Artificial neural network prediction of geotechnical class of base layers pavements made with mixing dune sand and slag waste

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Abstract:

Artificial neural networks (ANN) are now widely used in civil engineering disciplines including geotechnical, structural, traffic, and pavement engineering. The subgrade is a crucial layer in a flexible pavement because it serves as a secondary load distribution layer, a drainage layer, and a foundation for the building of the road base. It is necessary to know the geotechnical classification of soils in order to use it as a pavement layer. The Young's modulus and tensile strength are two important parameters for soil classification; predicting these two parameters for soil reconstituted or modified soil waste management is an important task prior to a project. This article discusses the use of artificial neural networks to predict the mechanical parameters of dune sand modified by slag waste which is an industrial waste available in abundance for use in the base layer or sub-base layer.

The experimental program includes developing the basic formulation of the mixture combination and determining its important mechanical properties, such as the Immediate Bearing Index (IBI) and the California Bearing Ratio (CBR), as well as evaluating compressive strength, tensile strength, and Young's modulus at different modification contents.

The results suggest that treating dune sands with slag waste enhances their mechanical performance, which improves their classification for use in pavement layers, particularly base foundation layers. We also demonstrate that utilizing artificial neural networks (ANN) to predict the mechanical properties of dune sand treated with slag is useful for determining the classification of modified sand and its application in pavement layers.

Keywords: *Dune sand, slag waste, tensile strength, Young's modulus, artificial neural network*

1. INTRODUCTION

Utilizing dune sand in pavement construction has been extensively studied in various regions like Algeria and Tunisia. Research has shown that incorporating dune sand in pavement foundations can enhance mechanical characteristics, making it suitable for road construction projects (Borcheni et al., 2023, Smaida et al., 2022). Additionally, the addition of dune sand has been found to stabilize clayey soils, modifying their physico-chemical and mechanical properties, ultimately improving their compressibility and reducing swelling tendencies (Smaida et al., 2022). Furthermore, studies have explored the use of dune sand along with other materials like reclaimed asphalt pavement (RAP), bitumen, and lime to predict the viscoelastic behaviour of asphalt mixtures, aiming to reduce the consumption of natural resources while enhancing the rigidity of the mix at high temperatures (Ouslimane et al., 2023). These findings highlight the potential of dune sand in sustainable pavement construction practices.

Pavement construction can also benefit from utilizing slag waste as a sustainable alternative to traditional materials. Research has shown that slag-based materials, offer cost-efficiency, reduced environmental impact (Yamanaka et al., 2023, Bai et al., 2023, Abiola et al., 2021). Incorporating slag materials in asphalt concrete mixtures has been found to enhance durability and reduce construction costs for road pavements (Kovalev et al., 2021). Waste slag, in particular, presents a promising solution for addressing the scarcity of high-quality aggregates and mitigating environmental pollution, offering benefits like ant abrasion properties, angularity, and hardness for various pavement layers (Liu et al., 2022).

The combination of dune sand and waste slag has shown promising applications in civil and pavement engineering (El-Mir et al., 2022, Buitrago et al., 2020). Furthermore, the incorporation of slag waste activated by lime in dune sand mixtures has shown increased bearing capacity, compressive strength, and tensile strength, making them suitable for semi-rigid pavement layers (Omar et al., 2021, Hayet et al., 2021). These findings collectively support the viability of utilizing dune and slag waste mixtures in various civil and pavement engineering applications.

Artificial Neural Networks (ANNs) have gained significant traction in geotechnical and pavement engineering, offering solutions to complex problems. In the field of pavement engineering, ANNs are extensively utilized for pavement performance prediction, distress intensity detection, maintenance planning, and pavement condition index prediction (Kurian & Sunildutt, 2021, Yang et al., 2021, Saoudi & Haddadi, 2021). Moreover, ANNs have been successfully employed to correlate sub-base California Bearing Ratio (CBR) with primary soil data, aiding in CBR estimation and identifying key factors influencing sub-base strength (Al-Busultan et al., 2020). Therefore, using ANNs to predict the geotechnical properties of base layers consisting of mixed dune sand and waste slag could provide a reliable and efficient approach for pavement construction and management.

2. MATERIALS AND METHODS

2.1 Materials

The first basic constituent of the mixture used in this study is silica sand (dune sand DS) with a fine particle size (0/1 mm) from the Boussaâda region (Msila, Algeria). The silica content (SiO2) is 97.10%.

The second major constituent in the mixture used in this study is limestone sand (Crushed Sand CS) from the Kedara quarry (Bouira, Algeria) with a grain size of 0/6 mm; the carbonate content (CaCO3) is approximately 89%.

In this study we also used slag waste (SW) which is an industrial waste Figure 1, coming from El-Hadjar steel complex (Annaba, Algeria), obtained by rapid cooling with a particle size of 0/5 mm

Figure 1. Slag waste

The lime used in our study is slaked lime, acts as a basic activator of waste slag, produced in the Ghardaïa region, Algeria. Presents suitable characteristics for its use in roads, its CaO content is greater than 50%.

The following Table 1, summarized the principals physic characteristics of the aggregates used in this study

Material	**SW**	**DS**	**CS**	**Lime**
Density [g/cm³]	2.8	2.65	2.81	2.58
Friability (%)	19	–	40	–
Blaine specific surface (cm2/g)	2057	–	–	10165
Piston sand equivalent (%)	–	73.79	94	–
Methylene blue values	–	0.4	0.5	–
Basicity modulus	1.3	–	–	–
Fineness modulus	3.21	0.88	4.2	–
Coefficient of uniformity Cu1	3.39	1.97	14.75	–

Table 1. Physic characteristics of the used materials.

The table 2, summarized the Chemical characteristics of the used materials

Material	**SW**	**DS**	**CS**	**Lime**
CaO (%)	45.78	0.54	40.61	64.27
SiO2 (%)	34.99	97.1	5.94	2.85
CaCO3 (%)	–	3.39	89.65	–
Al2O3 (%)	9.79	0.71	8.85	0.56
MgO (%)	3.92	0.06	3.56	0.45
Fe2O3 (%)	0.67	0.39	3.25	0.27

Table 2. Chemical characteristics of the used materials.

As part of the preparation of the database we formulated five mixtures of slag sand (DS+CS+SW+lime) by varying the percentage of slag waste according to the immediate stability conditions, table 3 summarizes the percentage compositions of each mixture, and their uniformity and curvature coefficients.

Mixture	**SW (%)**	**CS(%)**	**DS(%)**	**Lime %**	**Cc**	**Cu**
1	0	20	80	1	4.8	1.7
2	10	30	60	1	6	1.7
3	20	20	60	1	6	1.2
4	25	25	50	1	6.4	1.12
5	30	20	50	1	8.4	1.15

Table 3. Slag sand formulations contents and their uniformity and curvature coefficients.

The mechanical characteristics such as the optimal water content (W_{opm}), the Maximum dry density (δ_{dopm}) and the immediate bearing index (IBI) of the proposed mixtures are summarized in table 4.

Mixtures	**SW(%)**	**W_{opm} (%)**	**$\delta d_{opm}(t/m^3)$**	**IBI (%)**
1	0	6.9	1.99	43
2	10	6.2	2.07	70.47
3	20	7.54	2.12	74.6
4	25	5.4	2.13	116.47
5	30	5.5	2.16	148.5

Table 4. Mechanical characteristics of used materials

2.2 Methods

Simple compression tests play a crucial role in understanding the mechanical properties of slag sand for various applications. Compressive strength and Young's modulus are two key results from these simple compression tests.

The test is carried out on standardized test pieces manufactured in accordance with standard NF P 98- 230 -2, compacted to optimal water content and stored at a temperature of 20°C for well-defined periods.

Ninety (90) samples were manufactured, i.e. three samples for each mixture, stored and tested at 0, 7, 28, 60, 90 and 180 days.

The simple compression test on the manufactured specimens is carried out on triaxial machine with crushing speed of 1.14 mm/min, in accordance to standard NF EN 13286-41.

The test made it possible to obtain the force – deformation curves of mixtures made with different slag waste contents. Figures 2-5 that follow; we represent some results of the tests carried out.

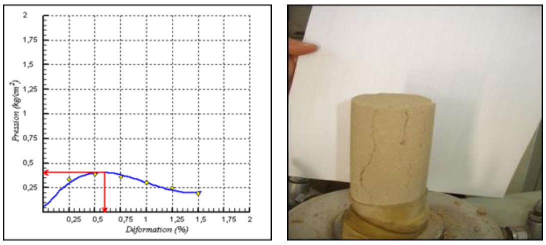

Figure 2. Immediate crushing at 0 % of SW

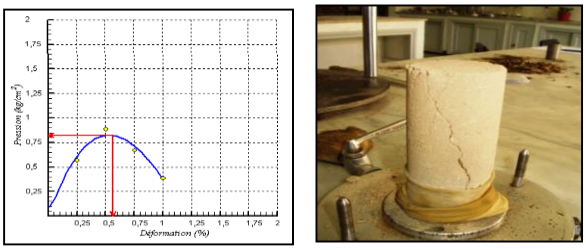

Figure 3. Immediate crushing at 10 % of SW

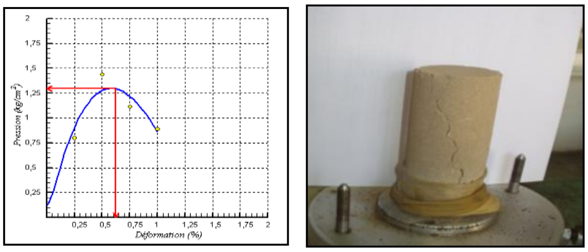

Figure 4. Immediate crushing at 20 % of SW

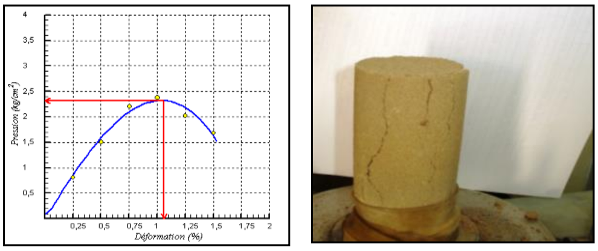

Figure 5. Immediate crushing at 30 % of SW

Another test for indirect tensile strength is performed in accordance with standard NF EN 13286-42, which provides a method for evaluating the indirect tensile strength (splitting test or Brazilian test) of cylindrical specimens of mixtures treated with hydraulic binders. The test is carried out by compressing a cylindrical specimen between the plates of the press figure 6. Bursting of the specimen is produced by traction at the center of the specimen, and the indirect tensile strength force is given by the following equation (1).

Figure 6. Indirect tensile test

$$F_t = \frac{F}{RH\pi} \qquad (1)$$

Where F_t = Indirect tensile strength
F = Force
R = radius of specimen
H = height of specimen

The direct tensile resistance is deduced by the following relationship (2):

$$R_t = 0.8\, F_t \qquad (2)$$

Where R_t = direct tensile resistance

Thirty (30) specimens manufactured for all the mixtures, i.e. three specimens for each mixture, crushed respectively at 90 and 180 days.

Evaluation of the tensile strength and the Young's modulus corresponding at 360 days is carried out according to the NF P 98-114-2 standard which provides equations for estimating tensile strength and Young's modulus from experimental measured values at 90 days.

$$R_{t360j} = \frac{R_{t90j}}{0.70} \qquad (3)$$

$$E_{360j} = \frac{E_{90j}}{0.75} \qquad (4)$$

Where R_{t360j}=tensile strength resistance at 360 days

R_{t90j}= tensile strength resistance at 90 days
E_{360j}= Young's modulus at 360 days
E_{90j}= Young's modulus at 90 days

All the results measured in this experimental work on all the crushed specimens will serve as a database for the proposed neural network, the following table 5, summarizes the variation of the different parameters measured and used as input and output of the artificial neural network.

	Properties of specimens	**Data**
Input data	**SW contents %**	0, 10, 20, 25 and 30%
	Times (days)	0, 7, 28, 60, 90 and 180 day
	Compression stress (Mpa)	Min 0.37, Max 20.86
	optimum water contents %	Min 5.4%, Max 7.54%
	Maximum dry density (g/cm^3)	Min 1.99, Max 2.16
	IBI %	Min 43, Max 148.5
Target	**tensile stress (Mpa)**	Min 1.02, Max 5.34
	Young modulus (Mpa)	Min 80, Max 4600

Table 5. Properties of the test specimens.

2.3 ANN architecture

When selecting an artificial neural network (ANN) architecture and propagation algorithm, it is crucial to consider the specific application requirements. Different ANN architectures and propagation algorithms have varying strengths and weaknesses. For example, the Back Propagation (BP) algorithm is commonly used for supervised learning in multi-layer feed-forward networks (Haykin, 2009). The selection of an ANN architecture and propagation algorithm should be based on the specific requirements of the task at hand, taking into account factors such as convergence speed, accuracy and efficiency (Kazarian et al., 2021) (Botelho & Akamine, 2018).

To determine the optimal number of neurons in the hidden layer of a neural network, various techniques and methods have been proposed in the literature. These include the incremental cell contribution method to select the optimal number of hidden units based on network size reduction and graphical analysis (Kazarian et al., 2021). In our study, the method of optimal structure of hidden layers involves comparing different structures based on error calculation to find the most efficient architecture was used (Saoudi & Haddadi, 2021).

The following Figure 7, shows the variation of the training MSE of the network and the number of neurons in the hidden layer. According to this method we chose, the neural network with the lowest MSE is composed of eight neurons in the hidden layer.

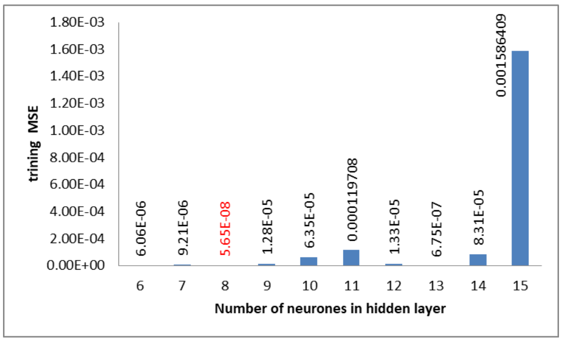

Figure 7, variation of MSE according to number of neurones in hidden layer

The final architecture of the network used in this study is composed of three layers, an input layer with six parameters, a hidden layer with eight neurons and a tangent hyperbolic sigmoid activation function; two output layer parameters and linear activation function were used.
The performance of the model is measured by the mean square error function (MSE), done on equation (5), and correlation values “R”, done on equation (6).

$$MSE = \frac{1}{N}\sum_{k=1}^{n}(Y_k - \bar{Y}_k)^2 \qquad (5)$$

$$R = \frac{\sum_{k=1}^{n}(Y_k - \bar{Y}_k)(Y_k^* - \bar{Y}_k^*)^2}{\sqrt{\sum_{k=1}^{n}(Y_k - \bar{Y}_k)^2 \sum_{k=1}^{n}(Y_k^* - \bar{Y}_k^*)^2}} \qquad (6)$$

Where Y_k is the desired value;
Y_k^* is the estimated value;
N is the number of neurons in the output layer;
n is the number of vectors presented to the network;
$\bar{Y}_k = \frac{1}{n}\sum_{k=1}^{n} Y_k$
$\bar{Y}_k^* = \frac{1}{n}\sum_{k=1}^{n} Y_k^*$

R, value equal or close to 1; implies a precise relationship, R value equal or close to 0 implies a random relationship. The superb performance of the model it has been ensured by the higher R value and lower MSE value.

Among the 90 database carried out, we retained five data to later examine of selected ANN. The 85 data were used in the three phases of development of the ANN and randomly divided into three parts: training (70%), testing (15%) and validation (15%). A training dataset was used to train the ANN model. The validation dataset was used to stop the training process, and the test dataset was used to evaluate the performance of the ANN model, after the training process was completed.

Each dataset consists of input vectors and the corresponding target. First, the data will be normalized between 0 and +1. Before submitting them to the ANN, they must agree with the limits of the activation transfer function used in the hidden layers and the output layer.
The proposed model was trained, tested and validated set using the back-propagation algorithm. The implementation and simulation were carried out using MATLAB software.

3. RESULTS AND DISCUTIONS

3.1 Experimental results

In accordance with the experimental work carried out, we can conclude that the progressive incorporation of slag waste results in a modification and increase in the characteristics of dune sand such as dry density and immediate Bering index thus increasing the mechanical compressive, tensile strength of the mixture over time.
The following figure 8-9, show evolution of dry density and IBI with SW contents.

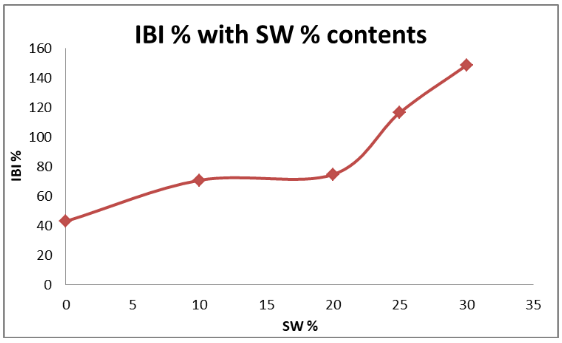

Figure 8. Evolution of IBI % accordance to SW contents

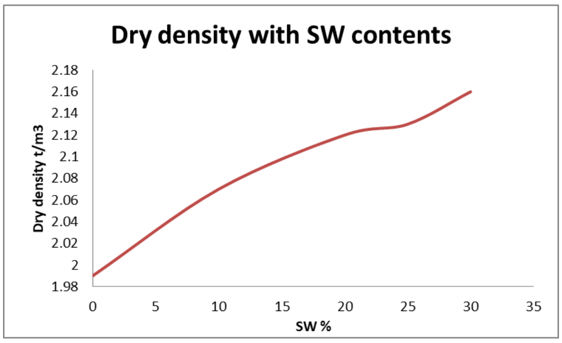

Figure 9. Evolution of dry density with SW contents

In both Figures 10 and 11, we notice that the compressive strength and Young's modulus increase considerably as function of slag waste contents.

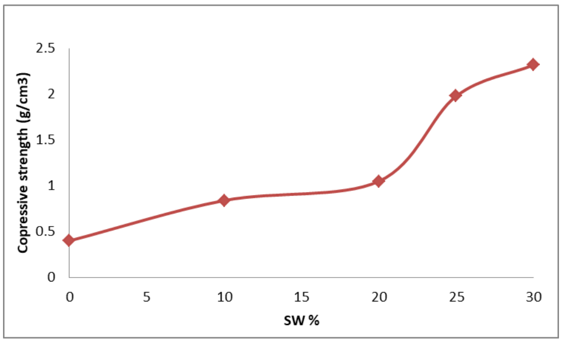

Figure 10. Evolution of compressive strength according to SW contents at 0 day

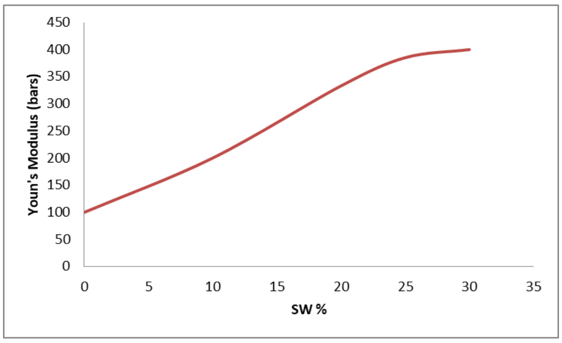

Figure 11. Evolution of Young's modulus according to SW contents at 0 day

The main objective of this study is the prediction according to standard NFP 98-114-2, of the geotechnical class of a mixture consisting of dune sand; quarry sand, the lime and slag waste, using ANN.

Two essential parameters used in the classification of sands according to standard NFP 98-114-2, which are tensile strength and Young's modulus at 360 days.

The first step in this study consists of predicting the Young's modulus and the tensile strength at 90 days according to the inputs parameters which are the compressive stress, slag waste contents %, IBI%, the time in days, water content% and the dry density, then Young's modulus and tensile strength at 360 days are estimated according to NF P 98-114-2 standard.

The correlation between the Young's modulus and tensile strength predicted values and experimentally measured values are represented in figure 12.

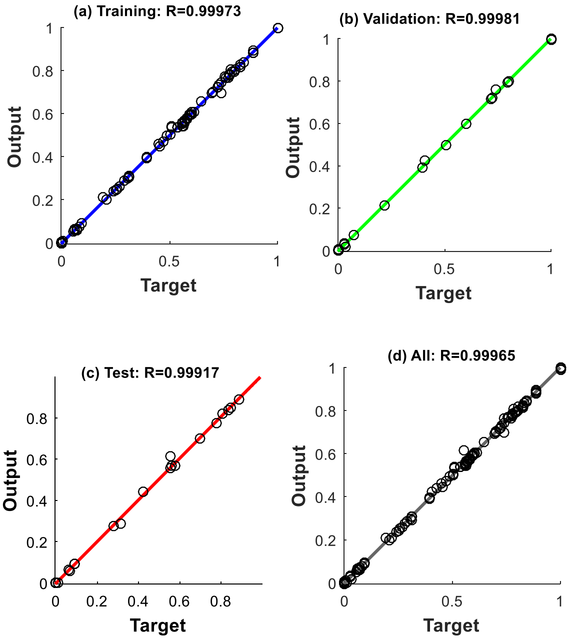

Figure 12. Relationship between the Real and ANN predicted values for (a) training data, (b) validation data, (c) testing data, and (d) all data.

It can be observed that the predicted values are very close to the experimental values, the correlation coefficient R values during training, validation and testing of the dataset are 0.99973; 0.99981; 0.99917 and 0.99965, respectively. This result implies that, the developed model has considerable accuracy for prediction.

The neural network was applied to predict the Young's modulus and the tensile strength of database which were previously retained. Figure 13-14 shows the correlation between the predicted and measured values of Young's modulus and tensile strength for the five proposed mixtures at 360 days,

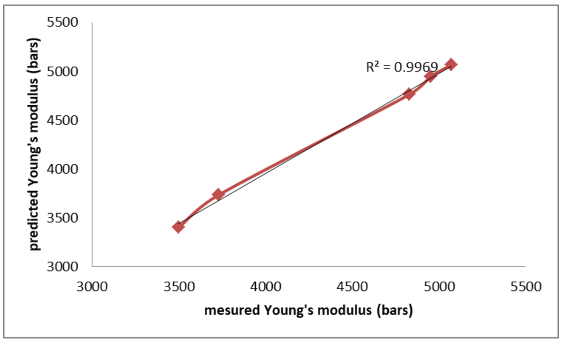

Figure 13. Correlation between predicted and measured Young’s modulus at 360 days for all the mixtures

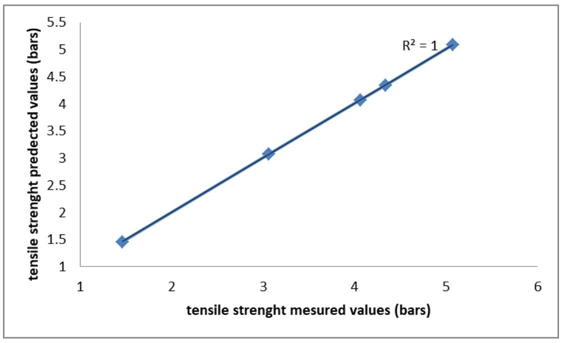

Figure 14. Correlation between predicted and measured tensile strength at 360 days for all the mixtures

We can see that the two predicted parameters, Young’s modulus and tensile strength have an excellent correlation with estimated parameters, the correlation coefficient R equal to 1 for tensile strength and to 0.999 for Young's modulus, we can use this two predicted parameters for classified the mixtures that we have proposed. The following figure 14 shows the classification of sand mixtures according to the NF P 98-114-2 standard; we can clearly see that the class of dune sand is significantly improved from S0 to S2 depending on the slag waste content.

Table 6 summarizes the mechanical characteristics Young's modulus and tensile strength at 306 days of the proposed sand mixtures predicted with proposed ANN.

Mixtures	**SW% contents**	**$E_{360days}$ (bars)**	**$\sigma_{t360days}$ (bars)**
1	0%	3500	1.459
2	10%	3729.60	3.061
3	20%	4828.58	4.071
4	25%	4952.95	4.071
5	30%	5073.79	5.073

Table 6. Mechanical characteristics of all the mixtures at 360 days

In order to use natural soil or reconstituted soil based on sand mixtures in the pavements layers, the soil must be classified according to the standards. The following figure 15 shows the graphical classification of the different sand mixtures previously proposed.

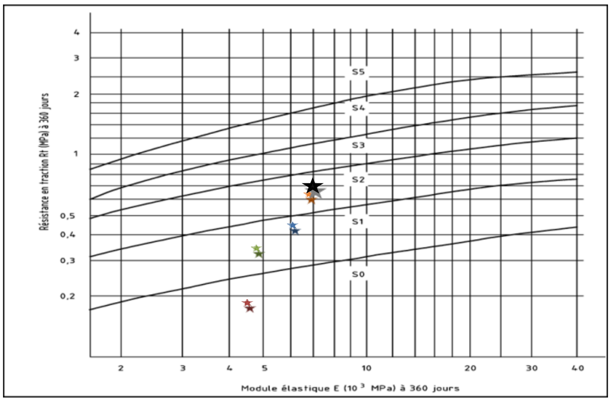

Figure 15. Graphical Sand mixtures classification according to SW contents: ★0% , ★10%,★ 20%, ★25% and ★ 30%

4. CONCLUSION

Our work aims to predict with an artificial neural network two essential parameters for classifying a sand mixture composed primarily of dune sand and slag waste according to the NF P 98-114-2 standard for possible use as a base layer for flexible pavements. The two essential parameters are Young's modulus and tensile strength at 360 days.

An experimental study was designed to characterize all the different components of the mixture and build a database that would be used to train the neural network. The following conclusions should be reached:

- The incorporation of slag waste improves the mechanical resistance of dune sand over time.
- Waste slag's chemical role in improving the microstructure of the mixture, similar to that of cement, is responsible for the remarkable mechanical performance.

Sand treated with varying amounts of slag waste has higher mechanical resistances in simple compression and traction than untreated sand.

In three steps to construct the ANN, the correlation coefficient R is greater than 0.999, indicating that the proposed ANN model has a better ability to predict Young's modulus and tensile strength in a short period of time with low error. It indicated a good match between predicted and experimental values.

The neural network was used to another database to estimate Young's modulus and tensile strength at 360 days, according to the NF P 98-114-2 standard, and the results were extremely good.

The findings of this study allow us to conclude that dune sand, classified (S0) according to the NF P 98-114-2 standard, can be improved by the addition of slag waste, resulting in high resistance and reclassification of the mixture to higher classes S1 and S2 according to NF P 98-114-2 standard, implying that the mixture can be used in the base layer of pavements.

The ANN proposed in this paper is extremely useful for designing future project studies because it allows for the estimation of the tensile strength and Young's modulus of a sand mixture over time, implying a primary decision on the composition of the mixture required to achieve these mechanical characteristics.

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