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Multiple-response optimization of Open Graded Friction Course reinforced with fibers through CRITIC-WASPAS based on Taguchi methodology

Abstract

Multiple benefits in terms of safety, water quality runoff and noise mitigation have been reported from using Open graded Friction Courses (OGFCs) as wearing course. However, their use is quite limited due to raveling phenomenon. The main objective of this study is to evaluate the functional and mechanical performance of OGFCs reinforced with nylon and polypropylene fibers. To this purpose, a Design of Experiments (DOE) was conducted considering three control factors named as fiber type, binder content and fiber content. Different responses such as total air voids, interconnected air voids, particle loss in dry conditions and particle loss in wet conditions were recorded. In addition, a multi-objective optimization was carried out through the CRITIC-WASPAS methodology. The results showed the effect of adding nylon fibers on the increase of the abrasion resistance in dry and wet conditions. According to the multi-criteria decision-making analysis, the design involving nylon fibers, 4.80% binder content and 0.06% fiber content turned out to be the experimental design better ranked.

Keywords: OGFC, durability, CRITIC, WASPAS, Taguchi.

Highlights

- Experimental lab tests were performed to evaluate the functionality and durability of OGFCs.
- The design of experiments were conducted based on Taguchi L18 orthogonal array.
- The most influential factor on air voids response was the binder content.
- Better durability results were obtained when adding nylon fibers instead of polypropylene fibers.
- Multi objective optimization problem was carried out through the CRITIC-WASPAS method.

1. Introduction

The majority of countries employ dense-graded hot mix asphalt as wearing course in the construction of their road infrastructures. However, other types of mixtures such as the open-graded asphalt mixtures have become an attractive alternative for the development of new pavement structures. This mixture, commonly known as Open Graded Friction Course (OGFC) or Porous Friction Course (PFC) in the United States [1,2], Porous Asphalt (PA) mixture in some regions of Europe [3,4] and Permeable Asphalt Concrete (PAC) in China [5], is considered an innovative eco-friendly solution due to the many benefits that this type of mixture offers [1]. Among its advantages, the better water runoff quality due to the high content of voids (i.e. usually in the range between 18-22%) highlights [6,7]. Similarly, Open graded Friction Courses (OGFCs) help to mitigate the noise generated by the path of the vehicles and to decrease the risk of hydroplaning and wet skidding [1]. Other advantages include the reduction of the urban heat island effect [8] and the decrease of the accident rate due to the improved visibility, especially in wet weather conditions [9].

Despite the multiple environmental benefits that the OGFCs offer, some drawbacks regarding the durability have been evidenced [10]. Raveling phenomenon that can be defined as the loss of bonding between the stone particles and bitumen due to the abrasion caused by the traffic [11] is considered the principal distress reported as the cause of failure in OGFCs [12]. In fact, when raveling appears the destruction rate increases and as a result raveling is gradually accelerated [13]. In addition, due to the high content of voids in the mix, the bitumen is prone to suffer an oxidation process for the exposition to the air and water [14]. Therefore, the adhesive layer between mortar and coarse aggregates or the cohesive forces generated in the mortar bridges are susceptible to aging and debonding [15]. In order to improve the resistance and increase the service life of porous asphalt mixtures, the use of modified binders with polymers has extended all over the world. However, the cost of OGFC containing polymer modified binders can exceed the cost of a dense graded hot mix asphalt with unmodified binder in more than 50%, both having similar life expectancies [6,16]. Even so, the use of a high viscosity asphalt modifier like TAFPACK – SUPER (TPS) for developing modified binders in China has been well-recognized and widely used for its good performance [5,17]. In this regards, it has been found that the production of rubber elastomers contained in TPS generates a tremendous amount of waste gas emissions. Likewise, the plasticizer, which is another component of the TPS, generates pollutants such as lipid solid reactants and alcohol wastes [5,18].

On the other hand, different type of fibers have been widely used as additives in conventional mixtures and results have been quite promising from a mechanical point of view. In fact, properties such as rutting, fatigue and fracture energy have improved [19–21]. The high tensile strength of fibers relative to hot mix asphalt brings the potential to increase the cohesive forces in the mix [19]. In addition, the interconnection existing between fibers and aggregates helps the mixture to withstand additional strain energy and hence, brings ductility to the system [20]. Similarly, some researchers suggest that fibers can act as a barrier for preventing the formation and propagation of cracks [19]. Kim et al. [22] evaluated the mechanical performance of different types of synthetic fibers such as nylon, polypropylene, polyester and carbon in an asphalt concrete (AC) mixture. Distinct tests such as Marshall Stability test, indirect tensile strength (ITS) test, dynamic stability test and flexural test were performed. Results indicated that fiber reinforced asphalt concrete (FRAC) mixtures improved significantly the mechanical properties as compared to reference asphalt concrete without fibers. Based on these results, the authors reported that Nylon was the optimal fiber type for every test parameter. Similarly, the authors suggested that the optimum volume content of nylon fiber in the mix was 1.0%. In a different study, Yin and Wu [23] studied the behavior of waste nylon fibers on Stone Matrix Asphalt (SMA) mixtures. The experimental set-up included: Marshall Stability tests, wheel tracking test, three-point flexural test and moisture susceptibility test. Based on the results, the authors reported that waste nylon fibers improved the high temperature stability and the low temperature crack resistance. Accordingly, the authors suggested that nylon fibers generated a bridging effect that prevented the propagation of cracks [23]. In AC mixtures, fatigue energy properties were also studied in mixes containing nylon fibers. Rust et al. [24] concluded that adding 1.0% of nylon fibers by volume increased the fracture energy in more than 85% as compared to the control mixture without fibers. As for the polypropylene, Kockal and Kofteci [25] studied the effect of polypropyelene (PP) fibers as a reinforcement of hot mix asphalts. PP fibers were added in different quantities by weight of asphalt binder. Results showed that the Marshall Stability of the mixture increased when adding 7.5% PP fibers. Similar results were found by Tapkin [26], who concluded that PP fiber-reinforced specimens increased Marshall Stability values and decreased flow values.

Despite the multiple benefits that fibers provide to dense-graded hot mix asphalt, scarce scientific literature has been found on the use of fibers in OGFCs. In this type of mixtures, fibers are mainly used as stabilizer agents to prevent the drainage of the binder [19], being the cellulose fibers one of the most common additives in this respect due to their low cost, availability, and high absorption rate [27,28]. Regarding fiber as a reinforcing element, Tanzadeh and Shahrezagamasaei [29] recently evaluated the use of PP and glass fibers in porous friction course (PFC) mixtures. Based on the results, the authors concluded that fibers prevent the mixtures from binder drain down as well as increase their indirect tensile strength. Likewise, Zhang et al. [30] investigated the effect of adding carbon fiber composite materials in porous mixtures. According to the authors, these fibers improve the binder drainage as well as the rutting resistance.

As said before, raveling is the most common damage observed in OGFCs and few research efforts have focused on the study of the particle loss resistance of open-graded asphalt mixtures reinforced with PP fibers. On the other hand, despite of the potential of nylon fibers to enhance the mechanical properties of dense-graded mixtures, no investigations have been reported about OGFCs reinforced with these fibers. For this reason, and due to the low service life expectancy and low durability of the open-graded asphalt mixtures, this research is focused on evaluating their functionality and durability when they are reinforced with nylon and polypropylene fibers. As there might be an interaction effect between fiber content and binder content, a design of experiments based on Taguchi orthogonal array has been applied. Similarly, as multiple responses were obtained from a mechanical and functional point of view, a CRITIC-WASPAS approach was applied for transforming the multiple response into a single response and determining the optimum combination of the design factors. In this way, we can be sure that the resulting OGFC is the most effective and reaches the highest performance.

The paper is organized in sections. Section 2 describes the integrated CRITIC-WASPAS based on Taguchi methodology used for the development of the present research. Section 3 describes materials, sample preparation and experimental set-up. Section 4 presents the discussion and results. Signal to noise ratio values were used to identify the optimum levels of different factors and multiple regression models were developed for different responses. In addition, the CRITIC-WASPAS approach for the optimized selection is performed. Finally, section 5 includes the main conclusions of the research. The structured framework of the present research is shown in **Figure 1.**

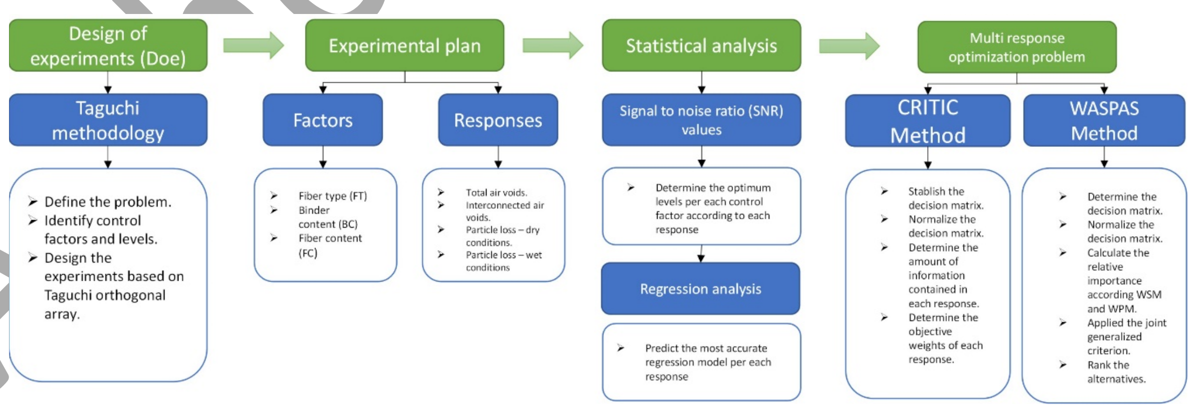

Figure 1. The structured framework of the present research.

2. Design of experiments

Due to the interdependence existing in the OFGCs between fiber content and binder content depending on the type of fiber, statistical methods such as the design of experiments (DOE) [31] can be applied to determine the main components of the mixture and their optimum proportions. A proper design of experiments helps to provide a mathematical regression model for the response to be expressed as a function of the different factors involved. Besides, the linearity, non-linearity and interaction effects of the input parameters, a.k.a. independent variables, can be observed in the response or dependent variable. In several fields, DOEs have been extensively applied [31–34]. For example, Varanda et al. [31] adopted a constrained mixture design to optimize a bitumen formulation. The response variables selected to optimize the mix were penetration value and softening point. In another research, Omranian et al. [32] employed a Central Composite Design (CCD) to determine the optimal design of an asphalt mixture from the short term aging standpoint, based on the fracture properties of the mixture. The input parameters considered were aging temperature, aging duration and duration in humidity and ultraviolet chamber. The output parameters were obtained using the Semi Circular Bending (SCB) test. Haghshenas et al. [35] applied a Response Surface Methodology (RSM) to optimize the binder, gradation, and lime powder content in the stripping process of the hot mix asphalt. Finally, other studies have applied the Taguchi orthogonal array method in order to characterize and optimize the complex behavior of different materials. Teimortashlu et al. [33] used it for the optimization of the compressive strength of tertiary blended self-compacting mortar. In this study, the Portland cement was partially replaced with other admixtures such as fly ash, slag and nano-silica. Sevinc et al. [36] tested different mineral additives for improving the durability of concrete and the Taguchi approach was used for reducing the number of experiments and to identify the optimum working conditions. Likewise, Joshaghani et al. [37] and Mehta et al. [38] made use of the Taguchi method for the optimization of the design of Pervious Pavements and to study the effect of different factors on the compressive strength and water absorption properties of fly ash based geopolymers, respectively. The successful application of this method suggests that it is suitable for its use in the characterization of an OGFC.

2.1 Taguchi Methodology

The Taguchi methodology was adopted to conduct the design of experiments. This approach enables the use of orthogonal arrays for different parameters, thus reducing the number of experiments [39]. Besides, this technique employs the concept of Signal to Noise Ratios (SNR) to indicate the optimum parameters from the response values [40,41]. The optimum design of an open-graded asphalt mixture involves good functionality while maintaining a suitable durability. For this, the maximization of the functional performance is necessary, what in this study was measured in terms of the total and interconnected air voids as well as the raveling resistance obtained from the Cantabro test in dry and wet conditions. As the main objective is to analyze the effects of Nylon and polypropylene (PP) fibers in the mix, control factors affecting the overall performance of the mix were assigned. Control factors are the input parameters that affect the different responses. Therefore, three control factors were selected: Type of fiber (FT), binder content (BC) and fiber content (FC). Different levels per each control factor were chosen to perform the experimental tests. An L_{18} $(2^1\ X\ 3^1)$ orthogonal array was chosen to optimize the design of the OGFC. **Table 1** shows the control factors considered with their respective levels.

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Table 1. Input Factors and their corresponding levels.

Factors	Notation	Level 1	Level 2	Level 3
Fiber Type	FT	Nylon	PP	-
Binder content (%)	BC	4.4	4.8	5.2
Fiber content (%)	FC	0	0.03	0.06

In Taguchi technique, SNR values can be obtained per each response value. Accordingly, SNR values measure the variation of the response under different noise conditions. SNR values can be divided in three categories commonly known as "the larger-the-better"," the smaller-the-better" and "the nominal-the-better". As the aim of this research is to maximize the voids in the mix and minimize the loss of particles, the first two categories were selected. Eqs (1) – (2) were used to calculate the corresponding SNR values:

$$SNR = -10\log\frac{1}{n}\left(\sum\frac{1}{y^2}\right) \quad \textbf{(1)}$$

$$SNR = -10\log\frac{1}{n}\left(\sum y^2\right) \quad \textbf{(2)}$$

Where *SNR* stands for the Signal to Noise Ratio, which depends on the response objective (i.e. maximize or minimize); *n* represents the number of observations; and *y* is the experimental value. **Table 2** shows the L_{18} orthogonal array for conducting the design of experiments. Three replicates per each mixture design and for each test were considered.

Table 2. Taguchi L18 Orthogonal array for conducting the design of experiments.

Design	Fiber type, FT	Binder content, BC (%)	Fiber content, FC (%)
1	Nylon	4.40	0.00
2	Nylon	4.40	0.03
3	Nylon	4.40	0.06
4	Nylon	4.80	0.00
5	Nylon	4.80	0.03
6	Nylon	4.80	0.06
7	Nylon	5.20	0.00
8	Nylon	5.20	0.03
9	Nylon	5.20	0.06
10	PP	4.40	0.00
11	PP	4.40	0.03
12	PP	4.40	0.06
13	PP	4.80	0.00
14	PP	4.80	0.03
15	PP	4.80	0.06
16	PP	5.20	0.00
17	PP	5.20	0.03
18	PP	5.20	0.06

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2.2 WASPAS Methodology

Multi-criteria decision making (MCDM) methods have served to handle with decision-making problems when multiple criteria are involved. In construction, a variety of methods have been suggested to deal with decision making problems such as Grey Relational Analysis (GRA), Techniques for Order Preferences by Similarity to Ideal Solution (TOPSIS), Analytic Hierarchy Process (AHP) or Evaluation based on Distance from Average Solution (EDAS), among others [42–45]. As more than one response is obtained, it is necessary to turn the multiple response into a single response optimization problem. In previous research works, MCDM methods have proved to be an easy and efficient tool to be integrated with the Taguchi method [34,44], being GRA and TOPSIS the most common methodologies for that purpose [46–49]. This article applies the Weighted Aggregated Sum Product Assessment (WASPAS) methodology to combine all the multi response values of the system into a single response value, thus obtaining the optimum parameter based on the Joint Performance Score (JPS). This technique, suggested initially in 2012 by Zavadskas et al. [50], is considered a new robust approach as being an integration of the Weighted Product Model (WPM) and the Weighted Sum Model (WSM) methodologies [51]. Following, the steps to employ the WASPAS technique are presented:

- Step 1. Arrange all the response variables in the form $X = [x_{ij}]\ m\ x\ n$, where x_{ij} corresponds to the performance of the i^{th} design with respect to the j^{th} response variable. Accordingly, *m* is the number of designs and *n* the number of responses.
- Step 2. Identify beneficial and non-beneficial criteria and normalize the decision matrix as follows.

$$\bar{x}_{ij} = \frac{x_{ij}}{\max_i x_{ij}} \ for\ beneficial\ criteria. \tag{3}$$

$$\bar{x}_{ij} = \frac{\min_i x_{ij}}{x_{ij}} \ for\ non\ beneficial\ criteria. \tag{4}$$

- Step 3. Determine the total relative importance of the i^{th} design according to WSM as follows.

$$WSM = Q_i^1 = \sum_{j=1}^{n} \bar{x}_{ij} * w_j \tag{5}$$

Where w_j is the weight of the j^{th} response variable.

- Step 4. Determine the total relative importance of i^{th} design according to WPM as follows.

$$WPM = Q_i^2 = \prod_{j=1}^{n} \bar{x}_{ij}^{w_j} \tag{6}$$

- Step 5. Apply a joint generalized criterion (λ) of weighted aggregation of the additive and multiplicative techniques as follows.

$$Q_i = \lambda Q_i^1 + (1-\lambda) Q_i^2 \tag{7}$$

2.3 CRITIC Methodology

Overall, the multiple responses assessed by the experiments must be quantifiable and the corresponding weights must be also assigned [43]. Normally, criteria weightage are assigned with equal value for each one of the responses considered. However, in this study the Criteria Importance Through Intercriteria Correlation (CRITIC) methodology was applied in order to carry out an objective determination of the weights of the response variables. According to this approach, the weights are assigned based on the contrast intensity and conflict assessment of the decision problem [52,53]. Furthermore, in this method the human intervention is not required for the assessment process, which contributes to automatize decision making processes [52,54]. A brief summary of the method is described below (details can be seen in [52,53]).

- Step 1. Establish the decision matrix that must contain the response values of the different designs with respect to the different criteria previously selected

$$A = [a_{ij}]_{m*n} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \quad \textbf{(8)}$$

Where a_{ij} corresponds to the performance value of the i^{th}design on the j^{th}response.

- Step 2. Normalize the decision matrix as follows.

$$a_{ij}^{+} = \frac{a_{ij} - \min(a_{ij})}{\max(x_{ij}) - \min(a_{ij})} \quad \textbf{(9)}$$

Where a_{ij}^{+} is the normalized performance value of the i^{th}design on the j^{th}response.

- Step 3. Determine the amount of information contained in the j^{th} response through the following multiplicative formula.

$$C_j = \sigma_j * \sum_{j^*=1}^{n} (1 - r_{jj^*}) \quad \textbf{(10)}$$

Where σ_j corresponds to the standard deviation of the j^{th}response, and r_{jj^*} is the correlation coefficient between two different responses.

- Step 4. Determine the objective weights of each response by normalizing C_j with the following formula.

$$W_j = \frac{C_j}{\sum_{j=1}^{n} C_j} \quad \textbf{(11)}$$

Where W_j is the objective weight of the j^{th}response. It is worth mentioning that this method gives high weights to those responses with high standard deviation and low correlation with other responses [53]. Similarly, higher values of C_j suggest a greater amount of information transmitted by the corresponding response and a higher relative significance of the response in the decision making problem.

3. Materials and methods

3.1 Materials

In the present research, a 60/70 penetration grade binder provided by Ecopetrol Company, the most important refinery in Colombia, was used. The main physical properties of the binder can be observed in **Table 3.** River stone materials extracted from the Coello river in Colombia were used as coarse aggregates (19 mm nominal size) and fines. The stones were milled and characterized according to Colombian standards. Different characterization tests adopted by the National Roads Institute (INVIAS by its acronym in Spanish) [55] were performed and resulting values are presented in **Table 4**. The open-graded gradation curve presented in **Figure 2** was used for the manufacturing of the open-graded asphalt mixtures.

Nylon and polypropylene synthetic fibers were used separately and served as the main additive for the improvement of the mechanical properties of the mixture. Although the use of polymer modified binders in OGFCs is a common practice to increase the durability of mixtures by providing stiffness and ductility [56], in this study the inclusion of fibers seeks to form a three dimensional net able to reinforce the OGFC and also to prevent the binder drainage. The illustration of the fibers and their main properties are shown in **Figure 3** and **Table 5,** respectively.

Table 3. Characteristics of 60/70 penetration grade binder according to Colombia and USA standards.

Characteristic	Colombia Standard	USA Standard	Value
Specific weight (g/cm^3)	-	-	1.03
Penetration at 25 °C	INV. E - 706	ASTM D - 5	61
Softening point (°C)	INV. E - 712	ASTM D - 36	47
Flash point (°C)	INV. E - 709	ASTM D - 92	240
Ductility @25°C (cm)	INV. E - 702	ASTM D - 113	> 100
Solubility of asphalt materials in trichloroethylene	INV. E - 713	ASTM D - 2042	>99

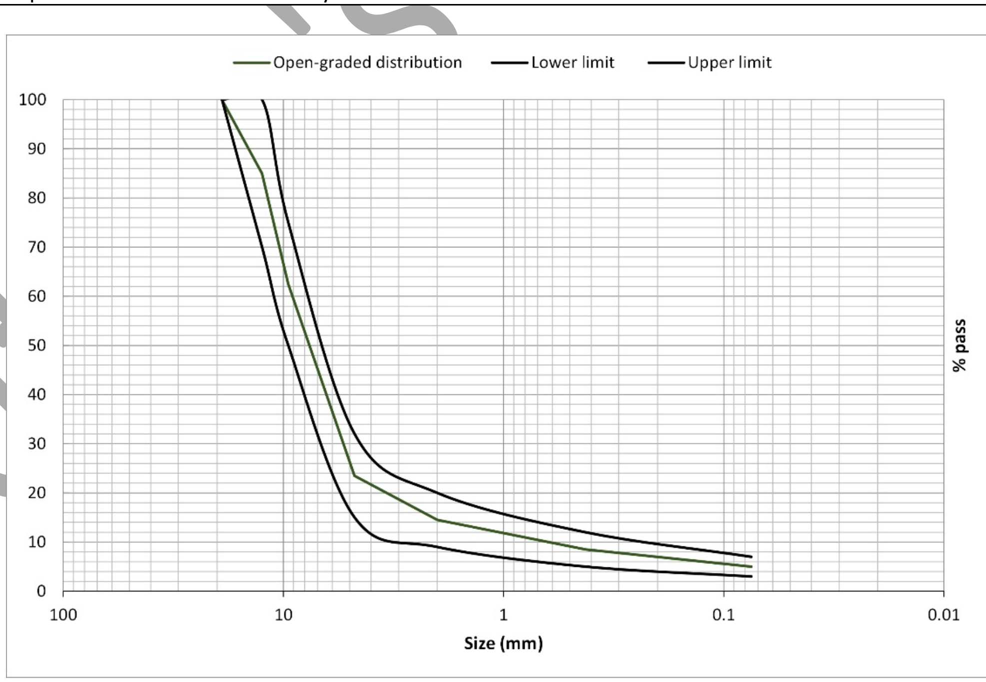

Figure 2. Open – aggregate gradations used in the present study.

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Table 4. Basic physical properties of aggregates used in the present study.

Characteristic	Colombia - Standard	USA - Standard	Value
Coarse Aggregate			
Percentage of fractured particles (%)	INV. E - 227	ASTM D5821	84
Apparent specific gravity	INV. E - 223	AASHTO T 85	2.73
Absorption (% abs)	INV. E - 223	AASHTO T 85	1
L.A abrasion (%)	INV. E 218, 219	AASHTO T 96	23
Fine Aggregate			
Sand Equivalent (%)	INV. E - 133	-	87
Methylene blue	INV. E 235	AASHTO TP 57	3.6
Apparent specific gravity	INV. E 224	AASHTO T 86	2.72
Absorption (% abs)	INV. E 225	AASHTO T 87	2.04

Table 5. Basic physical properties of Nylon (Ny) and Polypropylene (PP) fibers.

Fiber	Nylon Micro-fiber	Polypropylene Micro-fiber
Type of fiber	Monofilament	Monofilament
Specific gravity	1.16	0.91
Melting point (°C)	260	160
Length (mm)	19	19
Water absorption	No	No
Tensile Strength (MPa)	800	500
Elastic modulus (MPa)	5000	3500

Figure 3. Fibers used in the study: Nylon (left) and PP (right).

Regarding the specimens preparation, cylindrical Marshall Samples, 101.6 mm diameter and 63.5 mm height, were prepared in the laboratory following the Colombian standard methods specified in the INV E 760 – 13 Normative [55]. To prepare the samples, fibers were added into the mix by dry method. In other words, aggregates were initially mixed with fibers in order to achieve a proper dispersion and to prevent the formation of clusters in the mix. Afterwards, asphalt binder was added at 150°C and continuously

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blended to obtain a proper coating by the asphalt binder of the fiber-aggregate combination. Finally, the specimens were compacted with the Marshall Hammer by applying 50 blows per side.

3.2 Experimental set-up

The experimental testing plan aimed to evaluate the functional and mechanical performance of an OGFC. Initially, volumetric properties were tested in order to measure the total air voids (T_{AV}) of the mixture. As suggested by other researchers, the functionality of an open-graded asphalt mixture is highly influenced by its T_{AV} [57]. Although the total air voids in the mixture is considered one of the most important parameters in the design of porous asphalt mixtures as according to the different governmental agencies around the world [1,6,12], the interconnected air voids (I_{AV}) could be considered another reasonable indicator of the functional performance [58]. The difference between both parameters is that I_{AV} corresponds to the water accessible air voids in the mixture while the T_{AV} takes into account all the voids within the mix. T_{AV} was measured in agreement with the INV E 736 – 13 Colombian standard method (i.e. AASHTO T 269 according to USA methods) whereas the interconnected air voids were calculated based on the procedure proposed by Alvarez et al. [59]. According to the volumetric characteristics of the specimens, T_{AV} and I_{AV} were calculated by using equations (**12**) and (**13**):

$$T_{AV} = \left(1 - \frac{m}{V * G_{mm}}\right) * 100\% \quad \textbf{(12)}$$

$$I_{AV} = \frac{V - \frac{m - m_{sat}}{\rho_w}}{V} * 100\% \quad \textbf{(13)}$$

Where m corresponds to the mass of the sample in the air; *V* is the volume of the geometrically measured sample; G_{mm} is the maximum theoretical specific gravity of the mix; and m_{sat} is the saturated sample mass measured in submerged conditions.

In addition, as OGFC are prone to present binder drainage problems mainly during production and transportation, the mixture stability was measured through the Schellenberg beaker method (EN 12697 – 18). The concept of the test lies in the determination of the amount of binder drained from a bituminous mixture after being subjected to a higher temperature than the mixing temperature. Based on literature data found, the binder drainage expressed in percentage does not exceed the limit of 0.3% [9]. According to the test [60], a non-compacted OGFC sample was prepared and placed in a beaker that was weighted. Then, beaker and sample set was disposed in an oven for one hour at a prescribed temperature of 175°C, which corresponds to the mixing temperature (i.e. 150°C) plus 25°C. At the end of that hour, beaker and sample set are removed from the oven, right after which the beaker is emptied without any shaking or vibration. Finally, the beaker is re-weighted and the binder drainage is calculated (in percentage) as follows:

$$BD\ (\%) = \frac{w_3 - w_1}{w_2 - w_1} * 100 \quad \textbf{(14)}$$

Where w_1 is the weight of the empty beaker; w_2 is the weight of beaker and sample set; and w_3 corresponds to the weight of the beaker after emptied.

Additionally, the mechanical performance of the mix was assessed with the Cantabro Test, for it is considered the most common test to evaluate the particle loss resistance of the mix [1,61–64]. Similarly, other authors considered that this test was appropriate to measure the disintegration resistance of the mixture [62]. In this test, carried out according to the INV E 760 – 13 (i.e. EN 12697 – 17) standard method, a compacted Marshall Specimen is placed in the Los Angeles Abrasion Machine without abrasion load and subjected to the rotating drum during 10 minutes at 30 rpm. Then the raveling resistance, measured in terms of a percentage of particle loss (PL), is evaluated by using Eq. **13**.

$$PL\ (\%) = \frac{w'_1 - w'_2}{w'_1} * 100 \quad \textbf{(15)}$$

Where w'_1 and w'_2 correspond to the initial and final weight of the specimens, respectively. Similarly, in order to evaluate the impact of the water on the particle loss resistance, the Cantabro test was conducted in wet conditions following the Spanish standard method NLT 362/92. In this case, the samples were conditioned by totally immersing them in a bath of water at 60°C during 24 h and then exposed them to dry conditions at 25°C during another 24 h.

4. Results and discussion

4.1 Binder drainage

In order to verify if the mixture designs present drain down problems, the binder drainage test was initially performed on the mixture without fibers and with the greatest amount of bitumen. Following, the binder drainage test was conducted on the designs with the greatest amount of bitumen and less quantity of fibers, as these mixtures are more susceptible to present binder drainage. Based on the results, no binder drainage problems were registered in the mixtures, as the designs did not exceed the limit of 0.3% (see **Table 6**). The filler content of the mixture might have affected positively in this regard. High values of filler increase the viscosity of the bitumen, thus reducing the adhesive contact with the beaker. In addition, the smaller the amount of bitumen, the lower the BD (%) as less quantity of asphalt binder can stick to the beaker. Although the mixtures design did not register binder drain down problems, fibers slightly contributed to minimize the drainage of the binder. As suggested by other researchers [27], this could be due to the surface area of the fibers, which could retain more bitumen at high temperatures. Likewise, fibers help to increase the thick coating of the mortar matrix, favoring the mitigation of the binder leakage. In this study, binder drainage was not considered a risk and hence, it was not taken into account as a response variable.

Table 6. Verification of binder drainage according to the Schellenberg beaker method.

Design	W_1	W_2	W_3	BD (%)
No fibers. Binder content 5.20%				0.08%

Ny fibers. Binder content 5.20% Fiber content 0.03%				0.03%
PP fibers. Binder content 5.20% Fiber content 0.03%				0.03%

4.2 Functional performance

In order to measure the functionality of the OGFCs, T_{AV} and I_{AV} were considered the response variables. Three replicates per each mixture design were recorded and the mean values of T_{AV} and I_{AV} per each mixture design are showed in **Table 7** along with their corresponding standard deviations (SD). Mean values of T_{AV} and I_{AV} were in the range of 16.08 – 20.51% and 9.56 – 12.57%, respectively. Likewise, mean values for total and interconnected air voids were 18.19% and 11.26%, respectively. Overall, in order to guarantee a proper functionality, OGFCs s with T_{AV} greater than 18.0% are considered acceptable [61]. However, higher air voids values are desirable in order to do the mixture more permeable. As previously said, the highest values of T_{AV} and I_{AV} are quite relevant for the functional performance of the OGFC. Therefore, the "Larger-the-better" equation was applied for calculating SNR values. Analysis of the effect of the different factors (FT,BC,FC) on total and interconnected air voids was performed based on the SNR values, as it can be observed in **Figure 4** and **5,** respectively. Highest SNR values in each factor determine the optimum levels of these control factors. As an example, the optimum levels based on SNR values for the control factors giving the best T_{AV} were identified as fiber type (FT) factor (level 2, SNR = 25.23), binder content (BC) factor (level 1, SNR = 25.46) and fiber content (FC) factor (level 3, SNR = 25.38). It means that the optimum T_{AV} response can be obtained with polypropylene fibers, with the lowest binder content and highest fiber content. The trend indicates that increasing the binder content affects the functionality as it reduces the voids in the mixture. On the other hand, fibers inside the mix contribute to increase the voids content, probably due to the bitumen-absorbing characteristics of the fibers' surface area. As suggested by Chen and Xu [65], fibers play a key role in the absorption of asphalt. Although synthetic fibers have smaller specific surface areas when compared to organic fibers (e.g. lignin), they still can absorb some amount of bitumen. Despite the slightly more negative effect of the nylon fibers in the air total voids response as compared to the PP fibers, the type of fiber is not as relevant as the binder content or the fiber content, as shown in **Figure 4**. Regarding the interconnected air voids response (see **Figure 5**), there is a direct positive correlation with the T_{AV} response, being the value of Pearson correlation coefficient equal to 85.72%. It means that increasing the total air content results in an increase of the interconnected voids. Comparing the results with those reported by Valeri et al. [3], open-graded mixtures with high total air voids content suppose an increase in the interconnected air voids. According to **Figure 5,** the optimum

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levels per each control factor in order to achieve the best I_{AV} were identified as factor FT, (level 1, SNR = 21.03), BC factor (level 1, SNR = 21.19) and FC factor (level 3, SNR = 21.41). In other words, optimum I_{AV} response was obtained with Nylon fibers, binder content of 4.40% and fiber content of 0.06%. Unlike for T_{AV} response, in I_{AV} the use of nylon fibers slightly contribute in a positive way to increase the voids. Although other researchers argue that fibers could decrease the porosity of the mixture, in this research this phenomenon was not observed. This is probably due to the lower fiber content employed, which made the interconnected air voids not to be affected [30].

Table 7. Response variables for total and interconnected air voids.

				Total air voids (%)		Interconnected air voids (%)	
Design	Fiber type	Binder content (%)	Fiber content (%)	Mean	SD	Mean	SD
1	Nylon	4.40	0.00	18.04	0.73	10.91	1.39
2	Nylon	4.40	0.03	18.09	1.06	11.13	2.11
3	Nylon	4.40	0.06	18.83	1.19	12.26	1.10
4	Nylon	4.80	0.00	17.97	1.37	10.80	0.86
5	Nylon	4.80	0.03	18.21	0.72	11.80	1.70
6	Nylon	4.80	0.06	18.09	0.17	11.06	0.70
7	Nylon	5.20	0.00	17.67	0.16	10.86	0.74
8	Nylon	5.20	0.03	17.99	0.36	11.45	0.68
9	Nylon	5.20	0.06	17.72	0.62	11.19	0.75
10	PP	4.40	0.00	18.04	0.73	10.91	1.39
11	PP	4.40	0.03	19.05	1.37	11.17	1.94
12	PP	4.40	0.06	20.51	0.15	12.50	0.28
13	PP	4.80	0.00	17.97	1.37	10.80	0.86
14	PP	4.80	0.03	18.85	1.75	11.63	1.62
15	PP	4.80	0.06	19.30	1.26	12.57	1.93
16	PP	5.20	0.00	17.67	0.16	10.86	0.74
17	PP	5.20	0.03	16.08	1.86	9.56	1.50
18	PP	5.20	0.06	17.26	1.19	11.14	1.81

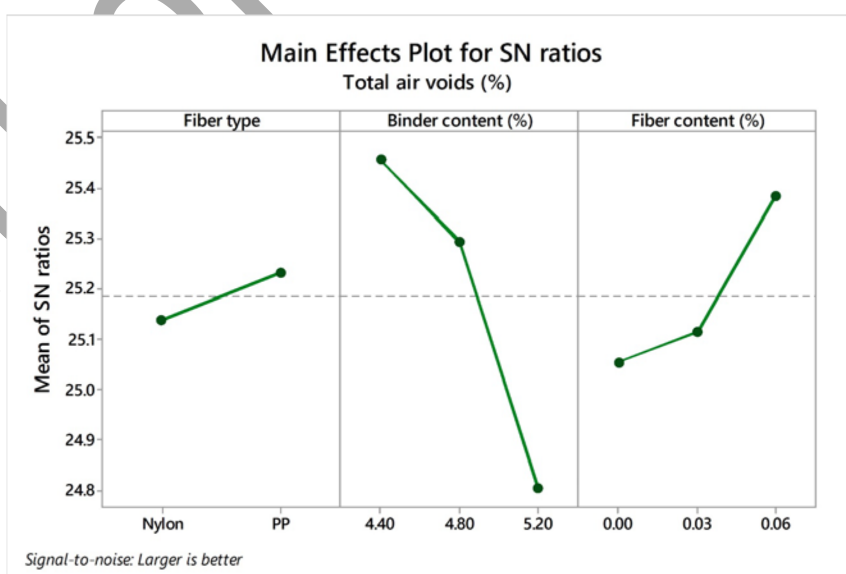

Figure 4. Effects of control factors on T_{AV} according to SNR values.

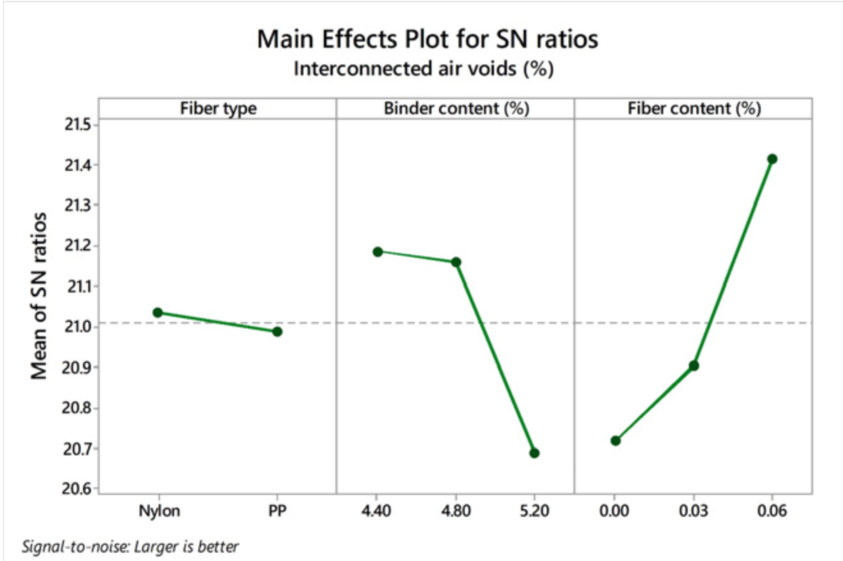

Figure 5. Effects of control factors on I_{AV} according to SNR values.

The variation of total and interconnected air voids for the two types of fibers in terms of fiber content and binder content were plotted (**Figure 6**). Different regression analysis including linear, linear plus squares, linear plus interaction and full quadratic were used for the modelling of the dependent variables. Based on the R^2 values, the proper regression analysis was finally identified in order to obtain the best predictive equations for T_{AV} and I_{AV} response as given below. **Table 8** shows the type of regression model adopted and the corresponding R^2 value for each of the responses. Overall, all the regression models seem to fit well as their R^2 values are greater than 75% except for the I_{AV} response for nylon fiber, which reached a slightly lower value of 61.95%.

Table 8. Regression models adopted and R^2 value obtained for T_{AV} and I_{AV} responses.

Type of fiber	Response	Regression model	R^2
Nylon	T_{AV}	Linear + Interaction	78.37%
	I_{AV}	Full quadratic	61.95%
PP	T_{AV}	Full quadratic	92.95%
	I_{AV}	Full quadratic	86.79%

For Nylon fibers.

$$T_{AV}\,(\%) = 18.86 - 0.199 * BC\,(\%) + 78.8 * FC\,(\%) - 15.30 * BC(\%) * FC\,(\%) \quad \textbf{(16)}$$

$$I_{AV} = 21.3 - 4.7 * BC\,(\%) + 131 * FC(\%) + 0.52 * BC^2 - 307 * FC^2 - 21.2 * BC(\%) * FC(\%) \quad \textbf{(17)}$$

For PP fibers.

$$T_{AV}(\%) = -64.3 + 35.4 * BC\,(\%) + 276 * FC(\%) - 3.78 * BC^2(\%) + 516 * FC^2(\%) - 60 * BC(\%) * FC(\%) \quad \textbf{(18)}$$

$$I_{AV} = -79.2 + 38.1 * BC\,(\%) + 107 * FC\,(\%) - 4.02 * BC^2(\%) + 751 * FC^2(\%) - 27.6 * BC(\%) * FC(\%) \quad \textbf{(19)}$$

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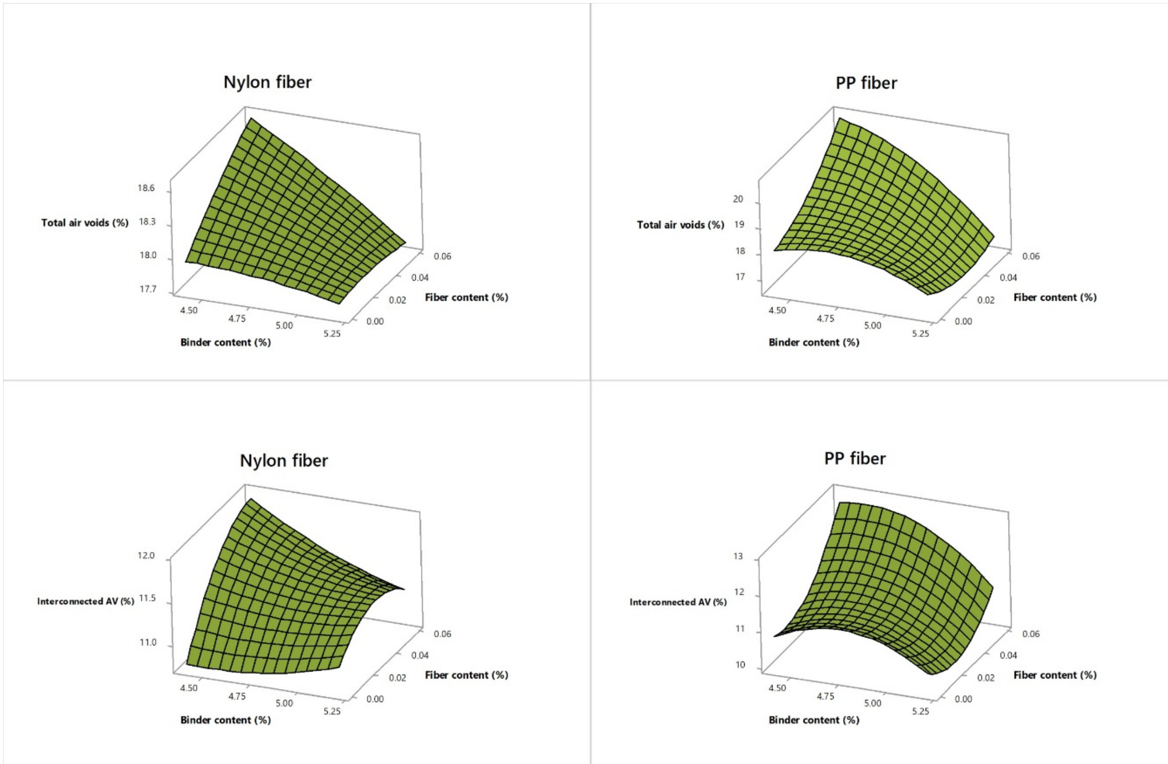

Figure 6. Variations on total and interconnected air voids response in terms of BC (%) and FC (%).

4.3 Mechanical performance

As said before, the mechanical performance of the OGFCs was here analysed through the Cantabro test. This test is one of the most employed to measure raveling, which is the distress most commonly reported as the main cause of failure in OGFC mixtures [6]. An illustration of the specimens after being subjected to this test can be observed in **Figure 7.** The particles loss results obtained from the Cantabro test in dry and wet conditions are displayed in **Table 9.** As with the air voids response, SNR values were calculated in order to optimize the measured control factors regarding durability. The lowest values of particles loss in dry conditions (PL_{DRY}) and particles loss in wet conditions (PL_{WET}) are considered desirable for obtaining an optimal OGFC. Therefore, the "smaller-the-better" formula was applied for calculating SNR values. **Figures 8** and **9** show the graphs corresponding to SNR values for the different levels of the control factors. Optimal design input parameters of the control factors for minimizing the particle loss in dry and wet conditions can be identified through these graphs. For PL_{DRY} response, the optimal levels of each control factor according SNR values were recognized as FT factor (level 1, SNR = -25.67), BC factor (level 3, SNR = -24.72) and FC factor (level 2, SNR = -25.23). It means that optimum values to PL_{DRY} value were obtained with nylon fibers, binder content of 5.20% and fiber content of 0.03%. Previous investigations of fiber reinforced asphalt concrete suggest that fibers can form a three-dimensional network in the asphalt matrix [66] that helps to reinforce the skeleton structure of the mixture. The same phenomenon may have occurred in the OGFC here analyzed. In addition, the PP fiber has a melting point of 160°C, very close to the production temperature of the OGFC, as mentioned in **section 3.1.** This means that some of the PP fibers are probably dissolved during the production process and so they do not reinforce properly the mix. Some authors argued that PP fibers degraded the mechanical properties of the mix [67] while others suggest that PP fibers act as a secondary reinforcement, thus providing better bond strength [68]. In this study, PP fibers improved the raveling resistance in dry conditions. As suggested by Tanzadeh et al. [69], fibers can firmly hold the particles within the matrix, thus preventing their detachment. However, in wet conditions the results were not as expected. It could be observed that the particles loss increased with the addition of PP fibers. Therefore, it could be said that the presence of water affects the cohesion bonding between the dissolved PP fibers and the binder. On the other hand, adding 0.03% of nylon fibers increased the raveling resistance of the mix no matter the amount of bitumen added. Due to their high thermal resistance and tensile strength, these fibers could have formed the three-dimensional-network and reinforced the mixture in a different way. Additionally, it is important to note that with 0.06% nylon fibers the mechanical performance of the mixture is affected in terms of an increase of the particles loss. Probably, increasing the amount of fibers means that the amount of bitumen is not enough for properly coating fibers and aggregates, making them more prone to be exposed to the water influence. It is well known that the presence of water inside the mix weakens the adhesive layer formed in the aggregate-binder interface, resulting in the debonding of the particles [70].

Figure 7. Specimens after being subjected to the Cantabro test.

Table 9. Cantabro test results obtained from the different designs of experiments.

Design	Fiber type	Binder content (%)	Fiber content (%)	Cantabro test results - Dry condition (%)		Cantabro test results - Wet condition (%)	
				mean	SD	mean	SD
1	Nylon	4.40	0.00	27.03	0.50	52.83	6.10
2	Nylon	4.40	0.03	24.19	0.32	44.67	7.62
3	Nylon	4.40	0.06	32.79	2.19	67.34	3.72
4	Nylon	4.80	0.00	26.22	1.35	48.77	0.83
5	Nylon	4.80	0.03	19.56	0.74	38.62	7.74
6	Nylon	4.80	0.06	9.98	1.93	25.74	4.30
7	Nylon	5.20	0.00	22.55	1.28	48.25	0.77
8	Nylon	5.20	0.03	12.25	7.10	36.58	5.52
9	Nylon	5.20	0.06	11.72	5.65	41.77	9.38
10	PP	4.40	0.00	27.03	0.50	52.83	6.10
11	PP	4.40	0.03	24.87	2.74	72.10	10.71
12	PP	4.40	0.06	23.56	1.10	87.20	1.29
13	PP	4.80	0.00	26.22	1.35	48.77	0.83
14	PP	4.80	0.03	17.90	2.68	72.59	5.61
15	PP	4.80	0.06	30.48	3.47	90.80	1.05
16	PP	5.20	0.00	22.55	1.28	48.25	0.77
17	PP	5.20	0.03	14.32	12.42	66.07	3.48
18	PP	5.20	0.06	24.97	2.40	68.06	30.85

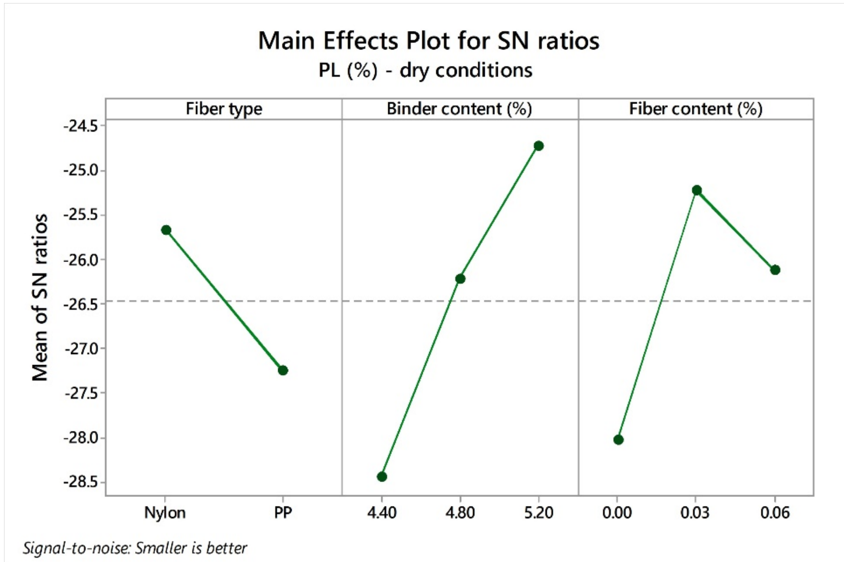

Figure 8. Effects of control factors on PL_{DRY} response.

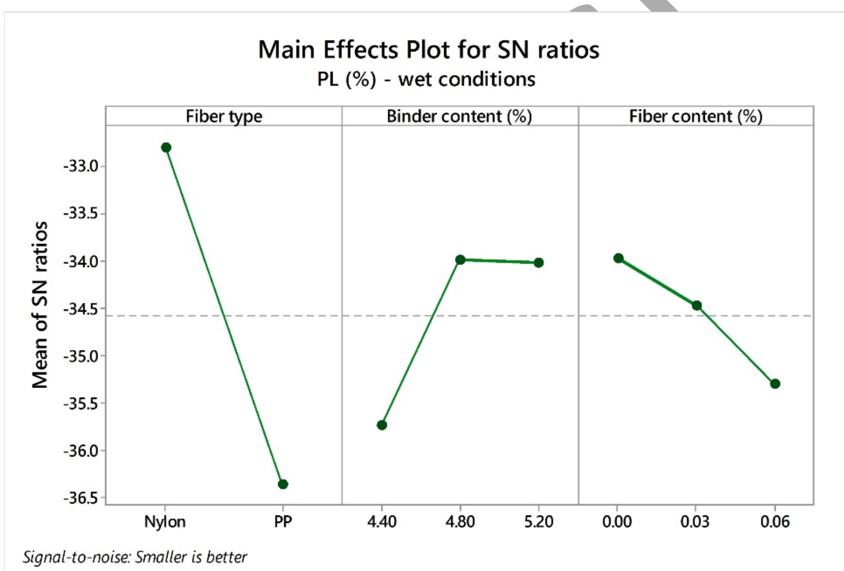

Figure 9. Effects of control factors on PL_{WET} response.

Comparably to T_{AV} and I_{AV}, the interactions between binder content and fiber content in terms of PL_{DRY} and PL_{WET} responses were plotted (**Figure 10**) for each type of fiber. Regression analysis were applied for analyzing the input parameters on the mechanical performance responses as shown in Eqs **(20) – (23)**. Similar than air void responses, different regression equations including linear, linear plus interaction, linear plus squares and full quadratic were initially modelled. Based on the R^2 resulting values (**Table 10**), the proper predictive equation was finally identified as given below. Regarding nylon fibers results, full quadratic was the most accurate regression model to relate predictive values and test results. For PP fibers, linear plus squares and full quadratic were the regression models that better fitted the particle loss in dry and wet conditions, respectively.

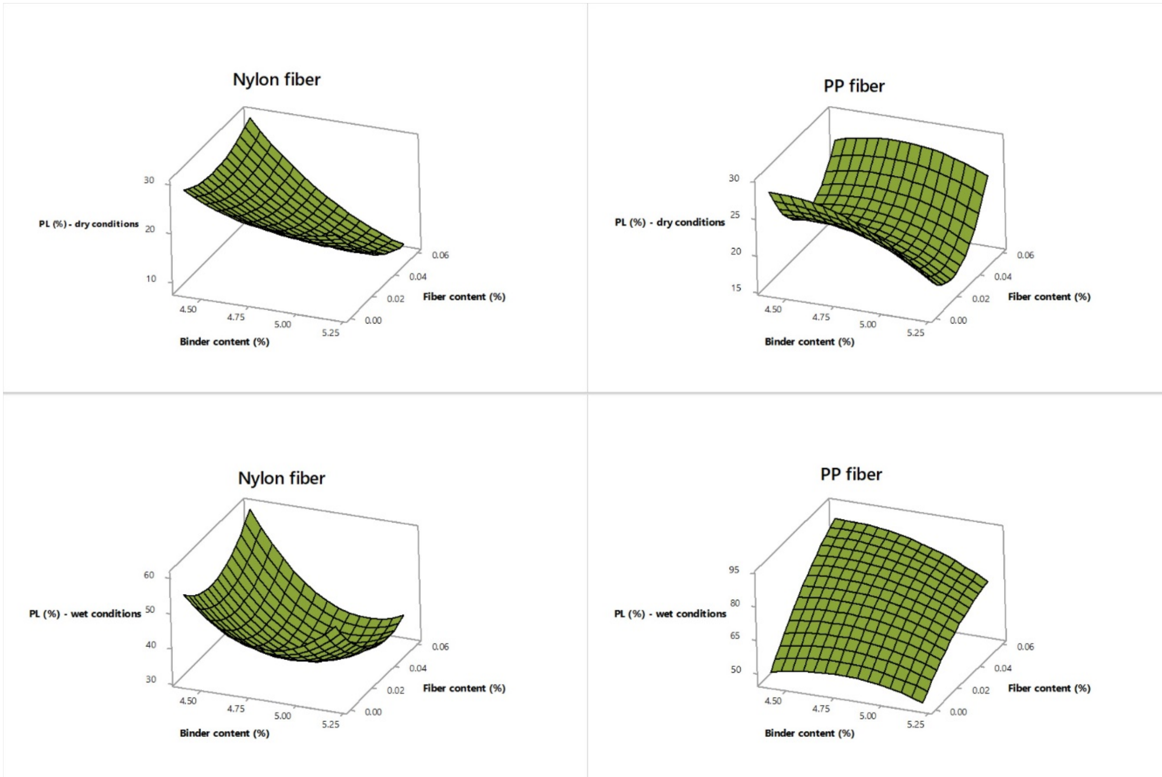

Figure 10. Variations of particle loss in dry and wet conditions in terms of BC (%) and FC (%).

Table 10. Regression models adopted and R^2 value obtained for PL_{DRY} and PL_{WET} responses.

Type of fiber	Response	Regression model	R^2
Nylon	PL_{DRY}	Full quadratic	83.38%
	PL_{WET}	Full quadratic	68.60%
PP	PL_{DRY}	Linear + squares	69.91%
	PL_{WET}	Quadratic	93.52%

For Nylon fibers.

$$PL_{DRY}(\%) = 505 - 195 * BC\,(\%) + 1337 * FC(\%) + 19.8 * BC^2(\%) + 3390 * FC^2(\%) - 346 * BC(\%) * FC(\%) \quad \textbf{(20)}$$

$$PL_{WET}\,(\%) = 1620 - 654 * BC(\%) + 1516 * FC(\%) + 67.9 * BC^2(\%) + 8327 * FC^2(\%) - 437 * BC(\%) * FC(\%) \quad \textbf{(21)}$$

For PP fibers.

$$PL_{DRY}(\%) = -232 + 113 * BC\,(\%) - 434 * FC(\%) - 12.4 * BC^2(\%) + 7525 * FC^2(\%) \quad \textbf{(22)}$$

$$PL_{WET}(\%) = -645 + 295 * BC(\%) + 1991 * FC(\%) - 31.1 * BC^2(\%) - 303 * BC(\%) * FC(\%) \quad \textbf{(23)}$$

4.4 CRITIC – WASPAS for decision making

Taguchi methodology has been employed to design the experiments and optimize single responses (T_{AV},I_{AV}, PL_{DRY}, PL_{WET}) based on SNR values. However, an optimum design of an OGFC requires the multiple criteria to be optimized. Therefore, it is necessary to turn the multiple responses into a single unique response optimization problem. Previous research works suggested that decision support systems can actually be integrated with the Taguchi technique [34]. As said before, TOPSIS and GRA are the most common techniques to be integrated with Taguchi approach [46–48,71]. However, in the present study, the novel CRITIC – WASPAS technique was proposed to be applied to the data given in **Table 7** and **9** for T_{AV},I_{AV}, PL_{DRY}, PL_{WET} responses. Unlike other studies that establish the same weights for the different criteria [48], in this investigation the weightage of criteria was defined in line with the CRITIC method. Among all the responses, T_{AV} and I_{AV} were considered beneficial criteria as higher values are desirable. On the other hand, PL_{DRY} and PL_{WET} were assumed the non-beneficial criteria as lower values are desirable. All the experiments designed were considered as the alternatives for the decision-making matrix. Using Eq. **(9)** the decision matrix was normalized as shown in **Table 11.** The last row refers to the standard deviation of each response. **Table 12** shows the values of Pearson correlation coefficient of the different criteria and **Table 13** displays the criteria weights as determined by using Eq. **(10)** and Eq. **(11)**. Based on this automated decision making technique, that allows the assignment of weights by considering the available data of the measures, the criteria weightage for T_{AV}, I_{AV}, PL_{DRY}, PL_{WET} were set to 0.20; 0.22; 0.29 and 0.29, respectively.

Table 11. Normalized decision matrix employing CRITIC method.

Design	T_{AV} (%)	I_{AV} (%)	PL_{DRY} (%)	PL_{WET} (%)
1	0.44	0.45	0.25	0.58
2	0.45	0.52	0.38	0.71
3	0.62	0.90	0.00	0.36
4	0.43	0.41	0.29	0.65
5	0.48	0.74	0.58	0.80
6	0.45	0.50	1.00	1.00
7	0.36	0.43	0.45	0.65
8	0.43	0.63	0.90	0.83
9	0.37	0.54	0.92	0.75
10	0.44	0.45	0.25	0.58
11	0.67	0.54	0.35	0.29
12	1.00	0.98	0.40	0.06
13	0.43	0.41	0.29	0.65
14	0.63	0.69	0.65	0.28
15	0.73	1.00	0.10	0.00
16	0.36	0.43	0.45	0.65
17	0.00	0.00	0.81	0.38
18	0.27	0.52	0.34	0.35
SD	0.21	0.24	0.29	0.27

Table 12. Correlation coefficient values of different criteria.

	T_{AV} (%)	I_{AV} (%)	PL_{DRY} (%)	PL_{WET} (%)
T_{AV} (%)	1.00	0.86	-0.36	-0.50
I_{AV} (%)	0.86	1.00	-0.33	-0.43
PL_{DRY} (%)	-0.36	-0.33	1.00	0.52
PL_{WET} (%)	-0.50	-0.43	0.52	1.00

Table 13. Weights of Criteria according CRITIC method.

Responses	$\mathbf{C_j}$	W_j
T_{AV} (%)	0.63	0.20
I_{AV} (%)	0.69	0.22
PL_{DRY} (%)	0.91	0.29
PL_{WET} (%)	0.92	0.29

Once the weights of the different responses were calculated, WASPAS approach was employed to turn the multiple-response optimization problem into a single optimization problem. Similarly, this approach enabled to rank all the set of experiments based on the Joint Performance Score (JPS). Thus, the experimental design that has the highest JPS is considered the optimum condition among all the experiments conducted. **Table 14** shows the JPS values calculated with Eqs. **(3) – (7)**. Based on the rank of alternatives and JPS values, experiment number 6 was identified as the best alternative followed by the experimental design number 8. On the other hand, design number 15 was found to be the alternative least recommended due to its lower JPS values. In general, the ranking of alternatives (from the most to the least preferred) is found as follow: 6 – 8 – 9 – 5 – 2 – 16 – 7 – 14 – 17 – 4 – 13 – 1 – 10 – 12 – 11 – 18 – 3 – 15. The multiple responses can be easily analyzed by using JPS values. The mean values of JPS served to calculate the SNR values and hence to determine the optimal levels of each control factor. The response graph for JPS in terms of SNR values can be observed in **Figure 11**. It suggests that level 1 for fiber type, level 3 for binder content and level 2 for fiber content constitute the optimal conditions. In other words, optimal conditions could be achieved with nylon fibers instead of PP fibers. Likewise, high binder contents lead to a reduction of the voids in the mixture but also to an improvement of the OGFC durability. As stated in previous investigations, high values of binder content allow to coat aggregates better, increase the binder film thickness and hence strength the adhesive zone between asphalt binder and aggregate [72]. Moreover, the addition of fibers showed to improve the overall performance of the mix according to the SNR graph in **Figure 11**. This might be because although the air voids response could be slightly reduced, the raveling resistance of the mix (especially in dry conditions) is notably enhanced after adding fibers. Similarly, positive effects on the raveling resistance under the action of water are shown when adding nylon fibers. Note that adding PP fibers increased the particles loss in wet conditions as shown in **Figure 9,** which affects the overall score obtained in terms of JPS values.

Table 14. WSM, WPM and JPS values.

Design	T_{AV} (%)	I_{AV} (%)	PL_{DRY} (%)	PL_{WET} (%)	WSM	T_{AV} (%)	I_{AV} (%)	PL_{DRY} (%)	PL_{WET} (%)	WPM	JPS	Rank
1	0.175	0.190	0.107	0.143	0.615	0.975	0.969	0.750	0.810	0.574	0.594	12
2	0.175	0.194	0.119	0.169	0.658	0.975	0.974	0.774	0.851	0.626	0.642	5
3	0.182	0.214	0.088	0.112	0.596	0.983	0.995	0.709	0.755	0.523	0.560	17
4	0.174	0.188	0.110	0.155	0.627	0.974	0.967	0.756	0.829	0.591	0.609	10
5	0.176	0.206	0.147	0.195	0.725	0.977	0.986	0.823	0.888	0.704	0.715	4
6	0.175	0.193	0.289	0.293	0.950	0.975	0.972	1.000	1.000	0.948	0.949	1
7	0.171	0.190	0.128	0.156	0.645	0.971	0.969	0.790	0.832	0.618	0.632	7
8	0.174	0.200	0.236	0.206	0.816	0.974	0.980	0.943	0.902	0.812	0.814	2
9	0.172	0.195	0.246	0.181	0.794	0.971	0.975	0.955	0.868	0.784	0.789	3
10	0.175	0.190	0.107	0.143	0.615	0.975	0.969	0.750	0.810	0.574	0.594	13
11	0.185	0.195	0.116	0.105	0.600	0.985	0.975	0.768	0.740	0.546	0.573	15
12	0.199	0.218	0.122	0.086	0.626	1.000	0.999	0.780	0.699	0.545	0.585	14
13	0.174	0.188	0.110	0.155	0.627	0.974	0.967	0.756	0.829	0.591	0.609	11
14	0.183	0.203	0.161	0.104	0.651	0.983	0.983	0.845	0.738	0.603	0.627	8
15	0.187	0.219	0.095	0.083	0.584	0.988	1.000	0.724	0.691	0.495	0.539	18
16	0.171	0.190	0.128	0.156	0.645	0.971	0.969	0.790	0.832	0.618	0.632	6
17	0.156	0.167	0.201	0.114	0.638	0.953	0.942	0.901	0.759	0.613	0.626	9
18	0.167	0.194	0.116	0.111	0.588	0.966	0.974	0.767	0.752	0.543	0.565	16

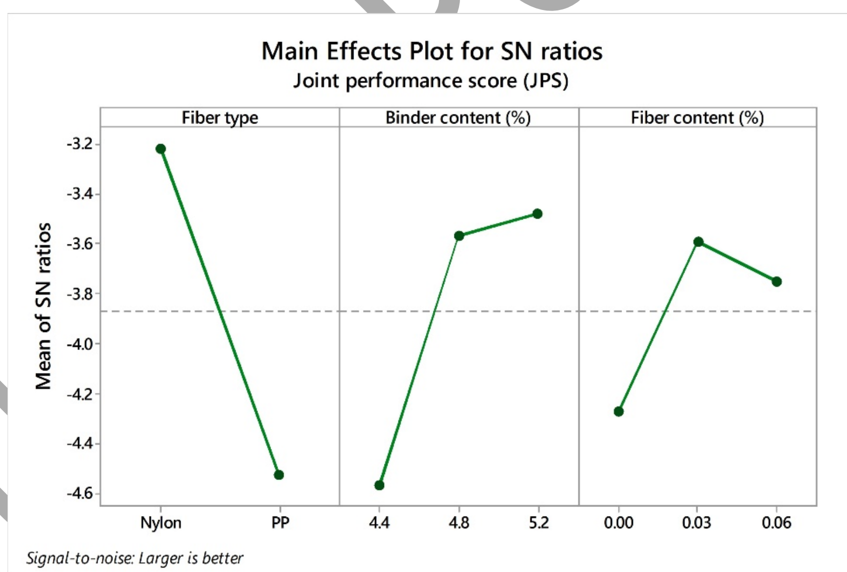

Figure 11. Effect of multiple responses on JPS values.

As with the individual responses, the effects of the input parameters were analyzed in terms of the JPS. **Figure 12** illustrates counter plots showing the effects of binder and fiber content on nylon and polypropylene fibers in terms of the JPS. Considering that JPS integrates all the different responses into an only optimization response, a linear plus interaction regression model was selected to integrate the three input control factors. The model was chosen due to its simplicity and because it can be easily applied. When a significant number of input parameters are involved in a model, the selection of those that make the mathematical model simpler is recommended. The suggested model was statically validated using the analysis of variance (ANOVA) as shown in **Table 15**. The p-values < 0.05 indicate the significant effects of the input parameters and their interaction effects on the JPS. Accordingly, the model is significant as well as its linear and interaction components, whereas square components were not considered as they were not significant. The model for JPS as a function of their input control factors is given by:

$$JPS = -0.254 + 0.732 * FT + 0.1827 * BC(\%) + 2.57 * FC(\%) - 0.154 * FT * BC(\%) - 3.38 * FT * FC(\%) \quad \textbf{(24)}$$

Figure 13 shows the comparison of the JPS values obtained from experimental results after applying the CRITIC WASPAS based on Taguchi methodology and those predicted by the regression model developed. The mean error obtained from test results and predicted values was approximately 6.0%. The results also indicate that the deviation between tested and predicted results was lower for polypropylene fibers than for nylon fibers.

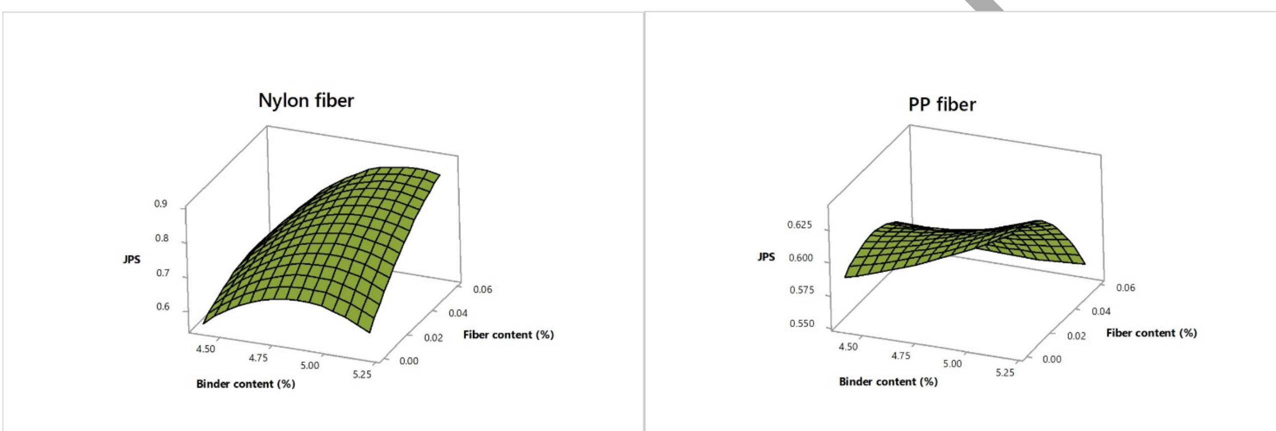

Figure 12. Effects of binder and fiber content on JPS values.

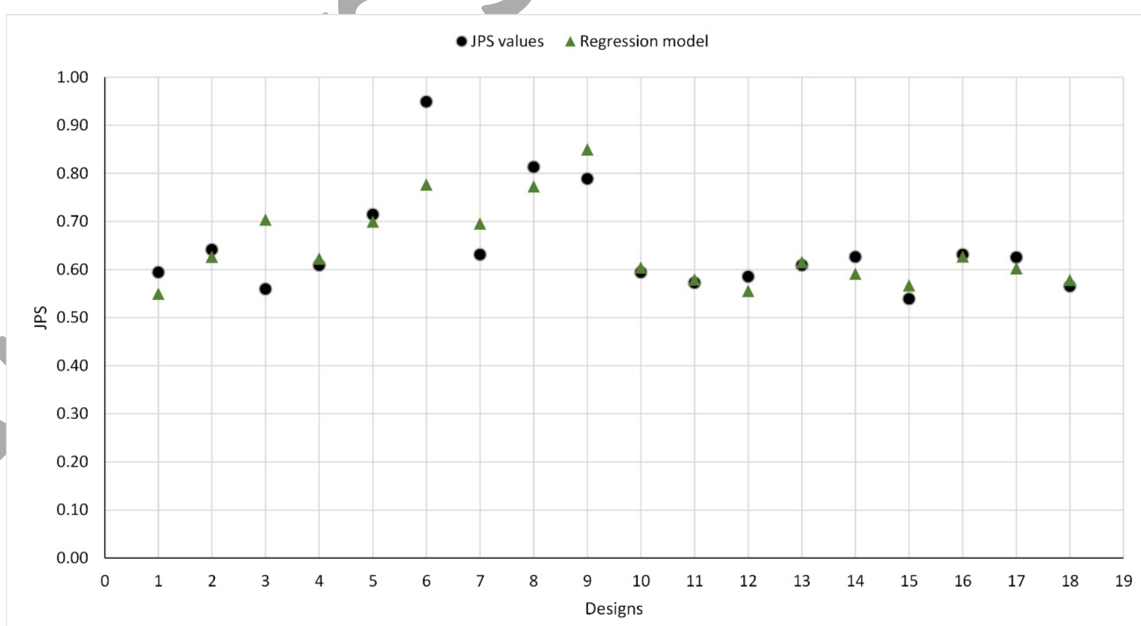

Figure 13. Comparison between test results and regression model on JPS values.

Table 15. Analysis of variance results for JPS.

Variance Source	Degree of freedom (DoF)	Adj SS	Adj MS	F-Value	P-Value	Significance
Model	5	0.12	0.02	4.43	0.02	Significant
Linear	3	0.08	0.03	4.85	0.02	Significant
Fiber type	1	0.05	0.05	9.12	0.01	Significant
Binder content (%)	1	0.02	0.02	3.90	0.07	
Fiber content (%)	1	0.01	0.01	1.53	0.24	
2-Way Interaction	2	0.04	0.02	3.81	0.05	Significant
Fiber type*Binder content (%)	1	0.01	0.01	2.05	0.18	
Fiber type*Fiber content (%)	1	0.03	0.03	5.57	0.04	Significant
Error	12	0.07	0.01			
Total	17	0.19				

5 Conclusions

This study evaluated the functional and mechanical performance of OGFCs reinforced with nylon and polypropylene fibers in an experimental and statistical manner. A design of experiments was performed according to the Taguchi methodology and the optimal levels for each control factor were identified for the functional and mechanical responses. Additionally, different regression analysis for each response as depending on the type of fiber was performed. CRITIC-WASPAS multi-criteria decision making analysis was carried out to turn the multi-response optimization problem into a single-one response optimization problem. Based on the experimental results of this research, the following conclusions can be drawn:

- As for the total and interconnected air voids responses, the type of fiber is not a relevant control factor that affects the functional performance of the mixture. Likewise, the binder content was the control factor that affected the functional parameters the most. Besides, adding fibers to the mix contributed to increase the voids in the mixture.
- Concerning the mechanical performance assessment, adding fibers is suitable to reduce the particles loss in the OGFCs, especially in dry conditions. In wet conditions, promising results were found when adding nylon fibers instead of PP fibers. In fact, the addition of 0.03% nylon fibers improved the raveling resistance in wet conditions for the three different binder contents employed in this research. On the contrary, using PP fibers decreased the raveling resistance when compared to the reference mixture. Therefore, their use is not recommended.
- In this research, the CRITIC method was used as an automated decision making technique to find the weights of the different responses. Particles loss in dry and wet conditions were identified with the highest weights, both with a value of 0.29, whereas total and interconnected air voids were assigned weights of 0.20 and 0.22, respectively.
- The WASPAS methodology enabled the conversion of the multiple responses into a single response in terms of a JPS value. This approach was also employed to rank all the experimental designs. Design number 6, with 4.80% bitumen content and 0.06% nylon fibers content was ranked as the most preferred alternative.
- CRITIC-WASPAS based on Taguchi methodology may be considered a very useful novel tool to be used in the optimization of multiple experimental studies.

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