Predicting Marshall stability and flow of bituminous mix containing waste fillers by the adaptive neuro-fuzzy inference system

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Abstract
The practice of using different non-biddable wastes in place of conventional filler is successively extended nowadays, leading it hard to predict the properties of modified bituminous mixes. The present work aims to explore the effect of using rice husk ash (RHA) and fly ash (FA) as an alternative filler in place of conventional filler like hydrated lime (HL) on Marshall stability and flow of bituminous mix by adaptive neuro-fuzzy inference system (ANFIS). This study involves the preparation of samples having seven different bitumen content varying from 3.5% to 6.5% with a 0.5% increment. Mixtures containing 2%, 4%, 6%, and 8% of HL, RHA, and FA separately as filler were fabricated and compared with the control mix (i.e. mix containing 2% hydrated lime as filler). Further, the Marshall mix design procedure was followed to determine the optimum bitumen content (OBC) of each mix. Experimental results showed that the replacement of conventional filler with RHA and FA improved the Marshall properties and decreased the OBC values of the modified mix when added with 4% filler ratio Further, to analyze parameters that are the most influential in the prediction of Marshall stability and flow, a sensitivity analysis using ANFIS network was carried out considering all the input variables. As per the results obtained, the filler types, percentage filler, and percentage bitumen have the most effect on modeling the Marshall stability and flow. Then by utilizing the selected input parameters, the Marshall stability and flow were modeled with Sugeno type ANFIS. In comparison, it is realized that predicted values are closely relevant to the actual one and the prediction ability of the ANFIS is suitable for getting the said values by avoiding the expensive, time consuming, and repetitive laboratory tests.

Keywords: Rice Husk Ash, Fly Ash, Marshall mix design, ANFIS, Sensitivity analysis.

Introduction

The bituminous mix or hot mix asphalt (HMA) is complex heterogeneous materials widely used in wearing the course of flexible pavement and primarily composed of graded aggregate, asphalt mastic (including asphalt binder, fine aggregate, and filler) with void space. The performance of such a mix depends on several factors like mix design, various properties of individual mix components, and quality control during construction. Although the filler particles are small in size (finer than 75 micrometre) (Ministry of Road Transport and Highways [MORT&H], 2013), it is well recognized that filler reveals a considerable impact on the characteristics and performance of bituminous mix (Roberts et al., 1996). Therefore, the choice of suitable filler in optimum proportion is very crucial for the ideal performance of the bituminous mix.

Various types of fillers e.g. crushed stone, cement, and lime have been used conventionally in the HMA from long ago (MORT&H, 2013). The ever-thriving concern of the society to safeguard the environment resulted in concentrated devotion on the possible re-use of waste as filler in the bituminous mix. These materials include recycled fine aggregate powder (Chen et al., 2011), glass powder (Tremblay et al., 2015), sewage sludge ash (Al-sayed et al., 1995), marble dust (Chandra et al., 2002), red mud (Choudhury et al., 2018), etc. which have been used in addition to or in place of conventional filler in the preparation of HMA. Among the range of alternative fillers, different types of ash from industry gets added value due to its potential environmental contamination. Fly ash (FA) from a thermal power plant and rice husk ash (RHA) from rice mill both are produced directly during the combustion of solid biomass in combustor facilities. It is estimated that every year India produces 184 million tons of FA (CEA, 2015) and 5.58 million tons of RHA (Mistry & Roy, 2015) respectively. FA as filler in the bituminous mix has been investigated by researchers for years (Chandra & Choudhary, 2013). On the other hand, some recent attempts have made to study the feasibility of using RHA in the bituminous mix (Mistry et al., 2018).

Many research works indicated that the use of non-conventional materials for paving applications required more futuristic approaches especially for the material mix design process (Tapkin, 2008). Among the various methods of bituminous mix design, Marshall mix-design is commonly used in India (MORT&H, 2013). The main purpose of such design is to find out the optimum bitumen content (OBC) for a particular aggregate blend by satisfying the standard criterion. However, selections of OBC sometimes become laborious, time-consuming as well as costly due to the repetition of tests required for archiving the correct results (Tapkin et al., 2010). On the other hand, Marshall stability and flow are the important mix design criteria that can only be measured in the laboratory (Tapkin, 2008). So, the determination of such criterion by any alternative way will help to reduce the number of trials for the design of a bituminous mix. Currently, a few numbers of investigators have made their study to predict Marshall test parameters of the bituminous mix using some soft computing techniques like artificial neural network (ANN) and fuzzy logic (FL) (Ozgan, 2009 and 2011; Tapkin et al., 2010). As per the authors' knowledge, replacement of conventional filler with RHA and FA is relatively new and the evaluation of their properties by ANFIS is rarely reported.

Consequently, based on the above-mentioned facts, it is noted that a knowledge-based predictive modeling system may provide a translucent and systematic analysis for modeling the effect of using different filler namely hydrated lime (HL), RHA and FA as mineral filler in various proportion on Marshall stability and flow of dense grade bituminous macadam (DBM) mix. The specific objectives of this study are: (1) to investigate the effect of using different percentage of HL, RHA and FA on Marshall properties of DBM mix experimentally; (2) to develop an Adaptive neuro-fuzzy inference system (ANFIS) based model that could be able to predict the Marshall stability and flow; (3) to verify the validity of the proposed predictive approach by several experimental data used as the testing set.

Experimental studies

Materials

Aggregate. Basalt type of crushed and sharp-edged aggregate was collected from the local quarry and used in this investigation. The physical properties of aggregates are detailed in Table 1. Collected coarse and fine aggregates were sieved to fit the continuous aggregate gradation of Dense Bituminous Macadam (DBM) grade-II set by Indian standard specification (MORT&H, 2013) is shown in Table 2.

Table 1. Evaluated properties of studied aggregates. Source: Self-elaboration.

Property	Values	Specified limits
Aggregate impact value	16%	max 27%
Loss Angeles abrasion value	19%	max 35%
Water absorption value	1.2%	max 2%
Specific gravity		
Coarse aggregate	2.89	2.5-3.0
Fine aggregate	2.73	
Combined Flakiness and Elongation Index	27.45%	max 35%

Table 2. Adopted gradation of the DBM grading II mix. Source: Self-elaboration.

Sieve Sizes (mm)	37.5	26.5	19	13.2	4.75	2.36	0.3	0.075
Lower-Upper Limits (%)	100	90-100	71-95	56-80	38-54	28-42	7-21	2-8
Adopted Gradation (%)	100	95	83	68	46	35	15	2,4,6,8

Bitumen. The commonly used binder in India i.e. VG 30 grade bitumen, collected from Haldia Petrochemicals, West Bengal, India was used in this investigation. Different engineering properties of the same evaluated in the laboratory as per the standard guidelines (IS 73 2013) are detailed in Table 3.

Filler. Two kinds of wastes were used as alternative fillers in this study: first, RHA gathered from a rice mill at Burdwan, a district of West Bengal, India, and second, FA from the Thermal Power Station at Kolaghat located in the district of Purba Medinipur, West Bengal, India. Traditionally used hydrated lime (HL) was incorporated to prepare control mixes for comparison of results. Table 4 exhibits the results of various physical and chemical properties of studied fillers.

Table 3. Evaluated properties of studied VG 30 bitumen. Source: Self-elaboration.

Property	Values	Specified limits
Penetration (at 25°C) (1/10th of mm)	57	45-60
Kinematic viscosity at 135°C sscSt	368	350-400
Softening Point, °C (Ring & Ball Apparatus)	49	47, min.
Ductility at 27°C (5 cm /min pull), cm	>100	40, min.
Specific Gravity	1.035	0.99, min.

Table 4. Physical properties and chemical composition of studied fillers. Source: Self-elaboration.

Fillers	Chemical compositions								Physical properties	
	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	K_2O	SO_3	LOI	SSA (m^2/kg)	SG
HL	3.24	72.41	0.41	0.32	0.46	0.13	1.22	21.69	431.2	2.15
RHA	86.68	1.84	1.66	1.06	0.97	0.42	0.12	6.11	565.3	2.00
FA	49.61	12.3	25.32	4.84	1.46	2.43	0.92	3.05	309.5	2.32

Design of DBM mixes

Marshall Method was implemented to design the DBM mix relative to various filler percentages and their type for reaching corresponding OBCs. For the preparation of DBM samples, the aggregate and fillers were preheated at 100 ± 5°C to ensure a moisture-free condition. As per the guidelines specified in MS-2 (Asphalt Institute, 1997), the temperatures to which bitumen should be heated to produce kinematic viscosities of 150-190 and 250-310 centistokes were considered as mixing and compaction temperature respectively. Based on these criteria, the mixing and compaction temperatures for all the mixes were 159 ± 2.5°C and 147 ± 2°C, respectively. Aggregates, fillers, and bitumen were thoroughly mixed at mixing temperature, and subsequently, compaction was done with manual compactor (75 blows on each side) at compaction temperature to manufacture Marshall specimen with a 100 mm diameter and 63.5 mm height. Three samples were prepared at each bitumen level, and a total of 252 samples (7 binder contents × 3 types of fillers × 4 filler contents × 3 replicates) were fabricated. Marshall stability and flow of prepared samples were determined (ASTM D6927, 2015). The increment of filler proportion in the mix adjusted by reducing the fine aggregate accordingly to satisfy the combined grading as shown in Table 2. In this study, the mix having 2% HL as the filler has been considered as the conventional mix.

Experimental Results and discussion

As mentioned earlier, the Marshall mix design method was used to determine the OBC of all the mixes. Figures 1-3 show the detail test results [unit weight, Air voids, voids in mineral aggregate (VMA), voids filled with bitumen (VFB), stability, flow and Marshall quotient corresponding to bitumen content] of bituminous mixes corresponding to studied percentages of HL, RHA, and FA as filler.

As it is known, increment in bitumen content slowly decreases the air void and all the studied fillers follow the said pattern individually. However, with increment in filler percentage, the air void in the mixture having HL continuously is increasing respective to same bitumen content for all the filler percentages as shown in Figure 1. This phenomenon may be occurred due to the presence of more fine particles of HL in the mixture pushes the coarse aggregates. As a result, the coarse aggregates suspend in the fine particles. All the alternative fillers (i.e. RHA and FA) nearly follow the same path as HL except 4% RHA, where air void values are less than that of 2% RHA corresponding to 5% and 5.5% bitumen content (Figure 2). This trend may be credited to the fact that RHA, due to its high SSA and porous structure, has a propensity to absorb bitumen binder, making the bitumen film on aggregate thicker, which efficiently reduced the air voids of the mixture (Arabani & Tahami 2017). A similar result is observed for FA at 4% and 6% for 5% bitumen content compared to 2% filler content (Figure 3). It is possible to state that the FA, also known as bitumen extender, can provide a partial replacement of bitumen (Sobolev et al., 2014), which decreases the air void of HMA.

Using the air void values given in Figures 1-3, the OBC against 4% air voids is obtained for all the mixes. In Table 5, the deviation in OBC for adding a variable amount of all the studied filler with corresponding Marshall properties is also observed.

Figure 1. Marshall properties of bituminous mixes containing studied percentages of HL. Source: Self-elaboration.

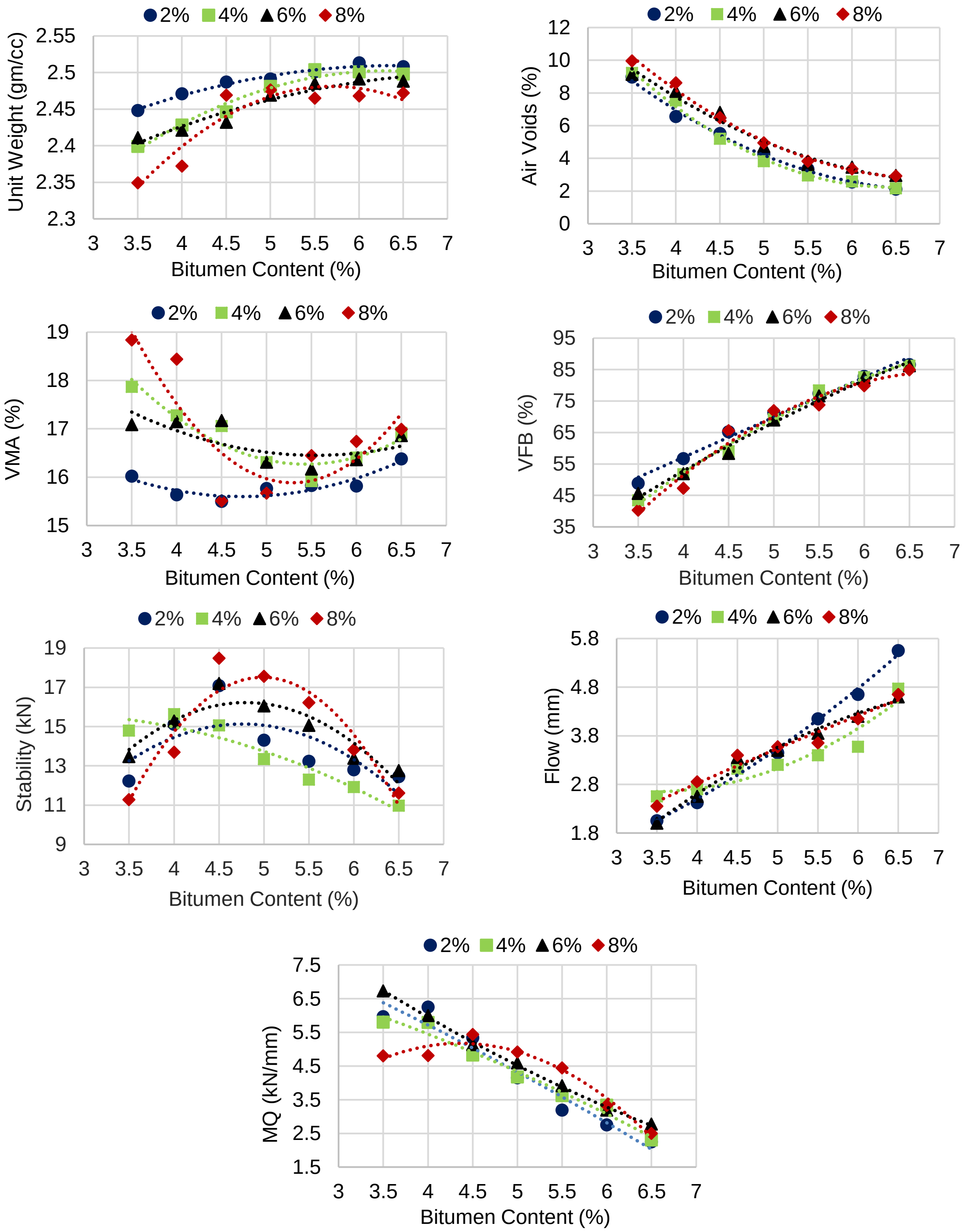
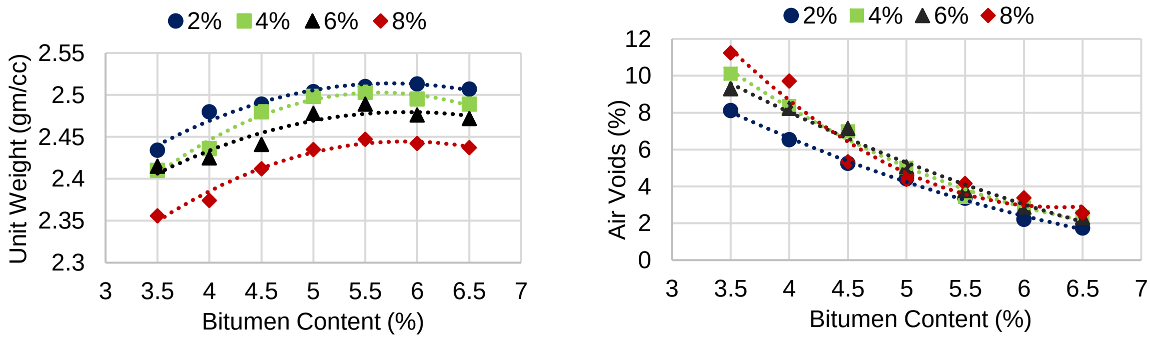


Figure 2. Marshall properties of bituminous mixes containing studied percentages of RHA. Source: Self-elaboration.



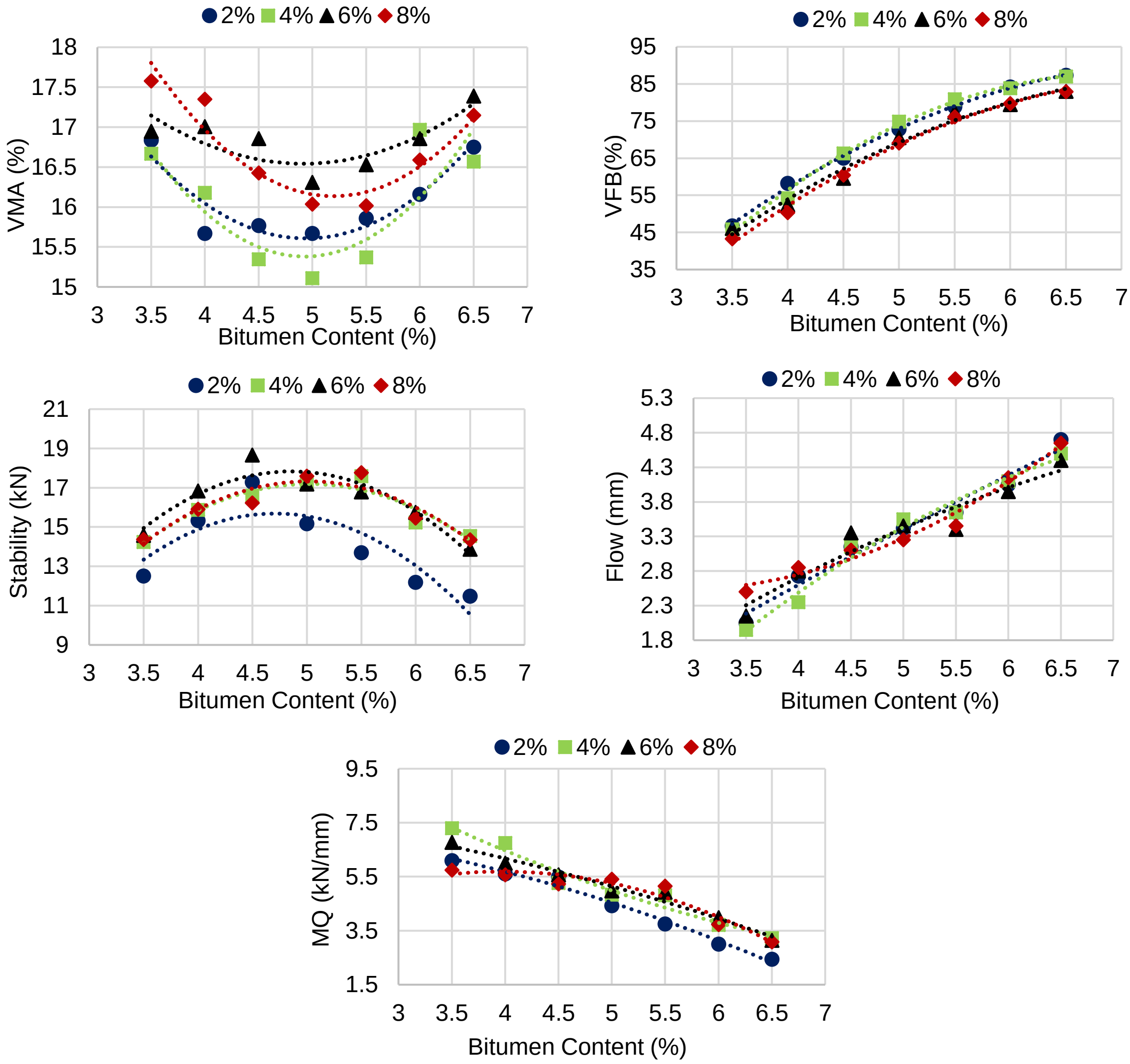
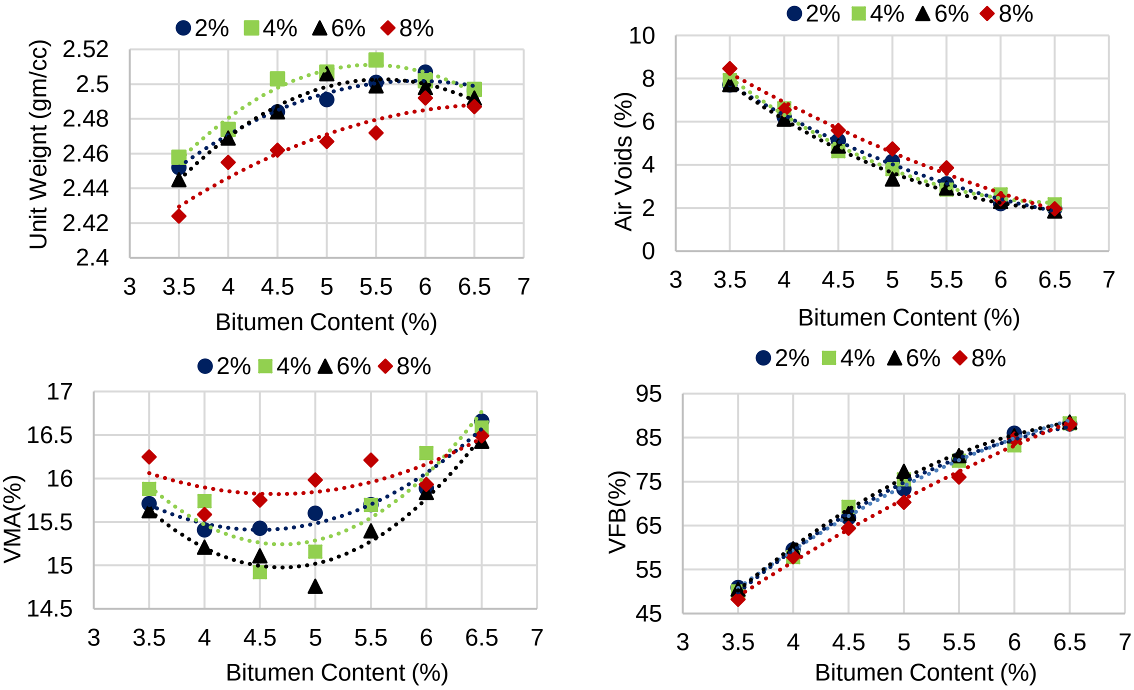
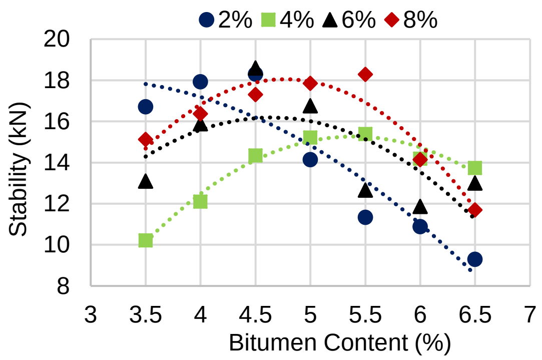
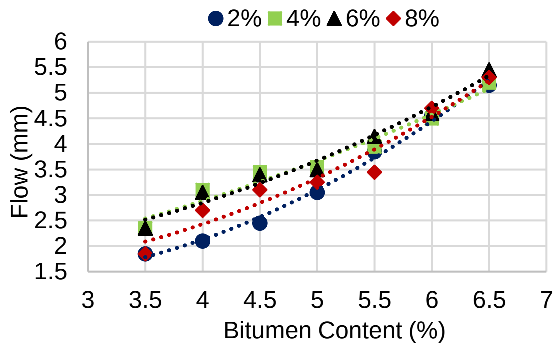
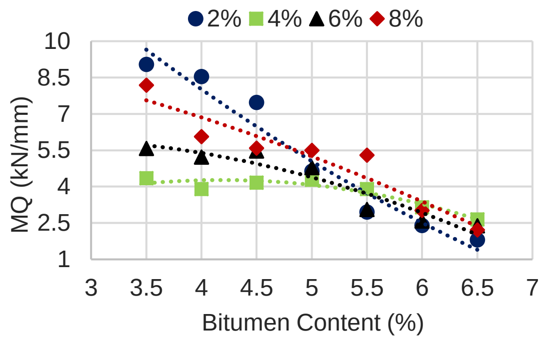


Figure 3. Marshall properties of bituminous mixes containing studied percentages of FA. Source: Self- elaboration.









According to Table 5, the OBC of the mix with 2% HL (control mix) is 5.21%, however, an increase in HL percentage (from 2% to 4%) decreases the said value to 5.18%. Yet, at 6% and 8% HL content the same has reached to 5.35% and 5.59%, respectively. The mix containing RHA and FA shows a lower consumption of OBC compared to that of HL for similar filler content. At 4% filler content both RHA and FA show a 5.9% and 4.9% reduction in OBC value compared to the control mix respectively. As in all mixes, the type of aggregate, gradation, binder type, and sources are similar, so the variance in OBC may be credited to the filler type and content only. The reason behind the deviation in OBC for both RHA and FA be connected to the fact that controls the change in air voids in the mixtures.

Table 5. Marshall Properties of the mixes corresponding to OBC at various filler content for HL, RHA, and FA. Source: Self-elaboration.

Filler type	Amount of filler (%)	OBC (%)	Stability (kN)	Flow (mm)	VMA (%)	VFB (%)	Marshall quotient (kN/mm)
HL	2	5.21	13.85	3.82	16.08	74.57	3.70
	4	5.18	14.96	3.77	16.17	72.59	3.96
	6	5.35	15.75	3.79	16.32	74.79	4.18
	8	5.59	14.18	3.36	16.5	74.85	4.21
RHA	2	5.14	14.5	3.65	15.3	70.44	4.24
	4	4.9	17.30	3.48	15.66	70.83	4.92
	6	5.37	18.6	3.3	16.21	73.34	5.15
	8	5.42	16.93	3.62	16.82	73.87	5.20
FA	2	5.07	13.75	3.16	15.61	74.28	4.35
	4	4.95	15.17	3.53	15.11	74.33	4.42
	6	4.81	17.52	3.35	16.16	73.62	5.04
	8	5.39	17.86	3.23	16.37	74.37	5.34
Requirements (MORTH, 2013)			9.00 (min)	2-4	13.00 (min)	65-75	2-5

Using the Figures 1-3, the Marshall test results of the mixtures corresponding to OBC having all the studied fillers are shown in Table 5. The average stability (MS) value of the control mix is 13.85kN. Further, the increase in HL content from 2% to 6%, the said value increases to 15.75 kN. However, at 8% HL the MS value decreases. Moreover, RHA shows improved MSs than HL for all the proportion of filler. For instance, The MSs of the mixture with RHA containing 2%, 4%, 6%, and 8% are increased to 6.9%, 27%, 37.16%, and 24.85% respectively compared to the control mix. Also, in the case of FA, the MS value at 2% is slightly high (13.75 kN) than the control mix. Yet, further addition in FA (from 4% to 8%) shows the raising of the MSs value to 15.17, 17.52, and 17.86 kN. This improvement in Marshall stability for RHA mixtures can be attributed to the irregular particles of RHA (Mistry et al., 2018) that may enhance the shear strength and stiffness of the modified binder. Further, for FA mixtures, one reason for the increase in Marshall stability is that the regular shape of FA particle (usually spherical) [Mistry et al., 2018] may act as rollers that enable less friction in the mastic during compaction, thereby resulting in a tighter packing. In the case of flow values, all the prepared mix lies between the specified limit of 2- 4 mm (MORT&H, 2013). Also, the voids in mineral aggregate (VMA) and voids filled with bitumen (VFB) values did not cross the specified limits. Furthermore, the change in Marshall Quotient (MQ) values may explain the nature of the obtained Marshall test results effortlessly. Marshall quotient (MQ) is defined as the proportion of stability (kN) to flow (mm), and as a hint of the stiffness of mixtures. It is well accepted that the MQ is a quantifier of the materials' resistance to shear stresses, permanent deformation, and hence rutting. The outcome of all the said fillers on MQ values is shown in Table 5. The MQ values for 2% of HL (control mix), RHA, and FA are 3.7, 4.24, and 4.35kN/mm, respectively. However, at 4% filler ratio, the RHA mix shows a 33% increment compare to the control mix. The HL-incorporated mixes do not display any noteworthy rise in MQ values with the increasing filler percentage. Nevertheless, with more added in filler quantity for RHA and FA mixes, the MQ values gradually escalate and surpass the maximum permissible specified limit of MQ of 5 kN/mm (MORT&H 2013). For this reason, despite having the lowest OBC among all the mixtures, 6% FA should not be used for field application. The increasing tendency in MQ values may be accredited to the fact that the higher concentration of studied waste fillers absorbs the light constituent of bitumen which upsurge the viscosity and stiffness of bituminous binder. This improves the adhesion between mastic and aggregates and boosts the overall ability of the HMA to bear loads.

Application of ANFIS

The concept of fuzzy logic represents the blurred state of the real-world problem with the help of a fuzzy set and fuzzy inference system (Zadeh, 1965). In the classical set theory, one component either belongs to a set or not. However, the fuzzy set theory permits partial belonging of a component to one or more subsets with changing membership degrees in linguistic notions. The key benefit of FL is that it needs only to set a simple controlling method based on engineering practice without handing tiresome mathematical calculations.

ANFIS method

ANFIS, first presented by Jang (Jang 1993), is extensively utilized in many engineering problems up to now (Tesfamariam & Najjaran, 2007; Shafabakhsh & Tanakizadeh, 2015; Bonakdari et al., 2015). ANFIS is a fusion of ANN and fuzzy inference systems. ANN is utilized to identify the fuzzy inference system variables. Sugeno type is one of the typical fuzzy inference systems. In this study, a first-order Sugeno fuzzy inference approach is used to find out the most effective input variables in predicting Marshall stability and flow. The MATLAB neuro-fuzzy logic toolbox (Math Works Inc 2016) was applied for training and testing the fuzzy inference system.

Model assessment

To assess the FIS model performance by measuring the goodness of the fit, the following statistical indicators were selected:

(1) Root-mean-square error (RMSE):

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - t_i)^2} \quad (1)$$

(2) Mean absolute percentage error (MAPE)

$$\text{MAPE} = \frac{1}{N}\sum_{i=1}^{N}\frac{|t_i - O_i|}{t_i} x\ 100 \quad (2)$$

where t is the experimental or actual value, $O$is the predicted value, N is the total number of the data point in each set of data,$\overline{O}$is the mean value of predictions, and $\overline{t}$ is the mean value of observations.

Sensitivity analysis

Input parameters. In this study, the Marshall mix design values of conventional and modified mixes were used to generate the ANFIS model. A total of 84 experimentally determined data sets were used: randomly selected 70% of them were employed for training to assess fuzzy base rules, and 30% were used for testing to validate model results. Past researchers showed that the same training and testing data set ratio could bring the best performance (Ghorbanzadeh *et al*. 2018; Tiwari *et al*. 2018). The input variables considered for the sensitivity analysis are filler types (FT), percentage filler (PF), bitumen content (BC), unit weight of compacted specimens, percentage air voids (Vv), voids in mineral aggregate (VMA) and voids filled with bitumen (VFB).

Sensitivity analysis of input variables using ANFIS. An extensive search was made within all the inputs to choose the most effective variables with the highest impact on both the outputs; Marshall stability and flow. First, the ANFIS was modelled for each input. To obtain the right inputs, fast in the sensitivity analysis, the ANFIS models were trained for ten epochs and the obtained results were reported. Primarily, the most effectual input for predicting the outputs was finalized and the RMSE values in the training and testing phase of the individual model are plotted in Figures 4 and 5. The figures undoubtedly show that the input parameter percentage bitumen has the least error and is most controlling in predicting Marshall stability and flow. In most of the soft computing techniques, the involvement of two or more input variables could lead to greater precision of any model (Bonakdari *et al*. 2015). Therefore, the three inputs which have the smallest error were considered to be the most appropriate variables. According to Figures 2 and 3, BC, PF, and FT were considered as input variables for developing the ANFIS prediction models.

Figure 4. Sensitivity analysis of different input parameters for Marshall stability. Source: Self-elaboration.

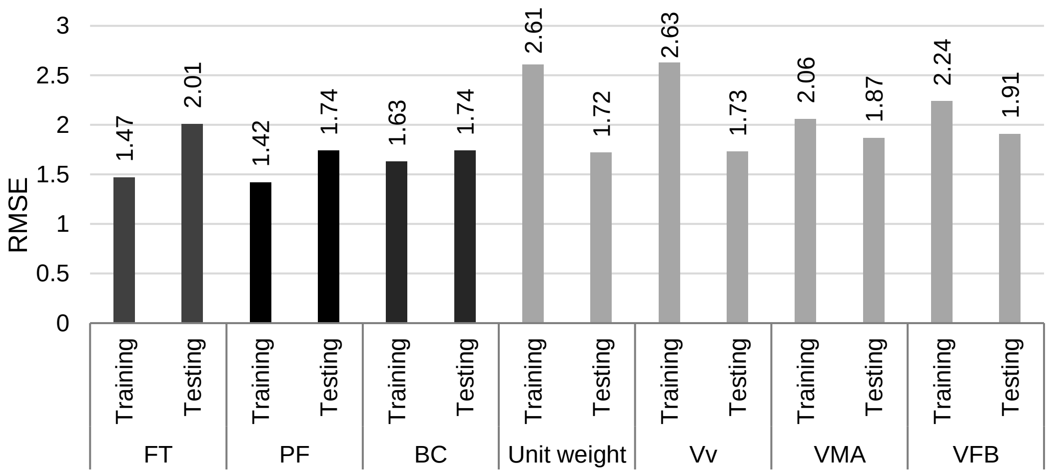
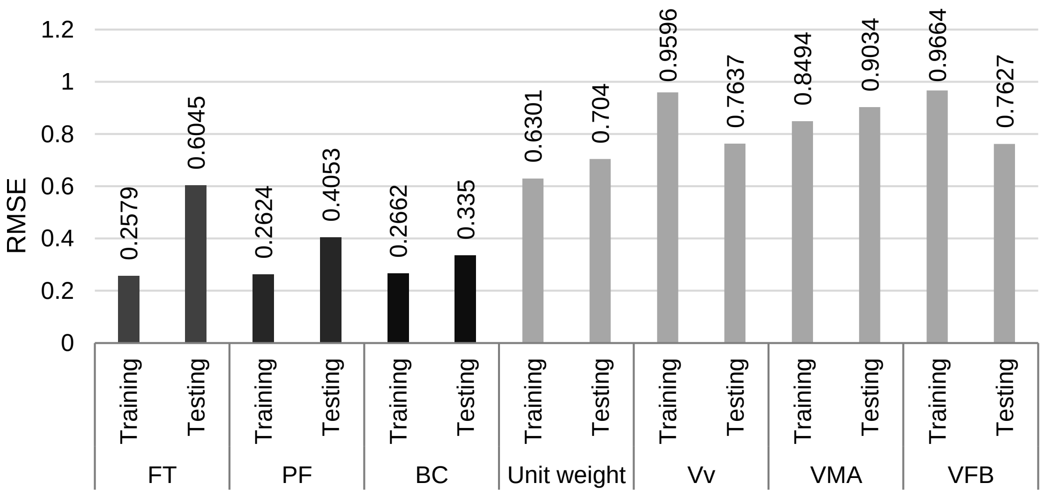


Figure 5. Sensitivity analysis of different input parameters for flow. Source: Self-elaboration.



Modelling of Marshall stability and flow based on ANFIS

In this study, the Sugeno type fuzzy inference system was utilized to develop two separate models to forecast Marshall stability and flow of bituminous mixtures. The most appropriate input variables that were detailed in the last section of sensitivity analysis are used in the process. The optimum model is acquired using the trial and error method. The optimum ANFIS models have the triangular membership function with 3, 4, and 4 membership functions for BC, PF, and FT respectively. The hybrid-learning algorithm is used for ANFIS. The combination of steepest descent (SD) and the least-squares estimator (LSE) in this algorithm helps to identify parameters quickly (Shafabakhsh & Tanakizadeh 2015). Finally, after about 100 epochs the optimum ANFIS models were obtained.

ANFIS results. Two separate ANFIS models were developed in the study to predict the Marshall stability and flow values of HMA containing HL, RHA, and FA as filler in different proportions. Figures 6 and 7 illustrated a comparison between the predicted and actual experimental data in the training and testing phase for Marshall stability and flow values respectively. The results of these figures indicated that the proposed ANFIS models could learn the relationship between the different input and output parameters. The performance of the ANFIS models measured by correlating the predicted data with experimental data for Marshall stability and flow values in training and testing sets. The said figures also include the least-square fit line, its equation, and coefficient of correlation (R^2) values. For the Marshall stability, the R^2 are 0.9988 and 0.9428 for training and testing set respectively. Further, the R^2 for flow is 0.9999 and 0.9519 in training and testing set respectively. The results obtained from the Mamdani-type fuzzy inference model for training and testing phases are very close to the actual experimental data. The test results indicated that the proposed ANFIS models were trained suitably.

Figure 6. Comparison between the actual and predicted Marshall stability values in the training and testing phase for the ANFIS model. Source: Self-elaboration.

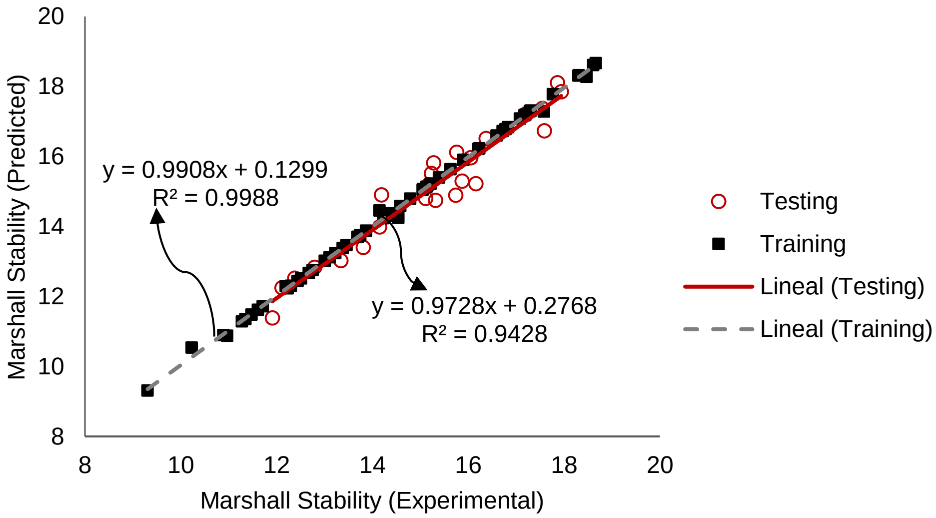


Figure 7. Comparison between the actual and predicted flow values in the training and testing phase for the ANFIS model. Source: Self elaboration.

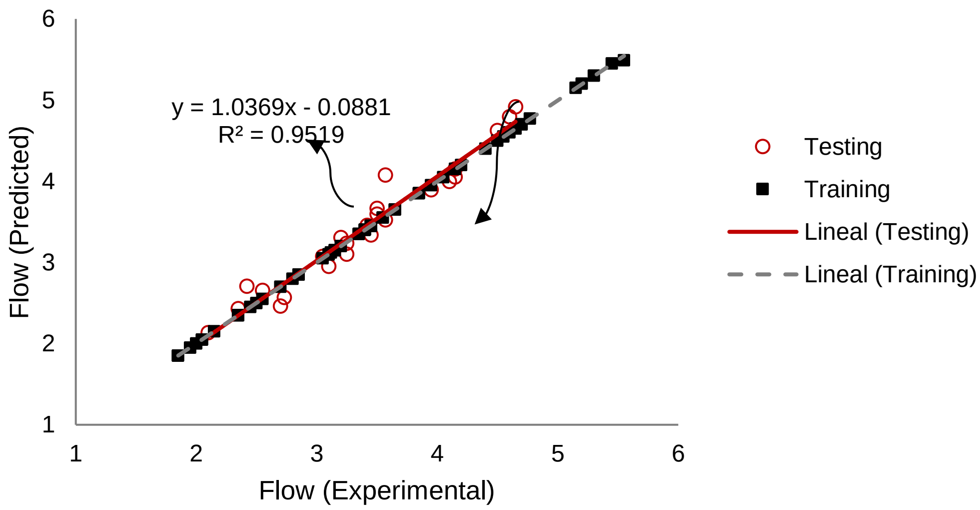


Table 6. The statistical values of the proposed models. Source: Self-elaboration.

Statistical performance indicator	Output parameters			
	Marshall stability (kN)		Flow (mm)	
	Training	Testing	Training	Testing
RMSE	0.0836	0.5411	0.0077	0.1705
MAPE	0.1939	2.7361	0.0181	3.9982

According to Table 6, statistical parameter values obtained from RMSE and MAPE for Marshall stability in training was found as 0.0836 and 0.1939 respectively, these values were found in testing as low as 0.5411 and 2.7361 respectively. Similarly, while the statistical values of flow were found in training as 0.0077 and 0.0181 respectively, for testing these values were 0.1705 mm and 3.9982 mm respectively.

Conclusions

In this study, the effect of using different fillers (HL, RHA, and FA) in various proportions on the Marshall properties of DBM mixtures was investigated. According to the experimental results, the OBCs of the mixtures with alternative fillers (i.e. RHA and FA) reduced when increase in filler content (up to 4%) with 23.25%, 9.24% higher stability and 32.43%, 19.45% higher MQ values compared to the control mix for RHA and FA respectively. This is an important aspect of this study for practical applications in terms of saving the consumption of bitumen along with the achievement of the better stability of the constructed pavement structures. Although at 6% FA displayed the lowest OBC, the MQ value exceeded the maximum permissible specified limit of 5 kN/mm.

Additionally, to predict the Marshall stability and flow of different HMA mixtures ANFIS system models were constructed with the experimental data using the Matlab toolbox.

First, the sensitivity analysis was carried out within all the inputs involved in the Marshall mix design to choose the most effective variables. The results demonstrated that BC is the most effective input variable and the three inputs which have the smallest error were considered to be the most appropriate variables to predict the said outputs. The Sugeno type fuzzy inference system was utilized to develop two separate ANFIS models with 70% data used for training and the remaining 30% was used in the testing phase. Further, by considering the R^2 values, it can be said that the predicted data in both the training and testing phase were close to the actual one. Besides, the statistical error values (RMSE and MAPE) obtained were also very tiny.

The results of the study reveal that the proposed ANFIS models can predict the Marshall test results of HMA mixtures containing different fillers in various proportions in a relatively short period with very good precision.

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