TecnoLógicas

Modeling of Mechanical Properties of Recycled Foamed Asphalt Mix by Nonlinear Regression and Artificial Neural Network and Ranking of Different Designs Using TOPSIS Method

Modelado de propiedades mecánicas de mezclas asfálticas espumadas recicladas mediante regresión no lineal y redes neuronales artificiales y clasificación de diferentes diseños utilizando el método TOPSIS

Mehrdad Mirshekarian Babaki[1]; Ali Pirhadi Tavandashti[2]

[1]Jemper Engineering Co, Tehran-Irán
[2]University of Georgia, Athens-United States of America
Correspondence: ali.piehadi@uga.edu

Received: 26 June 2024 **Accepted:** 28 January 2025 **Available:** 05 March 2025

How to cite / Cómo citar

M. Mirshekarian Babaki, and A. Pirhadi Tavandashti, "Modeling of Mechanical Properties of Recycled Foamed Asphalt Mix by Nonlinear Regression and Artificial Neural Network and Ranking of Different Designs Using TOPSIS Method," *TecnoLógicas*, vol. 28, no. 62, e3154, 2025. https://doi.org/10.22430/22565337.3154

Abstract

Foamed asphalt mixtures, created using reclaimed asphalt pavement (RAP) and foamed bitumen, offer energy savings, reduced use of virgin materials, and lower transportation costs, combining the characteristics of rigid and flexible pavements. This study evaluated the mechanical performance of foamed asphalt mixtures with varying bitumen content (1–3 %) and cement content (0–2 %) to identify the optimal combination for pavement applications. Samples were tested for uniaxial compressive strength (UCS), indirect tensile strength (ITS), resilient modulus (RM), and tensile strength ratio (TSR) under laboratory conditions. To predict the results, a nonlinear regression model and an artificial neural network (ANN) were employed. The ANN model demonstrated greater accuracy with significantly lower prediction errors compared to the nonlinear regression model. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method was then used to select the optimal combination of materials. TOPSIS prioritizes mixtures with the shortest geometric distance to the positive ideal solution (best values for all attributes) and the longest distance from the negative ideal solution. The results showed that UCS and RM increased as the bitumen content increased from 1 % to 2 %, but these properties decreased when the bitumen content exceeded 2 %. In contrast, ITS (dry and saturated) showed continuous improvement with an increase in bitumen content from 1 % to 3 %. TOPSIS analysis identified the mixture with 3 % bitumen and 2 % cement as the optimal combination, achieving the best overall performance in the UCS, ITS, RM, and TSR tests. This study highlights the utility of foamed asphalt mixtures for sustainable construction, demonstrating that ANN predictions and TOPSIS can effectively guide material selection to achieve superior mechanical performance while reducing environmental impact.

Keywords

Artificial neural networks, foamed bitumen, mechanical properties, nonlinear regression, reclaimed asphalt pavement, topsis method.

Resumen

Las mezclas de asfalto espumado, creadas utilizando pavimento asfáltico reciclado (RAP, por sus siglas en inglés) y betún espumado, ofrecen ahorros de energía, reducción del uso de materiales vírgenes y menores costos de transporte, combinando las características de pavimentos rígidos y flexibles. Este estudio evaluó el rendimiento mecánico de las mezclas de asfalto espumado con diferentes contenidos de betún (1–3 %) y contenidos de cemento (0–2 %) para identificar la combinación óptima para aplicaciones en pavimentos. Se realizaron pruebas de resistencia a la compresión uniaxial (UCS, por sus siglas en inglés), resistencia a la tracción indirecta (ITS, por sus siglas en inglés), módulo resiliente (RM, por sus siglas en inglés) y relación de resistencia a la tracción (TSR, por sus siglas en inglés) en condiciones de laboratorio. Para predecir los resultados se utilizó un modelo de regresión no lineal y una red neuronal artificial (ANN, por sus siglas en inglés). El modelo de ANN demostró una mayor precisión con errores de predicción significativamente menores en comparación con el modelo de regresión no lineal. Luego, se empleó el método de Técnica para el Orden de Preferencia por Similaridad a la Solución Ideal (TOPSIS) para seleccionar la combinación óptima de materiales. TOPSIS prioriza las mezclas con la distancia geométrica más corta a la solución ideal positiva (mejores valores para todos los atributos) y la distancia más larga de la solución ideal negativa. Los resultados mostraron que UCS y RM aumentaron a medida que el contenido de betún aumentaba del 1 % al 2 %, pero estas propiedades disminuyeron cuando el contenido de betún superó el 2 %. En contraste, ITS (seco y saturado) mostró una mejora continua con el aumento del contenido de betún del 1 % al 3 %. El análisis de TOPSIS identificó la mezcla con 3 % de betún y 2 % de cemento como la combinación óptima, logrando el mejor rendimiento general en las pruebas de UCS, ITS, RM y TSR. Este estudio destaca la utilidad de las mezclas de asfalto espumado para la construcción sostenible, demostrando que las predicciones de ANN y TOPSIS pueden guiar eficazmente la selección de materiales para lograr un rendimiento mecánico superior mientras se reduce el impacto ambiental.

Palabras clave

Redes neuronales artificiales, betún espumado, propiedades mecánicas, regresión no lineal, pavimento asfáltico reciclado, método TOPSIS.

1. INTRODUCTION

In recent years, the increase in greenhouse gases such as methane, carbon dioxide, water vapor, and nitrous oxide in the atmosphere has led to a steady increase in the Earth's temperature, causing significant changes in the environment and climate [1], [2]. Consequently, under the Kyoto Protocol of 1997, industrialized countries committed to reduce their greenhouse gas emissions by approximately 5 % over the next decade [3]. Thus, energy conservation and sustainable construction have become critical issues in pavement engineering, driving the adoption of foamed asphalt technology around the world [4]. Asphalt recycling helps reduce carbon dioxide production, and the use of cold recycling technology is expanding globally to mitigate the pollutants of hot asphalt, reduce environmental degradation, achieve economic savings, lower energy consumption, and conserve natural resources. On-site cold recycling using foamed bitumen is one of the latest advances in this field [5]-[7]. The term "foamed asphalt" refers to a mixture of pavement construction aggregates and foamed bitumen. Foamed bitumen, or expanded bitumen, is produced by injecting water into hot bitumen, causing spontaneous foaming. The physical properties of bitumen are temporarily altered as the injected water turns into vapor, which is trapped in thousands of tiny bitumen bubbles. The foamed bitumen is then completely mixed with fine and coarse aggregates [8], [9]. This technology has been widely adopted due to its environmental and economic benefits. Recent studies have shown that foamed asphalt mixtures can significantly reduce the carbon footprint of pavement construction by up to 40 % compared to traditional hot mix asphalt [10]. Additionally, the use of reclaimed asphalt pavement (RAP) in foamed asphalt mixtures further enhances sustainability by reducing the need for virgin aggregates [11].

TOPSIS, an acronym for the Technique for Order Preference by Similarity to Ideal Solution, is one of the most popular and well-known multi-criteria decision-making methods for ranking alternatives. The general philosophy of this method involves defining two hypothetical alternatives using the available data. An alternative includes the best values observed in the decision matrix, known as the positive ideal solution (best possible alternative). The other alternative includes the worst possible values, known as the negative ideal solution. The impact on decision criteria can be positive or negative, and the desirability of any criteria can be incremental or decreasing. This means that each indicator can have a positive or negative effect on choosing the ideal solution. The TOPSIS method calculates scores based on the geometric distance of each alternative from these hypothetical solutions, ranking the alternatives according to these scores [9]. TOPSIS has been successfully applied in various fields, including civil engineering, environmental management, and material science, to optimize decision-making processes [12], [13].

The interactions between recycled asphalt pavement and cement or foamed asphalt in the presence of water during the mixing, curing, and service phases are crucial to determining the strength development and deterioration of foamed asphalt cold recycled mixtures. However, these interactions are not yet fully understood [14]. In this study, the effects of cement as a cheap and active filler and the amount of bitumen in recycled foamed asphalt mixtures were evaluated using compressive strength, resilient modulus, and indirect tensile strength tests (saturated and dry). All aggregate materials used were selected from recycled asphalt. The results of these experiments were predicted using nonlinear regression and artificial neural networks (ANN), and the results of each method were compared with the actual values. In this research, 25 samples were made with 1-3 % bitumen and cement filler. When increasing the amount of cement and bitumen from 1 % to 3 %, the modulus of elasticity and compressive strength shows a different behavior. So, which of the combinations made (bitumen + cement filler) is the most desirable option? The TOPSIS decision-making method answers this question. Finally, the best combination of bitumen and cement was selected using the TOPSIS method.

This study aims to contribute to the growing body of research on sustainable pavement engineering by providing information on the optimal use of foamed asphalt mixtures. The findings will help develop more environmentally friendly and economically viable pavement solutions, aligning with global efforts to mitigate climate change and promote sustainable development.

2. LITERATURE REVIEW

The potential for foamed bitumen as a soil binder was first realized in 1956 by Dr. Ladis H. Csanyi at the Engineering Experiment Station at Iowa State University [10], [11]. Since then, foamed asphalt technology has been successfully used in many countries, evolving from the initial bitumen foaming process, as described in early applications, which involved injecting steam directly into heated bitumen [12]. Although this steam-based system was convenient for asphalt plants equipped with steam supplies, it was less practical for on-site foaming due to the requirement for specialized equipment, such as steam boilers [13]. In 1968, Mobil Oil Australia, after obtaining the patent rights for Csanyi's invention, refined the process by replacing steam injection with high-pressure injection of cold water into heated bitumen. This adaptation significantly improved the practicality and cost-effectiveness of the foaming process for broader applications [15], [16].

One major disadvantage of foamed asphalt mixtures is the high percentage of voids and the lack of proper bonding between bitumen and coarse aggregates. This reduces the strength and durability of foamed asphalt mixtures. To compensate for this defect, active fillers, such as cement, are used [17]. In foamed asphalt mixtures, the addition of an active filler (such as cement or lime) significantly improves the mixing of bitumen with coarse aggregates, increases the strength of the mixture, and reduces its moisture sensitivity and susceptibility to freezing-thaw cycles [12]. Technical standards limit the maximum cement content to approximately 2 % of the sample weight and recommend adding 1 % to 2 % cement as the optimum percentage. Uniaxial compressive strength tests, indirect tensile strength tests, and the Tensile Strength Ratio (TSR) are proposed to evaluate foamed asphalt mixtures [10]. However, NCHRP 807 for the design of foamed asphalt mixtures suggests the use of the resilient modulus test, the indirect tensile strength test, and the wheel tracking test [18]. The study by Hashemian and Kavussi on foamed asphalt mixtures showed that adding cement and lime fillers, and their mix (in equal ratio) by 1.5 % of the weight of the mixture increased the indirect tensile strength, compressive strength, and Marshall strength ratio. However, cement filler had a more significant effect on the mechanical properties and hardness of the samples compared to other designs [19], [20] demonstrated that the use of gabbro mineral filler increases Marshall strength and indirect tensile strength. They also developed a bivariate quadratic equation to estimate Marshall strength, indirect tensile strength, and resilient modulus as dependent variables, with the amount of fillers and bitumen as independent variables.

Various studies have shown that in foamed asphalt mixtures, the addition of active fillers such as cement improves the mixing of bitumen with aggregates, increasing the strength of the mixture and reducing its susceptibility to moisture [11]. Among fillers such as cement, cement clinker, lime, and fly ash, cement has shown superior performance in increasing the initial processing strength of the mixture. Fly ash acts similarly to mineral filler. In their study, [21] found that the indirect tensile strength of samples with 1 % cement filler was approximately five times that of the control sample. Buczynski's research on the effect of filler on moisture damage and frost resistance in foamed asphalt mixtures showed that cement filler performed better compared to hydrated lime powder and cement clinker. If the cement to filler ratio is less than 20 %, the effect of the active filler is minimal. Research by [22] on recycled foamed asphalt mixtures suggested that cement increases Marshall strength, indirect dry and saturated tensile strength, and improves resistance to moisture damage. According to the literature, cement filler plays a critical role in enhancing mechanical properties and reducing moisture susceptibility in foamed asphalt mixtures.

Divandari [23], using linear regression and combining the results of indirect tensile tests, Marshall Strength, and wheel tracking tests, developed a mathematical relation to predict rutting of asphalt mixtures and validated the model using an artificial neural network (1).

$$R\_d\ (mm) = 2.951D\_v - 0.736S\_m + 0.003S\_t + 2.737 \quad (1)$$

Where R_d is the depth of rutting obtained in the wheel tracking test in millimeters, D_v is the vertical displacement obtained by the indirect tensile test in millimeters, S_m is the Marshall Strength in KN, and S_t is the indirect tensile strength in KPa [23] also predicted the Flow Number of hot asphalt mixtures using the gyratory compaction slope and the semi-logarithmic curve slope of the gyratory shear stress; they employed the Multilayer Perceptron (MLP) artificial neural network. Initially, due to varying sample sizes, the input and output values were normalized. Then, an input layer with two neurons, an output layer with one neuron, and a hidden layer with variable neurons were defined. Finally, the most suitable structure of 2-20-1 was selected by trial and error.

3. MATERIAL AND METHODS

3.1 Aggregates

In this study, aggregates were obtained from reclaimed asphalt pavements (RAP) on the right runways no. 29 of Shahid Dastgheib International Airport in Shiraz, Iran. The RAP was milled using a WIRTGEN cold milling machine (W250) at an average depth of 10 cm. Due to the lack of proper coating and bonding of coarser particles by foamed bitumen, particles larger than 25 mm were removed from the mixture. Initially, the RAP was graded, and the particles were separated on the basis of sieve sizes.

The grading curve of the RAP materials used in this study is shown in Figure 1. The technical standards present the proposed limits for evaluating the quality of RAP, as shown in Table 1, which were also used in this study to investigate the properties of RAP. The optimal moisture content of the RAP materials in the laboratory was determined using the modified Proctor method D (AASHTO-T180), resulting in an optimal moisture content of 5 %. Therefore, the moisture content of the materials was set at this optimal level. As the RAP materials used were dry, this amount of water was added directly to the materials.

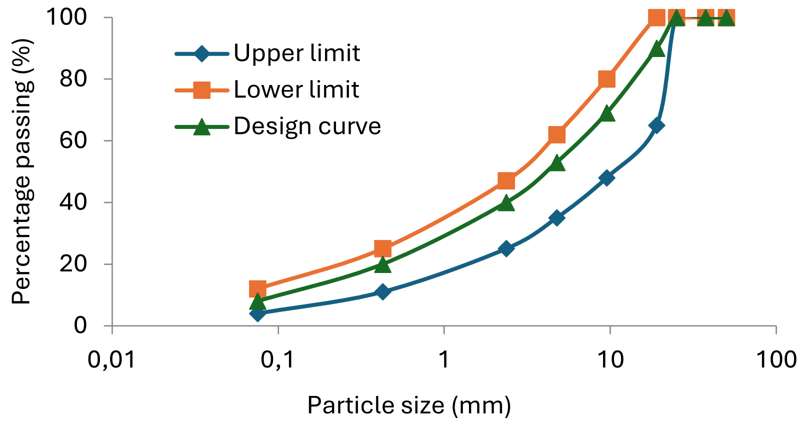

Figure 1. Grading curve of the asphalt chips and proposed limits of the curve. Source: own elaboration.

Table 1. RAP properties. Source: own elaboration.

Properties	Materials specifications	Standard specifications	Test methods (AASHTO)
Resistance to degradation of small-size coarse aggregate by abrasion and impact	30	Max. 40	T96
Weight loss against sodium sulfate	0.3	Max. 12	T104
Sand equivalent value of soils and fine aggregate	48	Min. 35	T176
Plasticity index	2	Max. 6	T89.90
Water absorption	1.8	Max. 3	T84.85
Organic materials	1	Max. 2	T194.267
Bitumen content in reclaimed asphalt pavement materials	4.5		T164

3.2 Selection of bitumen and bitumen production specifications

In this study, bitumen 85/100 produced by Tehran Refinery was used, its main characteristics are detailed in Table 2. Bitumen properties were evaluated using a laboratory-scale foamed bitumen plant (WLB10), depicted in Figure 2.

The plant comprises a bitumen heating container and two pumps with adjustable discharge rates for bitumen and water injections, along with a container to drain the bitumen outlet. The process involves injecting hot bitumen and specified quantities of cold water into an expansion chamber using compressed air, resulting in foamed bitumen discharged through another duct. This setup allows simulation of operational conditions by adjusting parameters such as bitumen pressure, water pressure, bitumen temperature, bitumen content, and inlet water.

At typical stabilizing machine speeds of 5 to 10 meters per minute, the bitumen pressure at the nozzle is maintained at 5 atmospheres, determined by the speed of the stabilizing machine.

Table 2. Characteristics of bitumen. Source: own elaboration.

Specifications	Amounts	Standard specifications	Standard
Penetration (Deci millimeter)	91	85-100	ASTM D5
Softening point (Celsius)	49	56-49	ASTM D36
Ductility (cm)	More than 100	More than 100	ASTM D113
Flash point (Celsius)	296	More than 232	ASTM D92
Kinematic viscosity at 135 C	410	-	ASTM D2170

Figure 2. WLB10 bitumen production plant. Source: own elaboration.

The bitumen was processed to form foamed bitumen at 170°C with different percentages of water (1 %, 2 %, 3 %, and 4 % by weight of the bitumen). The study measured half-life parameters, expansion ratio, and foamed bitumen index to evaluate variations in these parameters with respect to the percentage of water. The following parameters were used to assess the properties of foamed bitumen (adapted from Newcomb [18]):

-Half-life: The time in seconds it takes for the volume of foamed bitumen to reach half of its maximum foamed volume, indicating the stability and speed of foam disappearance during the mixing of bitumen and aggregates.

-Expansion Ratio: The ratio of the maximum volume of foamed bitumen to its initial volume of bitumen, determining how the bitumen is distributed within the mixture.

-Foam Index: Determined by the following relation, the foam index illustrates the integration of foamed bitumen with Reclaimed Asphalt Pavement (RAP) materials (2):

$$\mathrm{FI} = \frac{\mathrm{HL}}{\ln 2}\left[4 - \mathrm{ER} - 4\ln\left(\frac{4}{\mathrm{ER}}\right)\right] + \left(\frac{1+\mathrm{c}}{\mathrm{c}}\right)(\mathrm{ER} \times \mathrm{t_s}) \qquad (2)$$

FI: Foam Index

ER: Expansion Ratio

HL: Half-life

ts: The length of time required to discharge foamed bitumen C is calculated based on Table 3.

Table 3. The values of C (eq. 2). Source: own elaboration.

Bitumen discharge time (seconds)	Expansion coefficient	Half-life 2 seconds	Half-life 5 seconds	Half-life 15 seconds	Half-life 30 seconds	Half-life 60 seconds
	5	0.83	0.93	0.97	0.99	0.99
1	15	0.83	0.93	0.98	0.99	0.99
	25	0.83	0.93	0.98	0.99	0.99
	5	0.43	0.69	0.88	0.94	0.96
5	15	0.44	0.7	0.88	0.94	0.97
	25	0.44	0.7	0.88	0.94	0.97
	5	0.23	0.51	0.78	0.88	0.94
10	15	0.23	0.51	0.78	0.88	0.94
	25	0.23	0.51	0.78	0.88	0.94

As indicated in Table 4, the optimal water content of 3 % by bitumen weight was selected based on the half-life, expansion ratio, and foam index results.

Table 4. Expansion Ratio, half-life, and foam Index vs. Water Percentage. Source: own elaboration.

Amount of water (by weight of bitumen)	Expansion ratio	Half-life	Foam index
1	7.4	22.4	69
2	12.3	17.3	160
3	17.2	12.2	224
4	22.1	8.1	218

3.3 Selection of bitumen and bitumen production specifications

The RAP materials were mixed with cement filler at approximately 100 % of the optimum moisture content. Cement filler percentages of 0 %, 0.5 %, 1 %, 1.5 %, and 2 % by mixture weight were added to the RAP materials and thoroughly mixed. The foamed bitumen, ranging from 1 % to 3 % by weight of the mixture, was then sprayed onto the aggregates, followed by mixing for 45 seconds. The foamed asphalt mixture was subsequently prepared for compression and sample formation.

Cylindrical samples with a diameter of 4 inches were prepared according to ASTM D6926 based on the Marshall method. Each sample was compacted using 75 strokes of a Marshall hammer on each side [24]. The percentage of air in the asphalt mixture after preparation is 4.5 %.

After 24 hours, the samples were removed from the molds and subjected to dry treatment conditions in an oven at 40°C for 72 hours. The samples were subjected to dry treatment for the following tests:

The resilient modulus test was performed according to ASTM D4123-82 standard.

The uniaxial compressive strength test was performed under compressive load at 140 kPa.

The indirect tensile strength test was performed according to the AASHTO-T283 method on dry and saturated treated samples (after drying for 24 hours in water at 25°C). For saturated samples, the saturated to dry tensile strength (TSR) ratio was calculated.

4. RESULTS AND DISCUSSION

The results of the experiments are summarized in Table 5.

Table 5. Test results. Source: own elaboration.

Cement (%)	Foamed bitumen (%)	Compressive strength (kPa)	Dry indirect tensile strength (kPa)	Saturated indirect tensile strength (kPa)	Resilient modulus (MPa)
0.0	1.0	1070	145	92	1821
0.5	1.0	1470	184	123	1954
1.0	1.0	1770	220	152	2048
1.5	1.0	1895	250	170	2450
2.0	1.0	1995	275	188	2852
0.0	1.5	1170	210	134	1884
0.5	1.5	1515	260	188	2057
1.0	1.5	1800	296	231	2118
1.5	1.5	2010	334	268	2778
2.0	1.5	1905	358	295	3336
0.0	2.0	1165	277	178	1965
0.5	2.0	1556	330	248	2119
1.0	2.0	1795	377	314	2230
1.5	2.0	1995	412	360	3050
2.0	2.0	2090	447	406	3870
0.0	2.5	1120	303	202	1908
0.5	2.5	1505	356	273	2034
1.0	2.5	1805	405	342	2146
1.5	2.5	1950	452	390	2987
2.0	2.5	2045	491	436	3819
0.0	3.0	1085	320	220	1793
0.5	3.0	1415	377	295	1929
1.0	3.0	1715	423	362	2008
1.5	3.0	1910	480	410	2850
2.0	3.0	1935	525	467	3692

4.1 Uniaxial compressive strength

In this test method, the strength of cylindrical samples of asphalt mixtures is measured under compressive loading. The degree of interlocking between aggregates significantly influences the strength of the sample. Figure 3 illustrates that the highest compressive strength was achieved in various mix designs with 2 % bitumen. Increasing the bitumen content from 1 % to 2 % increased the sample strength; however, the strength decreased as the bitumen content increased from 2 % to 3 %. The maximum compressive strength of 2090 kPa was observed for the mixture containing 2 % bitumen and 2 % cement, while the minimum strength of 1070 kPa was obtained with 1 % bitumen and no filler.

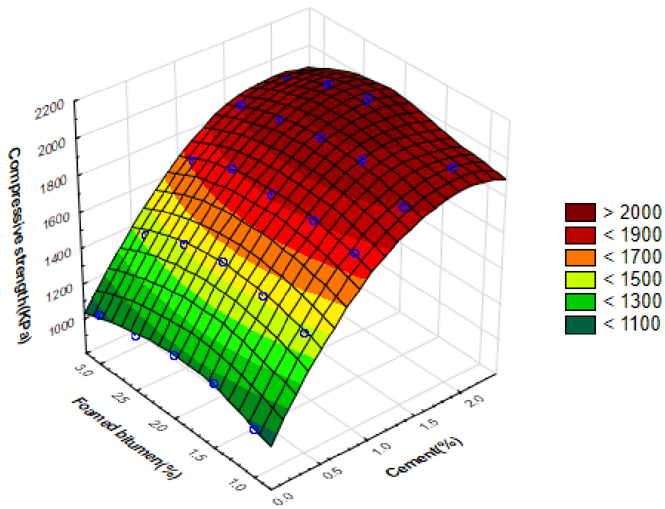

Figure 3. Uniaxial compressive strength in terms of cement and percentage of bitumen.
Source: own elaboration.

4.2 Indirect Tensile Strength (ITS)

The indirect tensile test was conducted using a standard loading blade with a steady speed of 51 mm/min. In this experiment, cylindrical samples were subjected to compressive loading on their lateral surfaces, inducing tensile stress along the diameter of the sample until failure [25]. This test method is also utilized to assess the susceptibility to moisture of asphalt mixtures. Figures 4 and 5 depict the results under saturated and dry conditions, respectively. The findings indicate that increasing the bitumen content improves the indirect tensile strength (both dry and saturated) in all designs. The adhesion between the aggregates and the foamed bitumen plays a crucial role in the strength of the sample, with a higher bitumen content improving the adhesion to the RAP. Consequently, the samples exhibited the highest indirect tensile strengths of 525 kPa (dry) and 467 kPa (saturated) with 3 % bitumen and 2 % cement. On the contrary, the lowest strengths were observed in filler-free samples with 1 % bitumen, producing 145 kPa (dry) and 92 kPa (saturated).

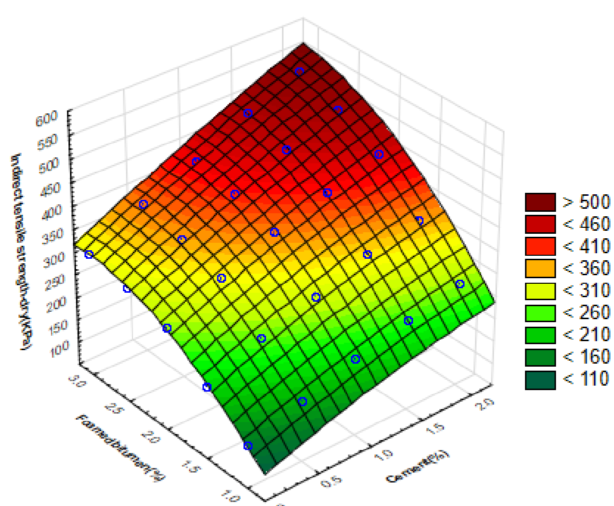

Figure 4. Indirect dry tensile strength in terms of cement and percentage of bitumen.
Source: own elaboration.

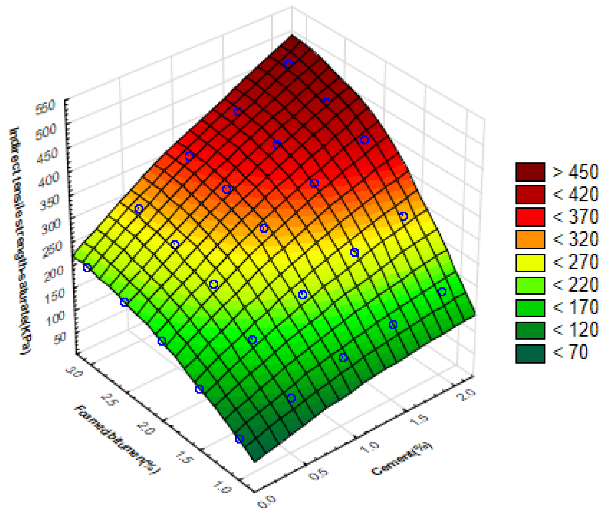

Figure 5. Saturated indirect tensile strength in terms of cement and percentage of bitumen. Source: own elaboration.

Furthermore, increasing the cement content improves the strength of the sample, as indicated by the increase in slope. The cement reacts with moisture in the aggregates and foamed bitumen, increasing the adhesion of the bitumen to the aggregate surface. Moisture damage to asphalt can lead to various types of failures, such as potholes, alligator cracks, and rutting. The susceptibility of asphalt samples to moisture damage is assessed using the Tensile Strength Ratio (TSR). Figure 6 illustrates the TSR values corresponding to varying amounts of cement and bitumen. As depicted in Figure 6, increasing the percentages of bitumen and cement reduces susceptibility to moisture, resulting in higher TSR ratios. The maximum TSR value of 0.89 was observed with 3 % bitumen and 2 % cement, while the minimum TSR value of 0.63 occurred with 1 % bitumen and no cement.

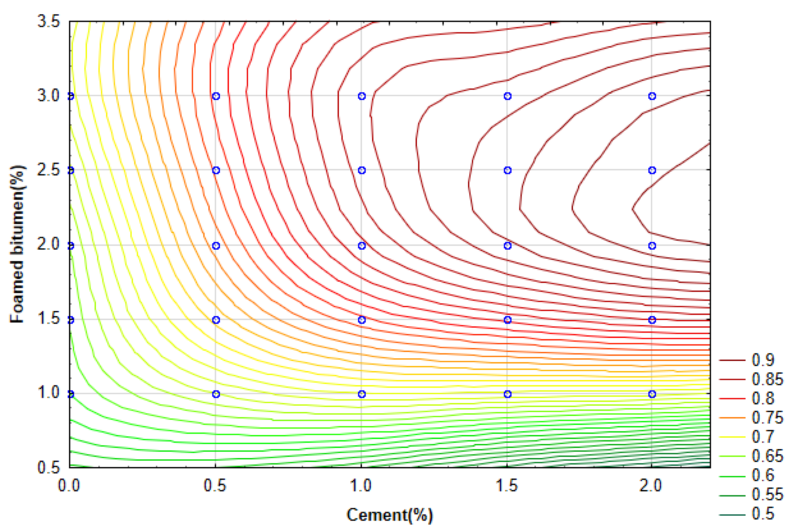

Figure 6. TSR ratio in terms of cement and percentage of bitumen. Source: own elaboration.

4.3 Resilient Modulus

Resilient modulus, measured according to ASTM D4123 standard using the indirect tensile strength method, is a fundamental technique for evaluating the stress-strain characteristics and elastic properties of asphalt mixtures. In this study, the resilient modulus of samples prepared under dry conditions at 25°C was evaluated, with results shown in Figure 7. The experimental findings indicate that increasing bitumen content from 1 % to 2 % initially enhances the resilient modulus. However, as bitumen content is further increased from 2 % to 3 %, the resilient modulus decreases. The highest resilient modulus observed was 3870 MPa for samples containing 2 % bitumen and 2 % cement, whereas the lowest resilient modulus measured was 1821 MPa for samples with 1 % bitumen and no cement filler. Furthermore, samples without cement filler exhibited a resilient modulus of 1965 MPa with 2 % bitumen, marking the highest value in this category.

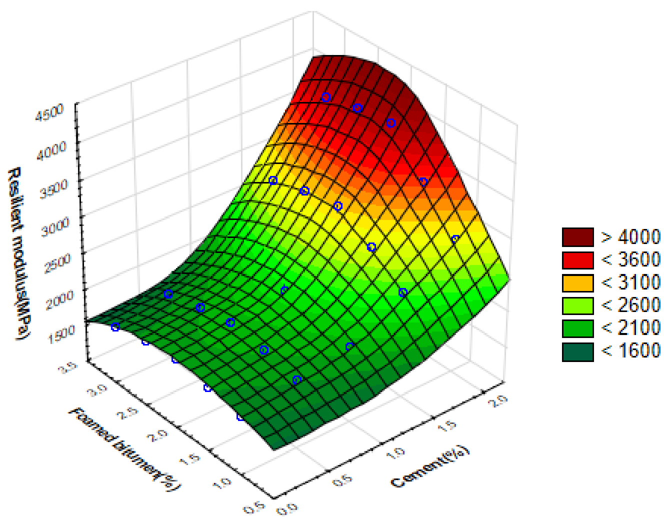

Figure 7. Resilient modulus in terms of cement and bitumen percentage. Source: own elaboration.

4.4 Non-linear regression

Regression analysis is a statistical method that is used to estimate the relationships between variables. It involves various techniques for modeling and analyzing the interactions between dependent and independent variables. In this study, mathematical functions were used to express the relationships between the independent variables (X) and the dependent variable (Y). The correlation coefficient (R) quantifies the strength of these relationships. Table 6 presents the independent variables used in each regression model.

Table 6. Independent variables of each model. Source: own elaboration.

Factor (independent variables)	Values	Unit	Average
Foamed bitumen (FB)	0.5, 1.0, 1.5, 2.0, 2.5, 3.0	percent	2.1
Cement(C)	0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0	percent	1.0

In this study, the dependent variables chosen were compressive strength, dry and saturated indirect tensile strength, and resilient modulus. The independent variables considered were the percentages of cement and foamed bitumen. To predict these dependent variables, a bivariate quadratic equation (3) was used. This equation allowed modeling and prediction of how variations in the percentages of cement and foamed bitumen influence the mechanical properties of the asphalt mixtures under investigation.

$$f(FB, C) = \mathrm{A} + \mathrm{Bx}_1 + \mathrm{Cx}_2 + \mathrm{Dx}_1^2 + \mathrm{Ex}_2^2 \quad (3)$$

FB; Foamed bitumen (%)
C; Cement (%)

In (4) to (7), mathematical models are presented for each test result, along with the analysis of variance for each function at a 95% confidence level, as shown in Tables 7 to 10. In the following relations, P represents the compressive strength in kPa, ITS denotes the indirect tensile strength in kPa, Mr means the resilient modulus in MPa, C denotes the percentage of cement, and F.B represents the percentage of foamed bitumen.

$$\mathrm{P} = 836 + 879 + \mathrm{C} + 334 \times \mathrm{F.B} - 219 \times \mathrm{C}^2 - 86 \times \mathrm{F.B}^2 \quad (4)$$

$$\mathrm{ITS - DRY} = -\frac{111}{2} + 104 \times \mathrm{C} + \frac{277}{84} \times \mathrm{FB} - \frac{9}{94} \times \mathrm{C}^2 - 43 \times \mathrm{FB}^2 \quad (5)$$

$$\mathrm{ITS - Saturated} = -204 + 129 \times \mathrm{C} + 289 \times \mathrm{FB} - \frac{16}{6} \times \mathrm{C}^2 - \frac{46}{4} \times \mathrm{FB}^2 \quad (6)$$

$$\mathrm{MR} = -707 - 163 \times \mathrm{C} + 1204 \times \mathrm{F.B} - 490 \times \mathrm{C}^2 - 271 \times \mathrm{F.B}^2 \quad (7)$$

Table 7. Analysis of the variance of the compressive strength model. Source: own elaboration.

Model	Sum of squares	Degrees of freedom	Average of squares	Test statistics	Significance level
Regression	7218068	5	1443613	11188	0.00
Residual	25806	20	1290		
Total sum	722064	25			

Table 8. Analysis of the variance of the indirect dry tensile strength model. Source: own elaboration.

Model	Sum of squares	Degrees of freedom	Average of squares	Test statistics	Significance level
Regression	3132193	5	626439	343	0.00
Residual	2885	20	144		
Total sum	3135078	25			

Table 9. Analysis of the variance of the indirect saturated tensile strength model. Source: own elaboration.

Model	Sum of squares	Degrees of freedom	Average of squares	Test statistics	Significance level
Regression	2079721	5	415944	770	0.00
Residual	10803	20	540		
Total sum	2090523	25			

Table 10. Analysis of the variance of the resilient modulus model. Source: own elaboration.

Model	Sum of squares	Degrees of freedom	Average of squares	Test statistics	Significance level
Regression	1621547	5	324309	1019	0.00
Residual	636636	20	104019		
Total sum	1627913	25			

4.5 Artificial Neural Network

Artificial Neural Networks (ANNs) simulate biological nervous systems and are versatile tools for solving complex problems that lack straightforward algorithms. Among ANN types, Multilayer Perceptron (MLP) networks are prominent, featuring feed-forward architectures ideal for supervised learning tasks. These tasks involve iterative training via algorithms such as backpropagation to adjust interlayer connection weights.

An MLP network comprises an input layer, at least one hidden layer of neurons, and an output layer. The neurons in each layer are fully interconnected through weighted connections to neurons in subsequent layers. The output Y is computed by passing the sum of the weighted inputs through an activation function f (8):

$$Y = f(\sum(x_i w_{ij} + b)) \tag{8}$$

x_i, is the activation of i^{th} hidden layer node.
w_{ij}, is the weight of the connection joining.
b, bias for the neuron.

Validation of mathematical models often employs ANN alongside methods such as fuzzy logic and genetic algorithms. ANN is widely utilized in research to predict dependent variables. In this study, ANN was applied to predict the test results (compressive strength, dry/saturated indirect tensile strength, and resilient modulus) based on cement and bitumen.

MATLAB 2019 [26] facilitated the analysis using ANN. The network required input data (bitumen and cement) and output values (targets), with 70 % for training, 15 % for validation, and 15 % for testing. To optimize accuracy, various hidden layer configurations (3 to 10 neurons per layer) were tested, selecting the most suitable configuration through iterative adjustments. The MLP method was employed with the Levenberg-Marquardt training algorithm, as depicted in Figure 8.

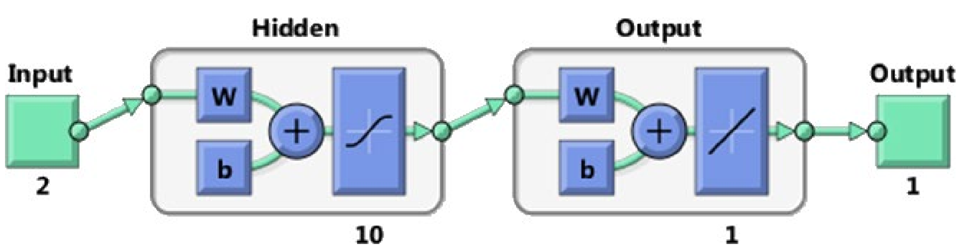

Figure 8. Neural Network Structure (MLP). Source: own elaboration.

Figure 8 illustrates the network architecture used in this study, comprising an input layer with two neurons representing percentages of cement and bitumen, respectively. The output layer consists of one neuron responsible for predicting the output values for each experiment. Between the input and output layers, a hidden layer with varying numbers of neurons was employed. Initially, the analysis began with 3 neurons in the hidden layer, gradually increasing to 10 neurons. The optimal number of neurons was selected on the basis of minimizing the error relative to the actual values. Table 11 provides a summary of the results of the neural network analysis for each test, while Figures 9-12 depict the predictions of the neural network for indirect tensile strength (dry and saturated), compressive strength, and resilient modulus, alongside the actual experimental results. By comparing the results obtained from nonlinear regression and artificial neural network methods, error values relative to the actual test results were calculated for each experiment. Figure 13 illustrates the absolute sum of errors in percentage for both regression and neural network methods. The research results showed that the artificial neural network predicts the outcomes with significantly higher accuracy and its error is lower compared to the nonlinear regression method. According to Figure 13, the average error in all tests performed using the artificial neural network method is 0.5 %, while the nonlinear regression method has an average error of 1.16 %. In the artificial neural network approach, a portion of the data is allocated for training and validating the model. The developed model is optimized through repeated trials and errors, resulting in fewer errors in its predictions compared to the nonlinear regression method.

Table 11. Results of the implementation of the artificial neural network. Source: own elaboration.

Tests	Network structure	Training (R^2)	Validation (R^2)	Test (R^2)	Model Sum (R^2)
Compressive strength	2-7-1	0.998	0.995	0.996	0.992
Dry indirect tensile strength	2-6-1	0.996	0.996	0.992	0.991
Wet indirect tensile strength	2-7-1	1.000	0.990	0.996	0.996
Resilient modulus	2-7-1	0.999	1.000	0.993	0.996

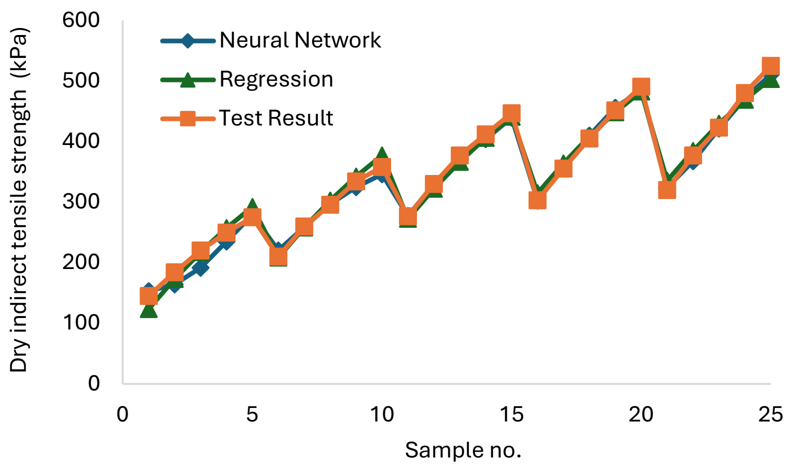

Figure 9. Comparison of the regression method and the artificial neural network with real results to predict dry indirect tensile strengths. Source: own elaboration.

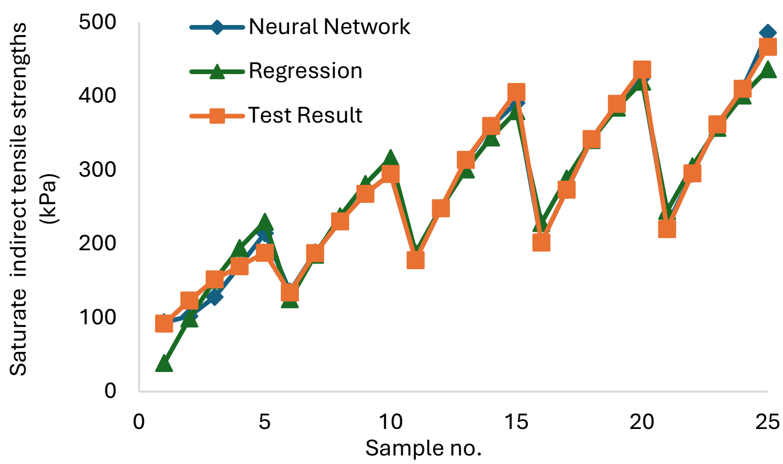

Figure 10. Comparison of the regression method and the artificial neural network to predict saturated indirect tensile strength values. Source: own elaboration.

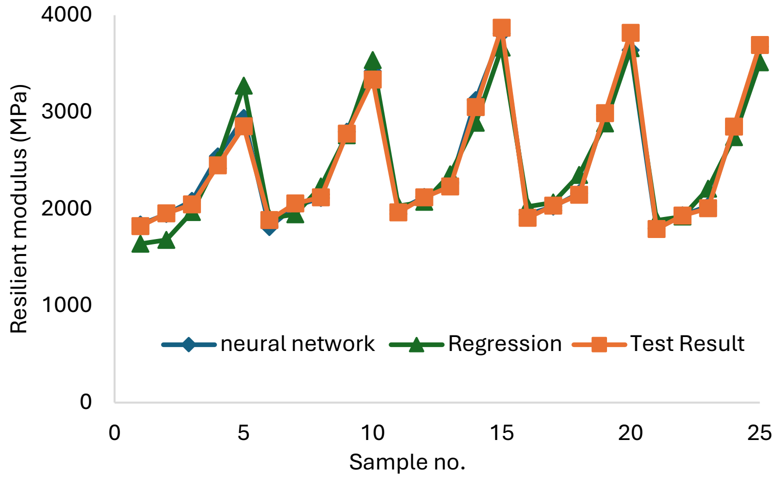

Figure 11. Comparison of the regression method and the artificial neural network to predict resilient modulus values. Source: own elaboration.

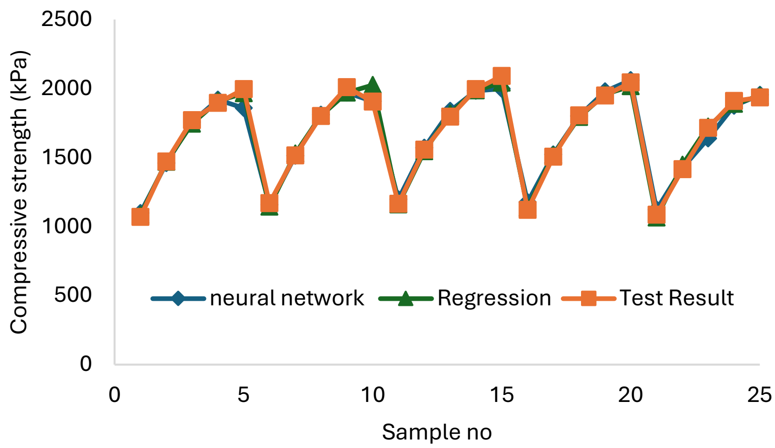

Figure 12. Comparison of the regression method and the artificial neural network to predict compressive strengths. Source: own elaboration.

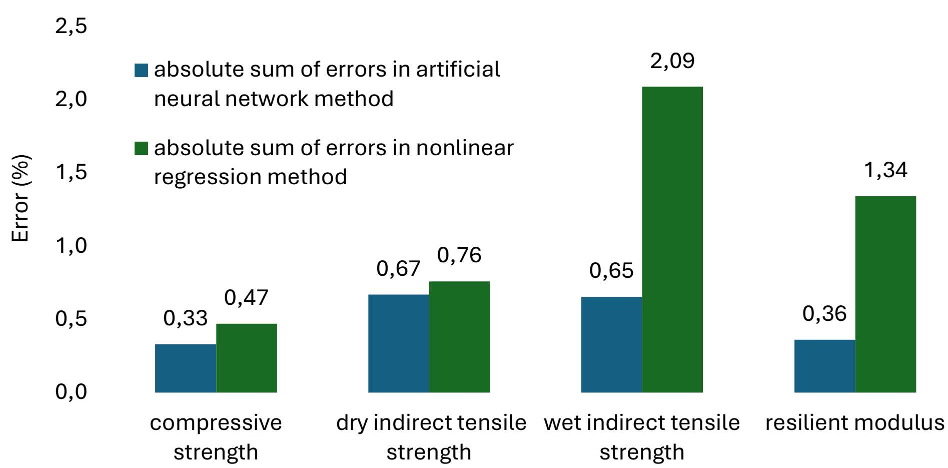

Figure 13. Comparison of the error rates in the regression method and ANN for each experiment. Source: own elaboration.

4.6 TOPSIS

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a method for multi-criteria decision analysis. In this approach, multiple alternatives are evaluated against a set of criteria to determine their ranking. The technique operates on the principle that the most suitable alternative should be closest to the ideal positive solution (best alternative) and farthest from the ideal negative solution (worst alternative) according to the criteria. In TOPSIS, m alternatives are evaluated through n criteria, forming a matrix where each row represents an alternative and each column represents a criterion in (9).

$$\begin{bmatrix} r_{11} & \cdots & r_{j1} \\ \vdots & & \vdots \\ r_{i1} & \cdots & r_{ij} \end{bmatrix} \tag{9}$$

The matrix is then normalized using the normalization method (10).

$$n_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^2}} \tag{10}$$

Then each criterion must be assigned a weight, forming the WWW vector. These weights can be chosen directly by the decision maker so that each weight falls between zero and one, and the sum of all weights equals one (11).

$$W = \{w_1, w_2, \dots, w_n\} \tag{11}$$

Then the normalized matrix is multiplied by the diagonal matrix of the criteria weights, resulting in the balanced normalized matrix (12).

$$V = N_D \times W_{n\times n} \tag{12}$$

To determine the positive ideal alternatives (A+), the best value is selected in each column of the normalized balanced matrix. Subsequently, the distance of each alternative from the positive and negative ideals is calculated. Then, according to (13), the best alternative is chosen based on its maximum distance from the negative ideal.

$$CL = \frac{d_i^-}{d_i^+ + d_i^-} \tag{13}$$

Where:
d_i^+ is the distance of alternative i from the positive ideal alternative.
d_i^- is the distance of alternative i from the negative ideal alternative.

The CL value ranges from zero to one, where a value closer to one indicates closer proximity to the ideal solution, thus representing a better solution. According to the findings of this study, the behavior of the foamed bitumen mixtures varied significantly in experiments involving bitumen and cement. Therefore, TOPSIS was employed to identify the most suitable design for determining the optimal proportions of bitumen and cement (i.e., the best mixture).

In this study, various alternatives to bitumen and cement mixtures (5 alternatives to cement and 5 alternatives to bitumen, totaling 25 alternatives) were evaluated according to criteria such as uniaxial compressive strength (P), dry indirect tensile strength (ITS), TSR ratio, and resilient modulus (Mr). Higher values of uniaxial compressive strength, TSR ratio, indirect tensile strength, and resilient modulus were considered favorable in bitumen mix designs. Therefore, all criteria were assumed to be incremental, with the same weighting for quantitative criteria, according to (14).

$$W_{n\times n} = \begin{bmatrix} P & ITS & TSR & Mr \\ 0/2 & 0 & 0 & 0 \\ 0 & 0/2 & 0 & 0 \\ 0 & 0 & 0/2 & 0 \\ 0 & 0 & 0 & 0/2 \end{bmatrix} \quad (14)$$

After completion of the analysis, the findings summarized in Table 12 and Figure 14 were obtained. Since the analysis prioritizes the longest distance from the negative ideal alternative, the alternative with the highest value is selected as the best choice. Therefore, according to TOPSIS, the top three alternatives are:

1: 2.0 % cement and 3.0 % foamed bitumen.
2: 2.0 % cement and 2.5 % foamed bitumen.
3: 2.0 % cement and 2.0 % foamed bitumen.

Table 12. Ranking of alternatives. Source: own elaboration.

Alternative no.	Cement (%)	Foamed bitumen(%)	Score of each alternative
1	0.0	1.0	0.016095
2	0.5	1.0	0.175101
3	1.0	1.0	0.287697
4	1.5	1.0	0.390599
5	2.0	1.0	0.476018
6	0.0	1.5	0.126446
7	0.5	1.5	0.288708
8	1.0	1.5	0.396258
9	1.5	1.5	0.55235
10	2.0	1.5	0.662111
11	0.0	2.0	0.242062
12	0.5	2.0	0.395284
13	1.0	2.0	0.519099
14	1.5	2.0	0.706000
15	2.0	2.0	0.861079
16	0.0	2.5	0.278985
17	0.5	2.5	0.419097
18	1.0	2.5	0.538284
19	1.5	2.5	0.738566
20	2.0	2.5	0.933936
21	0.0	3.0	0.294418
22	0.5	3.0	0.428982
23	1.0	3.0	0.530748
24	1.5	3.0	0.728142
25	2.0	3.0	0.936927

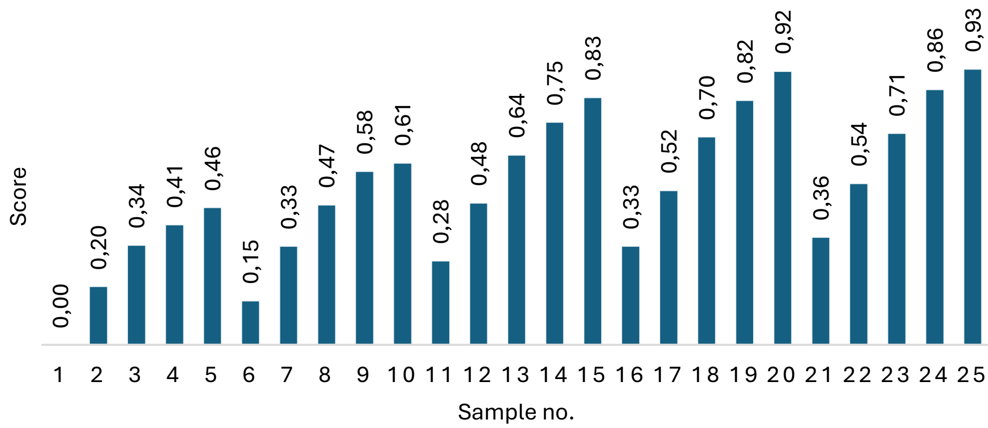

Figure 14. Ranking of alternatives. Source: own elaboration.

The findings of this study are consistent with previous research on the mechanical properties of asphalt and asphalt mixtures. For instance, [17] demonstrated that adding cement and lime fillers to foamed asphalt mixtures significantly increased indirect tensile strength, compressive strength, and Marshall strength ratio. Similarly, our study found that the addition of cement filler enhanced the compressive strength, indirect tensile strength, and resilient modulus of foamed asphalt mixtures.

Furthermore, [5] investigated the influence of cement on the strength and microcosmic properties of cold recycled mixtures using foamed asphalt (CRMF). They found that cement significantly improved indirect tensile strength (ITS) and resistance to moisture damage. The addition of cement also changed the distribution of the microstructure and air voids, as shown by SEM and CT tests. The results of the simple triaxial test (STT) showed increased internal friction, while the repeated loading deformation strength test (RLDST) indicated an improved resistance to permanent deformation. The X-ray CT test revealed changes in the distribution of the air voids after freeze-thaw processes. In our study, we also observed that the addition of cement filler significantly improved indirect tensile strength (ITS) and resistance to moisture damage in foamed asphalt mixtures. The distribution of microstructure and air voids were affected by the addition of cement, as observed in our tests. The resilient modulus and compressive strength were improved, but the flexibility of the mixture was reduced, in accordance with the findings of [5].

Comparison with previous studies validates the effectiveness of using cement fillers in foamed asphalt mixtures to improve mechanical properties and reduce susceptibility to moisture.

5. CONCLUSIONS

In this study, recycled samples using foamed bitumen were prepared and subjected to compressive strength, resilient modulus, saturated and dry indirect tensile strength tests. Regression and artificial neural network methods were employed to predict the mechanical properties of foamed bitumen mixtures. Based on the results obtained from the foamed asphalt reclaimed materials tests in this study, the following conclusions are drawn.

Compressive Strength: The compressive strength increased as the bitumen content increased from 1 % to 2 % in all designs. However, it decreased as the bitumen content increased from 2 % to 3 %. The cement filler significantly improved the strength of the samples. In samples with 2 % bitumen, the addition of cement (1 % and 2 %) increased the compressive strength by 56 % and 77 %, respectively, compared to samples without fillers.

Indirect Tensile Strength: The addition of cement and foamed bitumen to bitumen mixtures increased the dry and saturated indirect tensile strength. Cement had a more pronounced effect in increasing the tensile strength compared to bitumen. Increasing the cement from 1 % to 2 % increased the strength in dry and saturated conditions by an average of 21 % and 28 %, respectively. The study also revealed that a higher cement and bitumen content reduced moisture susceptibility to foamed bitumen mixtures. In particular, at 1 % bitumen, cement did not significantly increase the TSR ratio; however, at 2 % and 3 % bitumen, increasing cement showed nearly proportional increases in the TSR ratio.

Resilient Modulus: Incorporating cement into foamed bitumen samples increased resilient modulus. Increasing cement from 1 % to 2 % resulted in an average 50 % increase in modulus. Moreover, increasing cement from 0 % to 2 % increased the resilient modulus by 40 % in 1 % bitumen, 73 % in 2 % bitumen, and 83 % in 3 % bitumen. Thus, the effect of cement on the resilient modulus became more significant with a higher bitumen content.

Prediction Methods: Both regression and ANN methods effectively predicted the results of bitumen mix experiments with cement fillers with acceptable accuracy and minimal cost. However, after evaluating the error rates of each method, ANN demonstrated superior accuracy in predicting results compared to regression.

TOPSIS Method: The TOPSIS method applied in this study prioritized criteria including compressive strength, indirect dry tensile strength, TSR ratio, and resilient modulus. In this article, the TOPSIS method was used to select samples made with different percentages of cement and amounts of bitumen as the investigated options, with mechanical tests considered as criteria. Since higher values of the test results indicate increased favorability, the samples were ranked accordingly. Designs with higher test results in these criteria were ranked higher. Overall, this method identified the mixture with 2 % cement and 3 % bitumen as the best design among the options considered.

These conclusions provide valuable information on the optimization of foamed bitumen mixtures with cement fillers, highlighting the benefits of incorporating cement to improve mechanical properties and the efficacy of predictive modeling using the ANN and TOPSIS methods. In future research, different fillers will be used to enhance the mechanical properties of the mixture, and the ranking of the samples will be conducted using alternative methods.

6. ACKNOWLEDGEMENTS

The authors acknowledge the support of PNU University. This work was conducted with assistance from the Civil Engineering program unit at PNU. Funding for this study was provided by the authors. The authors also express gratitude to the Ministry of Roads and Urban Planning, Deputy of Education, for sharing valuable information on foamed asphalt.

7. REFERENCES

[1] K. Kuna, G. Airey, and N. Thom, "Mix Design Considerations of Foamed Bitumen Mixture with Reclaimed Asphalt Pavement Material," *Int. J. Pavement Eng.,* vol. 18, no. 10, pp. 902-915, Jan. 2016. https://doi.org/10.1080/10298436.2015.1126271

[2] B. Marquis, D. Peabody, R. Mallick, and R. Soucie, "Determination of Structural Layer Coefficient for Roadway Recycling Using Foamed Asphalt," Recycled Materials Resource Center, Instituto Politécnico de Worcester, Final Report, 2003. https://rmrc.wisc.edu/wp-content/uploads/2012/10/p26final.pdf

[3] G. Martinez-Argulles, F. Giustozzi, M. Crispino, and G. W. Flintsch, "Investigating physical and rheological properties of foamed bitumen," *Construction and Building Materials,* vol. 72, pp. 423-433, Dec. 2014. https://doi.org/10.1016/j.conbuildmat.2014.09.024

[4] H. Gui-Ping, and W. Wing-Gun, "Laboratory study on permanent deformation of foamed asphalt mix incorporating reclaimed asphalt pavement materials," *Construction and Building Materials,*

vol. 21, no. 8, pp. 1809-1819, Aug. 2007. https://doi.org/10.1016/j.conbuildmat.2006.05.024

[5] Z. Li, P. Hao, H. Liu, and J. Xu, "Effect of cement on the strength and microcosmic characteristics of cold recycled mixtures using foamed asphalt," *J. Clean. Prod.*, vol. 230, pp. 956–965, Sep. 2019. https://doi.org/10.1016/j.jclepro.2019.05.156

[6] F. V. Guatimosim, K. L. Vascocelos, L. Liedi, and J. Kim, "Laboratory and field evaluation of cold recycling mixture with foamed asphalt," *Road Materials and Pavement Design,* vol. 19, no. 2, pp. 385-399, Dec. 2016. https://doi.org/10.1080/14680629.2016.1261726

[7] K. J. Jenkins, and D. C. Collings, "Mix design of bitumen-stabilised materials-South Africa and abroad," *Road Mater. Pavement,* vol. 18, no. 2, pp. 331-349, Aug. 2016. https://doi.org/10.1080/14680629.2016.1213511

[8] H. Gui-Ping, and W. Wing-Gun, "Effects of moisture on strength and permanent deformation of foamed asphalt mix incorporating RAP materials," *Construction and Building Materials,* vol. 22, no. 1, pp. 30-40, Jan. 2008. https://doi.org/10.1016/j.conbuildmat.2006.06.033

[9] B. Şimşek, and T. Uygunoğlu, "Multi-response optimization of polymer blended concrete: A TOPSIS based Taguchi application," *Constr. Build. Mater.*, vol. 117, pp. 251–262, Aug. 2016. https://doi.org/10.1016/j.conbuildmat.2016.05.027

[10] Y. Kim, and H. "david" Lee, "Development of mix design procedure for cold in-place recycling with foamed asphalt," *J. Mater. Civ. Eng.*, vol. 18, no. 1, pp. 116–124, Feb. 2006. https://doi.org/10.1061/(ASCE)0899-1561(2006)18:1(116)

[11] M. F. Saleh, "Effect of aggregate gradation, mineral fillers, bitumen grade, and source on mechanical properties of foamed bitumen–stabilized mixes," *Transp. Res. Rec.*, vol. 1952, no. 1, pp. 90–100, Jan. 2006. https://doi.org/10.1177/0361198106195200110

[12] A. Saleh, and L. Gáspár, "Advantages and limitations of using foamed bitumen," *Acta Tech. Jaurinensis*, vol. 14, no. 3, pp. 300–314, Mar. 2021. https://doi.org/10.14513/actatechjaur.00587

[13] P. Fu, D. Jones, J. T. Harvey, and S. A. Bukhari, "Laboratory test methods for foamed asphalt mix resilient modulus," *Road Mater. Pavement Des.*, vol. 10, no. 1, pp. 188–212, Sep. 2011. https://doi.org/10.1080/14680629.2009.9690187

[14] T. Ma, H. Wang, Y. Zhao, X. Huang, and Y. Pi, "Strength Mechanism and Influence Factors for Cold Recycled Asphalt Mixture," *Adv. Mater. Sci. Eng.*, vol. 2015, p. 181853, Sep. 2015. https://doi.org/10.1155/2015/181853

[15] G. Narendra Goud, "Laboratory and Field Evaluation of Recycled Cold Mixes," M.S. thesis, National Institute of Technology Warangal, Warangal, India, 2006. https://acortar.link/E3QS5g

[16] J.-Z. Xu and P.-W. Hao, "Study of aggregate gradations in foamed bitumen mixes," *Road Materials and Pavement Design,* vol. 13, no. 4, pp. 660–677, Nov. 2012. https://doi.org/10.1080/14680629.2012.742627

[17] P. Fu, D. Jones, J. T. Harvey, and F. A. Halles, "Investigation of the curing mechanism of foamed asphalt mixes based on micromechanics principles," *J. Mater. Civ. Eng.*, vol. 22, no. 1, pp. 29–38, May. 2010. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000009

[18] D. E. Newcomb *et al.*, "Properties of foamed asphalt for warm mix asphalt applications," Transportation Research Board, Washington, D.C., 2015. https://doi.org/10.17226/22145

[19] A. Kavussi, and L. Hashemian, "Laboratory evaluation of moisture damage and rutting potential of WMA foam mixes," *Int. J. Pavement Eng.*, vol. 13, no. 5, pp. 415–423, Jul. 2011. https://doi.org/10.1080/10298436.2011.597859

[20] M. Iwanski, P. Buczynski, and G. Mazurek, "The use of gabbro dust in the cold recycling of asphalt paving mixes with foamed bitumen," B. Pol. Acad. Sci. Tech., vol. 64, no. 4, pp. 763-773, 2016. https://doi.org/10.1515/bpasts-2016-0085

[21] F. A. Halles, and G. Z. Thenoux, "Degree of influence of active fillers on properties of recycled mixes with foamed asphalt," *Transp. Res. Rec.*, vol. 2095, no. 1, pp. 127–135, Jan. 2009. https://doi.org/10.3141/2095-13

[22] M. Iwański, and A. Chomicz-Kowalska, "Laboratory study on mechanical parameters of foamed bitumen mixtures in the cold recycling technology," *Procedia Eng.*, vol. 57, pp. 433–442, 2013. https://doi.org/10.1016/j.proeng.2013.04.056

[23] H. Divandari, A. Modarres, S. M. Hosseini Aliabadi, and M. Rostami Enkas, "Presentation of a rutting model of asphalt mixes using indirect tensile strength and Marshall strength test results," *Transp. Infra. Eng.,* vol. 1, no. 2, pp. 41-54, Jul. 2015. https://doi.org/10.22075/JTIE.2014.163

[24] A. Ameli, S. YoussefDost, and R. Babagoli, " Characteristics of Asphalt Mixtures Made with the Foam Bitumen Technology," Transp. Res., vol. 14, no. 2, pp. 321-334, 2017. https://www.trijournal.ir/article_50995.html

[25] M. R. Keymanesh, H. Ziyari, A. Nasrollah Tabar, and N. Shahriari, "Potential Analysis of Microstructural

Parameters and Indirect Tensile Strength in Evaluation of Rutting Performance of Hot Asphalt Mixtures," *Transp. Infra. Eng.*, vol. 3, no. 1, pp. 69-82, May. 2016. https://doi.org/10.22075/JTIE.2017.1762.1167

[26] J. Little, and C. Moler. *MATLAB*. R2019B (2019). The MathWorks, Inc., Natick, Massachusetts, United States. Accessed: Apr. 25, 2024. [Online]. Available: https://la.mathworks.com/products/matlab/student.html

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHOR CONTRIBUTIONS

Mehrdad Mirshekarian: Conceptualization, Methodology, Validation, Formal Analysis, Writing - Original Draft, Project Administration, Validation.

Ali Pirhadi Tavandashti: Investigation, Software, Formal Analysis, Reviewing and Editing.