir otras herramientas multi-criterio para la ponderación de criterios (FAHP, BWM, ENTROPY) y para establecer un índice unificado que permita la clasificación de preferencias entre alternativas (por ejemplo, WASPAS, EDAS, VIKOR). La simulación estocástica de Montecarlo también se puede agregar para lidiar con la incertidumbre en el proceso de toma de decisiones.
- Aplicar el novedoso análisis integrado DOE-MCDM a otros casos de estudio. Las mezclas bituminosas, los suelos y el hormigón Portland son compuestos preparados con varios materiales y donde distintas respuestas son evaluadas. En este sentido, el análisis DoE-MCDM aparece como una herramienta muy útil para ser utilizada en la optimización de múltiples estudios experimentales.

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