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RESEARCH ARTICLE

Prediction of rutting potential of dense bituminous mixtures with polypropylene fibers via repeated creep testing by using neuro-fuzzy approach

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Abstract

This study investigates the potential use of the neuro-fuzzy (NF) approach to model the rutting prediction by the aid of repeated creep testing results for polypropylene modified asphalt mixtures. Marshall specimens, fabricated with M-03 type polypropylene fibers at optimum bitumen content have been tested in order to predict their rutting potential under different load values and loading patterns at 50°C. Throughout the testing phase, it has been clearly shown that the addition of polypropylene fibers results in improved Marshall stabilities and decrease in the flow values, providing an eminent increase of the service life of samples under repeated creep testing. The performance of the accuracy of proposed neuro-fuzzy model is observed to be quite satisfactory. In addition, to obtain the main effects plot, a wide range of detailed two and three dimensional parametric studies have been performed.

Keywords

Bitumen modification · asphalt · polypropylene fibers · rutting potential · strain accumulation · Neuro-fuzzy · modelling · parametric studies

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1 Introduction

The creep test, for many years, has been used to estimate the rutting potential of dense bituminous mixtures. This test is conducted by applying a static or a repeated load to an asphalt specimen and measuring the resulting permanent deformation. Extensive studies using the unconfined creep test (also known as simple creep test or uniaxial creep test) as a basis of predicting permanent deformation in dense bituminous mixtures has been conducted up to date [1–7].

The loss of pavement serviceability is a common result from rutting. Rutting is defined as the formation of the longitudinal depressions under the wheel paths caused by the progressive movement of materials under traffic loading in the asphalt pavement layers or in the underlying base through consolidation or plastic flow. Depending on the magnitude of the traffic load and the relative strength of the pavement layers, rutting can occur in the subgrade, base, or upper hot-mix asphalt layers. Recent studies indicate that the rutting generally occurs in the top 75 to 100 mm of asphalt pavements [8–12].

Rutting can significantly reduce both structural and functional performance of a pavement. Sometimes the rutting magnitude may not be alarming for structural performance, but it is important from the safety point of view [13]. Rutting can provide useful information in selecting rehabilitation methods if it is quantified and categorized [14, 15]. In case of consolidation and shear rutting, a thicker overlay can be used to improve serviceability. In case of shear rutting, rehabilitation strategies can involve milling or levelling with a new wearing course or recycling of the surface course [14, 16].

To solve this rutting problem in flexible pavements (and other problems such as fatigue and low temperature cracking), scientists have developed some techniques and methodologies called "asphalt (bitumen) modification". The most popular bitumen modification technique is polymer modification. To this end, novel binders with improved rheological characteristics are continuously being developed [17–21]

Understanding the effects of repeated creep which leads to the prediction of rutting potential of dense bituminous mixtures is very important for the design of asphalt pavements. During a hot summer day, a heavy vehicle with a full load, travelling on a climbing lane imposes a considerable distress on the pavement structure. The repetition of heavier axle loads becomes more pronounced with the increased amount of traffic. The loads from the repeated traffic can create pronounced amounts of permanent deformation or rutting. Even on straight road sections, because of the slow speed and heavy loads of the trucks and trailers, similar problems can be encountered. The pavement around traffic lights and bus stops are also known to have similar problems. Therefore, visible defects related to rutting are frequently found on these types of road sections.

It can be found in the previous pioneering studies that the creep test must be performed at relatively low stress levels (cannot usually exceed 206.9 kPa (30 psi)) and low temperature (cannot usually exceed 40˚C (104˚F)), otherwise the sample fails prematurely [3, 22, 23]. The test conditions consist of a static axial stress, σ, of 100 kPa being applied to a specimen for a period of 1 hour at a temperature of 40˚C. These test conditions were standardized following a seminar in Zurich in 1977 [24]. This test is inexpensive and easy to conduct but the ability of the test to predict performance is extremely questionable [13]. In place asphalt mixtures are sometimes prone to truck tire pressures of more than 828 kPa (120 psi) and temperatures higher than 60˚C (140˚F) [25]. Therefore, the conditions of static (and of course repeated) creep testing do not closely simulate in-place conditions and specifically speaking, there is not any “rule of the thumb” for the testing standards for repeated creep testing via universal testing machines that is being accepted by all of the research counterparts all around the world.

On the other hand, no rational model to predict rutting has been developed yet that would encompass all field variables. There are some studies in the literature that is dealing with asphalt by utilising simulation methods or package computer software [26, 27]. In this study, a neuro-fuzzy model has been proposed to predict the strain accumulation (rutting potential) developed in the polypropylene modified Marshall specimens during repeated load creep tests. The proposed study differs from the previous researches that have been carried up to date in the sense that, no studies have been carried out for the prediction of the repeated creep test results by the aid (carried out in the laboratory environment utilizing universal testing machine) of neuro-fuzzy modelling and parametric studies.

The first part of this study reviews the available literature on dense bituminous mixtures by the utilization of polypropylene fibers was presented. Afterwards, short information on creep (basically repeated) testing of dense bituminous mixtures is presented spanning in the last two decades about the actual loading simulation efforts being undertaken in the laboratory environment. Then, well-known application of neuro-fuzzy modelling techniques in transportation and pavement engineering is explored. Next, experimental program presenting the results of the repeated creep tests has been explored in a detailed manner. At this point, development and verification of the neuro-fuzzy model is presented. In order to obtain the main effect plot, a wide range of parametric studies have been performed by using the neuro-fuzzy models. The analysis of these two and three dimensional results is presented finally.

2 Polypropylene fiber modification of asphalt mixtures

Many valuable studies have been published about fiber modification of dense bituminous mixtures which can be found in a detailed manner in the relevant literature until 2008 [28]. Tapkın has found that the addition of polypropylene fibers into the asphalt concrete on a dry basis alters the behaviour of the mixture in such a way that, Marshall stability values increase, flow values decrease and the fatigue life increases significantly [29]. Tapkın et al. have also worked on the addition of polypropylene fibers to the asphalt concrete on a wet basis, and have shown that the most favourable and suitable polypropylene type was multifilament, 3 mm long (M-03 type) which increased the Marshall stability values by 20% as well as the stiffness of the asphalt concrete [28, 30–32]. Repeated load creep tests under different loading patterns have also shown that the time to failure of fiber modified asphalt specimens under repeated creep loading at different loading patterns increased by 5-12 times versus reference specimens, which is a very significant improvement [33]. In another accompanying study, it was found that polypropylene modification of bituminous binders developed the physical and mechanical properties of the mixture and substantially improved its resistance to permanent deformation. Polypropylene modification also results in a saving of 30% in the amount of bitumen, resulting in considerable cost savings [35]. There are also a number of other studies in the literature on different applications of polypropylene fiber modification of asphalt concrete in the last decade which deserve attention [34–42].

3 Creep testing and the relevant literature spanning the last two decades

In this study, a completely different loading pattern, loading stress level and testing temperature than the previous studies have been adopted [32]. First of all, the testing temperature was chosen as 50˚C to simulate actual *in-situ* conditions [28, 30, 31]. An axial stress, σ, of 500 kPa was applied to the specimens until the specimen enters the tertiary creep region to nearly failure point to simulate the actual in-place conditions in a realistic manner [32]. Also it has to be mentioned that, in today’s modern pavement engineering practices, there are also other bitumen modifying agents other than polypropylene fibers which need to be tested in actual stress levels in order to show the very positive contribution of these modifiers to the genuine mechanical behaviour of modified dense bituminous mixtures.

Repeated creep tests have been performed in order to log the accumulation mechanisms of the developing strains in the specimen body, or in other words rutting potential. The creep deformation of standard Marshall specimens was measured as a function of rectangular pulse counts or rather time. The load on the specimens was uniaxial and dynamic, which was representing the repeated application of axle loads. The dimensions of asphalt specimens were approximately the same for nearly all of the specimens. Therefore, a unity in the dimensions was standardized. Prior to testing, the specimens were put into the chamber for 24 hours in order to have the uniform temperature distribution. All of the tests were carried at 50˚C. For controlled temperature testing, the specimen's skin and core temperature were estimated by transducers inserted in a dummy specimen and located near the specimen under test [33]. To understand the behaviour of the asphalt specimens under different loading patterns, different constant stress values were chosen. These values were 100, 207 and 500 kPa. As polypropylene modification was carried out, utilizing lower stress values like 100 and 207 kPa was not feasible, since under such loading the tertiary creep region could not be observed within a reasonable period of time. Therefore, in order to be able to differentiate between the reference and fiber-reinforced samples, a real destructive loading level of 500 kPa (approximately 73 psi) was chosen as the standard stress value which is a main departure from the published pioneering literature of the rule of thumbs about creep testing [1–7]. This value very well represents the actual tire pressure of a loaded truck. The specimen strain during the pulsed loading stage of the test were measured in the same axis as the applied stress using two linear variable displacement transducers (LVDTs). The applied force was open loop controlled and rectangular in shape [32]. Load periods were chosen as 500 ms for all of the specimens and the rest periods were 500, 1000, 1500 and 2000 ms, respectively. Four specimens were tested for each loading pattern.

Matthews and Monismith have performed unconfined creep tests at temperatures 25˚C, 38˚C and 49˚C which is a main departure from the published literature up to date in the testing temperature manner and deserves attention [43]. In another study by Mallick et al., in order to simulate the average pavement temperature throughout the United States, 60˚C of testing temperature was utilised [44]. Ramsamooj and Ramadan had carried out creep tests at four stress levels under constant stresses of 150, 400, 650 and 900 kPa [45]. This was again an important deviation from the accustomed practices of creep testing that deserves attention. Zhang et al. had utilised a material test system to conduct repeated creep tests. A deviator stress along with a confining stress was applied on a hot mix asphalt (HMA) sample for 1 hour (3600 load cycles), with 0.1 second load duration and 0.9 second rest period intervals. After the 3,600 load cycles, the load was removed and the rebound was measured for 15 minutes. The strain observed at the end of this period was reported as the permanent strain. The permanent strain indicates the rutting potential of the mixtures [46]. The target air void content for mixtures tested by the confined repeated load test was 4.0% ± 0.5% in accordance with earlier studies. The test temperature was 60˚C. Test loading consisted of a 138-kPa (20-psi) confining pressure and an 827-kPa (120-psi) normal pressure [44]. Tashman et al. had carried out triaxial confined static creep test in determining the model parameters related to their studies. Both strength and creep tests were conducted at a temperature of 54.4˚C (130˚F) [47]. This is again a significant departure from the routine testing protocol of 40˚C temperature [24]. A static constant load had been applied until "tertiary flow" occurred. The test had been stopped at the initiation of the tertiary creep zone in order to avoid damaging the linear variable differential transformer (LVDT); thus the experimental tertiary creep pattern could not have been recorded naturally [47]. Chen et al. had investigated the mechanical responses and modeling of rutting in flexible pavements [48]. Goh and You have revised the repeated creep testing ambient temperature in a different manner than only utilising 40˚C [49]. Vardanega et al. have used a very similar ambient temperature and loading pattern to Tapkın et al. [32] in the studies that they have carried out (namely 50˚C and 0.5 (also 1.5) second loading and 1.5 (also 0.4) second unloading) depending on the argument which is also verified by the experience of QDMR (Queensland Department of Main Roads) [50]. Chen et al. investigated the utilization of recycled brick powder as alternative filler in asphalt mixture. They had carried out static and dynamic creep tests using Universal Testing Machine (UTM) to apply constant stress to asphalt specimens. Their specimens were 100 mm in diameter and 100 mm in height. These specimens were tested at 60˚C with a constant stress of 100 kPa for 3600 seconds and unloaded for the recovery of deformations for 5400 seconds. Also dynamic creep tests were applied with the same axial stress level and same temperature [51]. Also in some studies, in the last five years that was utilising the "standard" procedure depicted in Zurich [24] the testing temperature had been chosen as 30˚C which was again a departure from this technique [52–54].

4 Neuro-fuzzy applications carried out in pavement and transportation engineering applications in the last five years

Among the limited researches in the field, below, the reader may find some of the important studies.

The study by Filippo et al. presents a procedure for ranking environmentally valid highway restoration by priority, using a fuzzy multi-criteria model that supports decisions on which road segments require these works and services. This is a matter of much concern for the Brazilian Government, due to rising awareness of soil degradation and the depletion of plant cover, as accident rates and transport costs rise steadily [55]. In the dissertation by Chen, the main aim was to develop enhanced LCCA (Life-Cycle Cost Analysis) models using soft computing (mainly fuzzy logic) techniques. The proposed models used available "real world" information to forecast life-cycle costs of competing maintenance and rehabilitation strategies and support infrastructure management decisions. A critical review of available soft computing techniques and their applications in infrastructure management suggested that these techniques provide appealing alternatives for supporting many of the infrastructure management functions [56]. The paper by Quek et al. describes the application of a specific class of neuro-fuzzy system known as the Pseudo Outer-Product Fuzzy-Neural Network using Truth-Value-Restriction method for modelling traffic behaviour. This approach has been shown to perform better on such problems than similar architectures [57]. The study carried out by Bianchini and Bandini proposes a neuro-fuzzy model to predict the performance of flexible pavements using the parameters routinely collected by agencies to characterize the condition of an existing pavement. These parameters are generally obtained by performing falling weight deflectometer tests and monitoring the development of distresses on the pavement surface. The proposed hybrid model for predicting pavement performance was characterized by multilayer, feedforward neural networks that led the reasoning process of the "IF-THEN" fuzzy rules. The results of the neuro-fuzzy model were found to be superior to those of the linear regression model in terms of accuracy in the approximation [58].

5 Experimental analyses

Throughout the study, continuous aggregate gradation has been used to fit the gradation limits for wearing course Type 2 set by General Directorate of Turkish Highways [59]. The aggregate was calcareous type crushed stone obtained from a local quarry and 50/70 penetration bitumen was obtained from a local refinery were used for preparation of the Marshall specimens. Physical properties of the bitumen samples are given in Table 1. The physical properties of coarse and fine aggregates are given in Tables 2 and 3. The apparent specific gravity of filler is 2790 kg/m^3.

Tab. 1. Physical properties of the reference bitumen

Property	Test Value	Standard
Penetration at 25˚C, 1/10 mm	55.4	ASTM D 5-97
Penetration Index	-1.2	-
Ductility at 25˚C, cm	> 100	ASTM D 113-99
Loss on heating, %	0.057	ASTM D 6-80
Specific gravity at 25˚C, kg/m^3	1022	ASTM D 70-76
Softening point, ˚C	48.0	ASTM D 36-95
Flash point, ˚C	327	ASTM D 92-02
Fire point, ˚C	376	ASTM D 92-02

Tab. 2. Physical properties of coarse aggregates

Property	Test Value	Standard
Bulk specific gravity, kg/m^3	2703	ASTM C 127-04
Apparent specific gravity, kg/m^3	2730	ASTM C 127-04
Water absorption, %	0.385	ASTM C 127-04

Aggregate gradation for the bituminous mixtures tested in the laboratory has been selected as an average of the wearing course type 2 gradation limits given by General Directorate of Highways of Turkey which is stated in the Highway Technical Specifications [59]. The mixture gradation and gradation limits are given in Table 4.

Tab. 3. Physical properties of fine aggregates

Property	Test Value	Standard
Bulk specific gravity, kg/m^3	2610	ASTM C 128-04
Apparent specific gravity, kg/m^3	2754	ASTM C 128-04
Water absorption, %	1.994	ASTM C 128-04

Tab. 4. Type 2 wearing course gradation [59]

Sieve size, mm	Gradation limits, %	Passing, %	Retained, %
12.7	100	100	0
9.52	80-100	90	10
4.76	55-72	63.5	26.5
2.00	36-53	44.5	19.0
0.42	16-28	22	22.5
0.177	8-16	12	10.0
0.074	4-10	7	5
Pan	-	-	7

In the wet basis modification procedure of the asphalt concrete specimens, standard 50/70 penetration bitumen was modified by utilising polypropylene fibers. The fibers were premixed with bitumen using a standard mixer at 500 revolutions per minute for two hours. The mixing temperature was around 165-170˚C [60]. For the sake of testing reasons, the reference bitumen samples were also subjected to the same temperature to equalise the oxidative and aging effects of two hours of heat effect utilised in polypropylene modification. Three types of polypropylene fibers: M-03, M-09 and waste fibers were used in research. For M-03 type fibers, fiber contents of 3‰, 4.5‰and 6‰by weight of aggregate were premixed with bitumen and were used for the preparation of standard Marshall specimens [32]. For M-09 type and waste fibers only 3‰fiber content was utilized as it was extremely difficult and cumbersome to mix fibers with greater lengths with bitumen using standard mixers other than high shear ones. According to the workability criteria, M-03 type fibers were found to be the best modifiers and, due to the consistency of the Marshall test results, 3‰fiber content was determined as the optimal addition amount. With these amounts, polypropylene fibers melt in bitumen and bitumen forms a continuous phase for polypropylene particles. The physical properties of the polypropylene fiber based bitumen samples with 3‰fiber content are given in Table 5.

The performance characteristics, such as penetration, penetration index, ductility, loss on heating, specific gravity, and softening point of the fiber modified bitumen samples were greatly improved as compared to reference specimens given in Table 1. Therefore, the addition of 3‰of M-03 type fibers clearly shows the decrease in temperature susceptibility of the reference bitumen (as shown by the eminent increase in the penetration index of polypropylene modified bitumen samples) providing the most significant effect on the properties of resultant asphalt concrete

Tab. 5. Physical properties of the polypropylene modified bitumen samples

Property	Test Value	Standard
Penetration at 25˚C, 1/10 mm	45.5	ASTM D 5-97
Penetration Index	-0.8	-
Ductility at 25˚C, cm	> 100	ASTM D 113-99
Loss on heating, %	0.025	ASTM D 6-80
Specific gravity at 25˚C, kg/m^3	1015	ASTM D 70-76
Softening point, ˚C	52.05	ASTM D 36-95
Flash point, ˚C	292	ASTM D 92-02
Fire point, ˚C	345	ASTM D 92-02

mixtures as an increase in the stiffness values. To determine the optimum bitumen content, the bitumen contents corresponding to the mixtures with maximal stability and unit weight, 4% air voids and 70% voids filled with asphalt, were found and averaged according to the limits given by the General Directorate of Highways of Turkey [59]. These optimum bitumen contents are represented in Fig. 1.

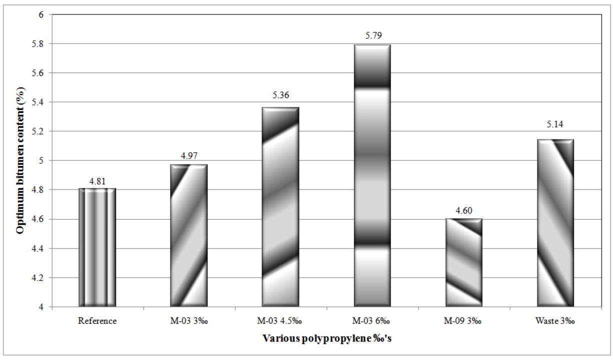

Fig. 1. Optimum bitumen content values

Based on the performed experiments, the optimum bitumen content varies depending on the type and dosage of fibers. However, the optimal polypropylene amount, the type, the homogeneity in the preparation of the Marshall specimens, the ease in the addition of the polypropylene fibers, the ease in the fabrication of the specimens and the fluctuations of the observed physical and mechanical properties are also very important. For example, specimens prepared with higher dosages of M-03 fibers, mixtures made with M-09 and waste fibers resulted in increased value of optimal bitumen contents. M-09 and waste fibers also had very little workability. The addition of these fibers into bitumen is difficult and results in very viscous modified bitumen samples that do not allow the fabrication of stable Marshall specimens. The fluctuations in the stability and flow values and Marshall Quotient values do support the above mentioned observations. Based on these results, M-03 polypropylene fibers at a dosage of 3‰by the weight of aggregates were selected as optimal polypropylene addition amount. Also, it can be seen that the optimum bitumen contents for reference and specimens with 3‰of M-03 fibers are 4.81% and 4.97%, respectively (Fig. 1). For the next step of experiments, these two values were taken as 5% for the sake of ease in preparation of the reference and modified asphalt specimens [32].

5.1 Repeated creep tests performed

The reference specimens utilised in the dynamic creep testing were prepared with 5% bitumen content. The fiber-reinforced (M-03 type with dosage of 3‰by the weight of aggregate) specimens were also prepared with 5% bitumen content. In the repeated creep test the accumulated axial strain, the resilient axial strain, peak vertical stress, resilient modulus and creep stiffness were calculated by Feeley [61]. The repeated creep test results are visualized through Figs. 2–5. These sets of graphs present the log of accumulated strains developed in the asphalt specimen bodies versus pulse counts. These graphs show the general trend of the four similar (in lieu of proximity of air void values concept) specimens under the specified loading and temperature conditions [33]. For the sake of uniformity reasons, the constant stress had been taken as 500 kPa and the test temperature was 50˚C for all the experiments. In all of the Figs. (2–5), the pulse count axis limits have been chosen as 0 - 40000 and the accumulated strain axis limits has been chosen as 0 – 80000.

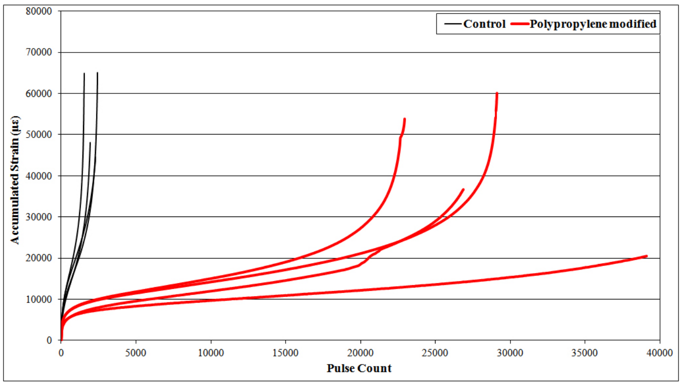

Fig. 2. Accumulated strain values for control and M-03 type polypropylene fiber modified samples (500 ms load – 500 ms rest)

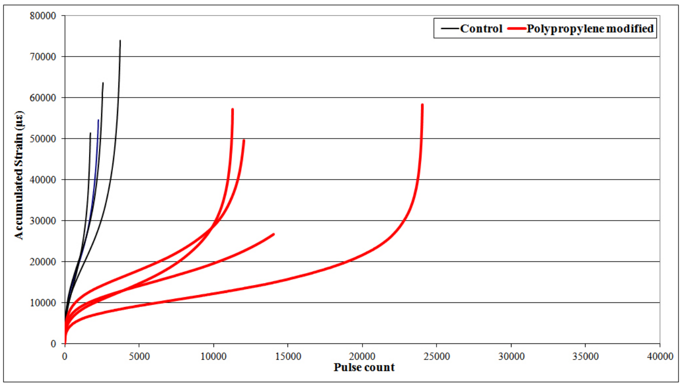

Fig. 3. Accumulated strain values for control and M-03 type polypropylene fiber modified samples (500 ms load – 1000 ms rest)

As can be seen from Figs. 2 to 5, the service life of fiber-reinforced specimens (5 % optimum bitumen content, 3‰of M-03 type fibers) are respectively longer than the control specimens under the same testing conditions. This is a very significant difference showing the positive effect of polypropylene fibers. As can be seen from all figures, the control specimens are entering to the tertiary stage of creep only at around 2000 pulse

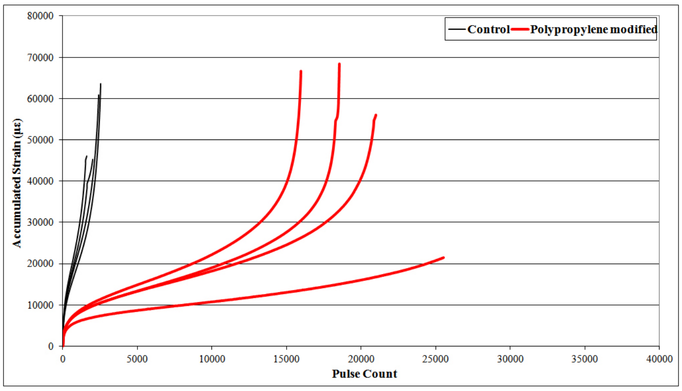

Fig. 4. Accumulated strain values for control and M-03 type polypropylene fiber modified samples (500 ms load – 1500 ms rest)

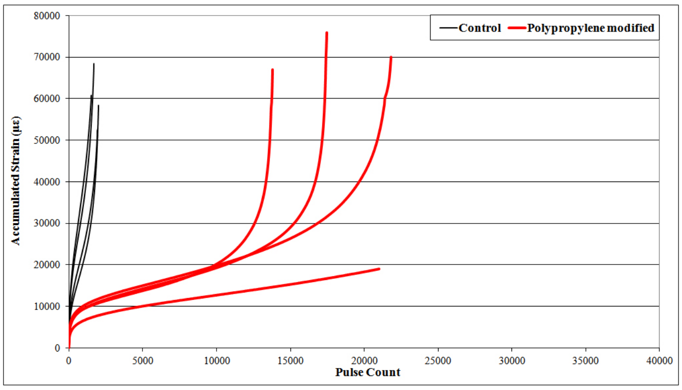

Fig. 5. Accumulated strain values for control and M-03 type polypropylene fiber modified samples (500 ms load – 2000 ms rest)

counts; this loading rate corresponds to the primary creep stage for the polypropylene fiber modified specimens. Fiber modified specimens reach the tertiary creep stage only at the much higher pulse counts. At the end of the repeated creep tests, the control specimens have a total collapse, while the modified specimens did not show any sign of failure (so, the fiber modified specimens would have had even a longer service life if the tests were continued). Therefore it can be easily concluded that polypropylene modification substantially increases the service lives of asphalt specimens under repeated loading. Rutting problems are not encountered in the polypropylene modified specimens until late pulse counts. This is valid for all of the loading patterns covered in this study. But the question is: can these accumulated strain values be estimated by some means so that the rutting potential of asphalt mixes can be predicted in an accurate manner? This study tries to find a solution to this problem from this point forward.

6 Background on fuzzy-logic

Over the last decade, fuzzy logic, which was invented by Lotfi Zadeh, has been applied to a wide range of fields covering engineering, process control, image processing, pattern recognition and classification, management, economics and decision making [62, 63]. Fuzzy systems can be defined as rule-based systems that are constructed from a collection of linguistic rules which can represent any system with accuracy, i.e., they work as universal approximators. The rule-based system of fuzzy logic theory uses linguistic variables as its antecedents and consequents where antecedents express an inference or the inequality, which should be satisfied and consequents are those, which we can infer, and is the output if the antecedent inequality is satisfied. The fuzzy rule-based system is actually an IF–THEN rule-based system, given by, IF antecedent, THEN consequent [64].

Fuzzy logic operations are based on fuzzy sets where the input data may be defined as fuzzy sets or a single element with a membership value of unity. The membership values ($\mu 1$ and $\mu 2$) are found from the intersections of the data sets with the fuzzy sets as shown in Fig. 6 which illustrates the graphical method of finding membership values in the case of a single input [65].

A fuzzy set contains elements which have varying degrees of membership in the set, unlike the classical or crisp sets where a member either belongs to that set or does not (0 or 1). However a fuzzy set allows a member to have a varying degree of membership and this partial degree membership can be mapped into a function or a universe of membership values [66]. The implementation of fuzzy logic considers the following steps:

1. Fuzzification which requires conversion of classical data or crisp data into fuzzy data or membership functions (MFs); 2. Fuzzy inference process which connects membership functions with the fuzzy rules to derive the fuzzy output; 3. Defuzzification which computes each associated output [66].

6.1 Neuro-fuzzy systems

Fuzzy systems can also be connected with neural networks to form neuro-fuzzy systems which exhibit advantages of both approaches. Neuro-fuzzy systems combine the natural language description of fuzzy systems and the learning properties of neural networks. Various neuro fuzzy systems have been developed that are known in literature under short names. ANFIS developed by Jang et al. [Adaptive Network-based Fuzzy Inference System] is one of these neuro-fuzzy systems which allow the fuzzy systems to learn the parameters using adaptive backpropagation learning algorithm [63, 67]. Mainly three types of fuzzy inference systems have been widely employed in various applications: Mamdani, Sugeno and Tsukamoto fuzzy models. The differences between these three fuzzy inference systems are due to the consequents of their fuzzy rules, and thus their aggregation and defuzzification procedures differ accordingly [67]. In this study, the Sugeno FIS is used where each rule is defined as a linear combination of input variables. The corresponding final output of the fuzzy model is simply the weighted average of each rule's output. A Sugeno FIS consisting of two input variables x and y, for example, a one output variable f will lead to two fuzzy rules:

Rule 1: If x is A_1, y is B_1 then $f_1 = p_{1x} + q_{1y} + r_1$

Rule 2: If x is A_2, y is B_2 then $f_2 = p_{2x} + q_{2y} + r_2$

where p_i, q_i, and r_i are the consequent parameters of ith rule. A_i, B_i and C_i are the linguistic labels which are represented by fuzzy sets shown in Fig. 7.

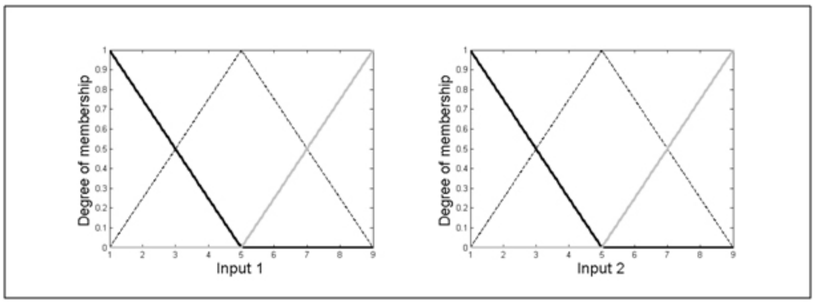

Fig. 6. Initial and final membership functions

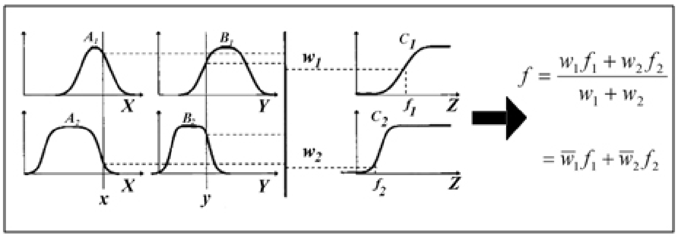

Fig. 7. The Sugeno fuzzy model (Jang et al.)

6.2 Solution of a sample problem with ANFIS

To illustrate how ANFIS works for function approximation, let's suppose one is given a sampling of the numerical values from the simple function below:

$$y_i = a^3 + b^2 \tag{1}$$

where a and b are independent variables chosen over randomly points in the real interval. In this case, a sample of data in the form of 17 pairs (a, b, y_i) is given where y_i is the value of the independent variable in the given interval {1, 9} and yi is the output of the function given in equation 1 and presented in Table 6. The aim is to construct the ANFIS model fitting those values within the minimum error for equation 1 by using the simplest ANFIS model that is available where the numbers of rules are 2 for each variable and the type of output membership function is constant.

Initial and final membership values of rules for each input are given in Fig. 6. Suppose one will find the output for input values of 1 and 9. The inference diagram of the proposed ANFIS model is given in Fig. 8 for input values of 1 and 9 with corresponding values of output membership which is chosen as constant. For the first input which is 1 the value of the membership function is observed to be 1 shown on the left side of Fig. 8. For the second input which is 9 the value of the membership function is observed to be 1 again shown on the left side of Fig. 8. Thus the final output will be: $82 \times 1 = 82$.

The exact result for $a = 1$ and $b = 9$ from equation 1 will be

$$y = 1^3 + 9^2 = 82 \tag{2}$$

7 Numerical Application

The main focus of this study is to explore an application of neuro-fuzzy modelling for the rutting prediction by the aid of repeated creep testing results for polypropylene modified dense bituminous mixtures. Therefore an extensive laboratory testing and data analysis phase has been performed throughout the study. The details of the experimental database including the ranges of parameters are given in Table 7.

Tab. 6. Data pairs for equation (1)

a	b	y_i
1	3	10
3	4	43
5	1	126
2	6	44
7	8	407
8	7	561
1	2	5
9	4	745
2	5	33
7	8	407
1	1	2
9	9	810
1	9	82
9	1	730
1	3	10
3	4	43
1	1	2

7.1 Results of neuro-fuzzy modelling

The input variables in the developed neuro-fuzzy model uses the physical properties of standard Marshall specimens such as polypropylene type, specimen height, unit weight, voids in mineral aggregate, voids filled with asphalt, air voids and repeated creep test properties such as rest period and pulse counts in order to predict the rutting potential of the fabricated specimens. It should be noted that the proposed neuro-fuzzy modelling is valid for the ranges of training set given in Table 7 and similar and specific type of aggregate sources, bitumen, polymer modification techniques, aggregate gradation, mix proportioning, modification technique and laboratory conditions. Statistical parameters of test and training sets of neuro-fuzzy formulations are presented in Table 8. The accuracy of the proposed NF models in terms of correlation coefficients (R^2) and coefficient of variation (COV) can be considered to be quite satisfactory.

Prior to NF modelling, the experimental results are divided into randomly selected training and testing sets among the ex-

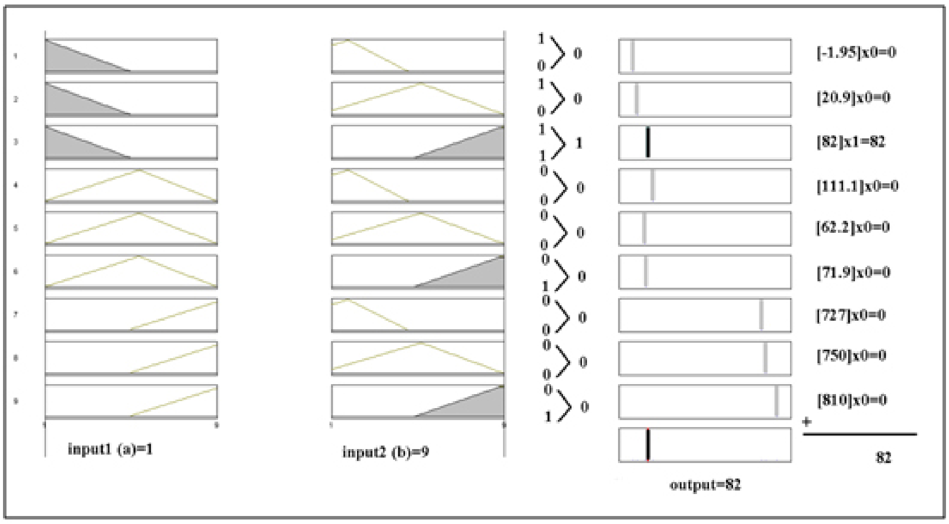

Fig. 8. Fuzzy inference diagram

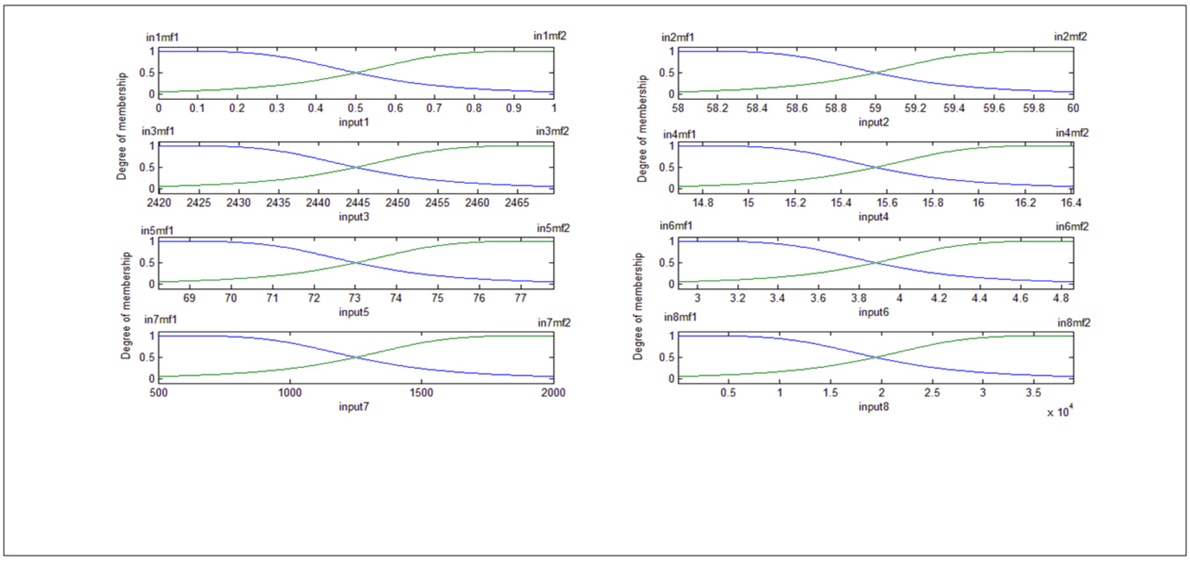

Fig. 9. Initial and final membership values for strain accumulation

Tab. 7. Ranges of experimental database used throughout the study

	Polypropylene type	Specimen height (mm)	Calculated unit weight (kg/m^3)	V.M.A. (%)	V_f (%)	V_a (%)	Rest period (ms)	Pulse count	Accumulated strain ($\mu\varepsilon$)
Maximum	3.00	60.00	2469.54	16.41	77.79	4.86	2000.00	39104.00	69937.00
Minimum	0.00	58.00	2419.80	14.69	68.24	2.90	500.00	2.00	459.70
Mean	1.45	58.80	2445.68	15.53	72.75	3.84	1217.86	5732.18	21681.79
Std. dev.	1.50	0.81	17.00	0.60	3.52	0.67	563.29	7052.19	11984.52

Tab. 8. Statistical parameters of the proposed ANFIS model

	Testing Set	Train Set	Total Set
MSE	13044066	11914117	12818076
MAPE	10.45896	10.64586	10.49634
R^2	0.907773	0.916093	0.909244
Mean	0.998492	1.001151	0.999023
COV	0.160876	0.155399	0.15976

perimental database with 80% and 20%, respectively. All neuro-fuzzy modelling are performed by MATLAB Fuzzy Logic Toolbox [64]. The neuro-fuzzy model is constructed with training sets and the accuracy is verified by testing sets which the neuro-fuzzy model faces for the first time. To illustrate the effectiveness of the neuro-fuzzy approach, the simplest ANFIS model is selected. The proposed ANFIS models use triangular, gaussian and generalized bell-shaped input membership functions with minimum number of rules which is 2. The output membership function is chosen as the simplest one available which is a constant value. These conditions will lead to the simplest available NF model. The initial and final membership functions for inputs are presented in Fig. 9. The input variables in Fig. 9 (namely input 1 to input 8) stand for the physical properties of standard Marshall specimens such as polypropylene type, specimen height, unit weight, voids in mineral aggregate, voids filled with asphalt, air voids and repeated creep test properties such as rest period and pulse counts respectively in order to predict the rutting potential of the fabricated specimens. Features of the proposed ANFIS model are given in Table 9 [68]. The performances of proposed NF models are presented in Fig. 10. The reader can visualise the superior performance of the NF models in Fig. 10 easily.

8 Parametric studies

The main effect plot is an important graphical tool to visualise the independent impact of each variable utilised in the carried analyses on accumulated strain values. This tool allows the reader to visualise a better and much simpler snapshot of the overall significance of variable effects on the outputs and will provide a general panorama. In the main effects plot, the mean output is plotted at each factor level which is later connected by a straight line. The slope of the line for each variable is the degree of its effect on the output. In order to obtain the main effects plot, a wide range of detailed parametric studies have been performed by utilising the proposed neuro-fuzzy model. The mean values of all variables are used to observe the general trend of each variable. The evaluation of separate interaction effects plot between any two variables is also presented by using the mean values of all variables. The main effects plot will also help further researchers willing to perform studies on rutting potential without carrying out destructive tests for similar and specific type of aggregate sources, bitumen, polymer modification techniques, aggregate gradation, mix proportioning, modification technique and laboratory conditions.

In Part 8.1, two-dimensional parametric analysis graphs that have been obtained at the end of parametric studies have been presented. The following part 8.2 is further presenting the three-dimensional parametric analysis results.

8.1 Two-dimensional parametric analysis results

In Fig. 11 and the rest of the figures, the y-axes represent the accumulated strain values in $\mu\varepsilon$ (PolType 1 stands for M-03 type polypropylene fiber modified asphalt specimens). Also in all of the corresponding parametric plots, creep stands for accumulated strain values. Finally P stands for pulse counts, UW stands for unit weight, VF stands for voids filled with asphalt, Va stands for air voids, L stands for rest period, VMA stands for voids in mineral aggregate.

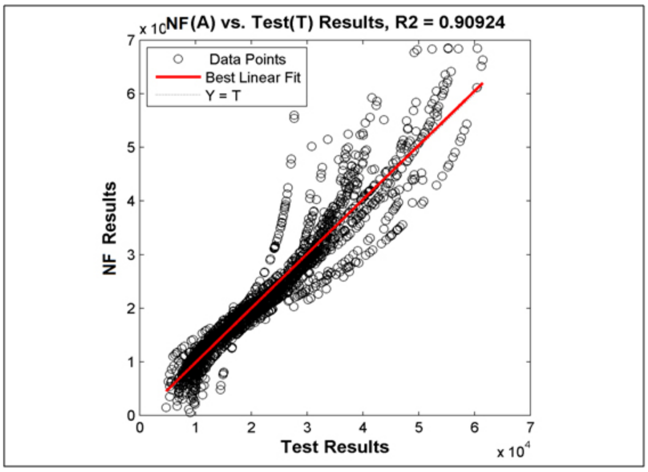

Fig. 10. Performance of neuro-fuzzy model versus test results for strain accumulation

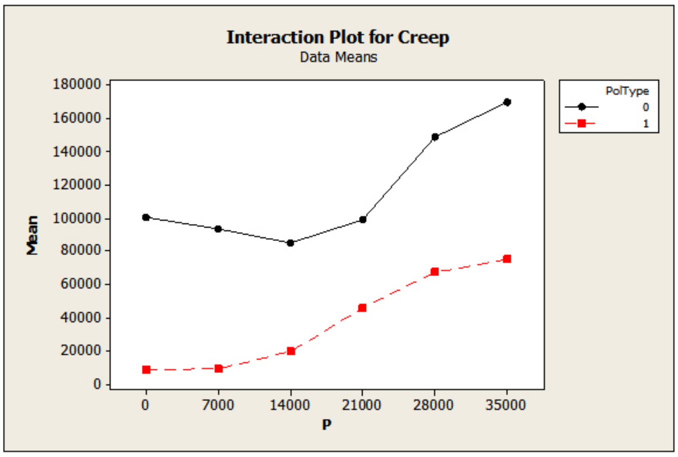

Fig. 11. Interaction plot for polypropylene type versus pulse counts

In Fig. 11, the reader can visualise the very positive effect of polypropylene modification with the visible decrease in the strain accumulation values by increasing pulse counts (P).

In Fig. 12, as the unit weight (UW) of the specimens decreases (that is showing the effect of polypropylene modification) the strain accumulation decreases with increasing pulse counts as can be clearly expected.

Tab. 9. Features of the proposed ANFIS model

Type	SUGENO
Aggregation Method	Maximum
Defuzzification Method	Weighted Average
Input Membership Function Type	Triangular, Gaussian, Generalized bell-shaped
Output Membership Function Type	Constant

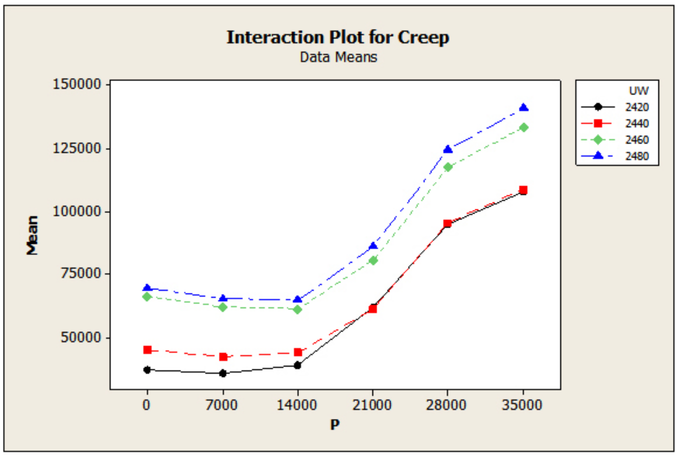

Fig. 12. Interaction plot for unit weight versus pulse counts

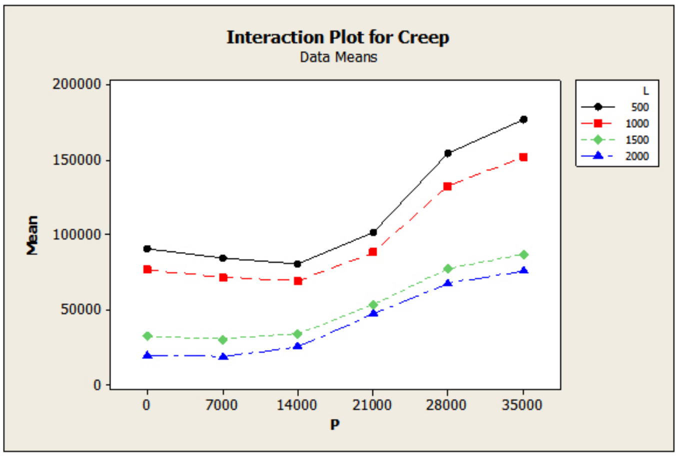

Fig. 15. Interaction plot for pulse width with asphalt versus pulse counts

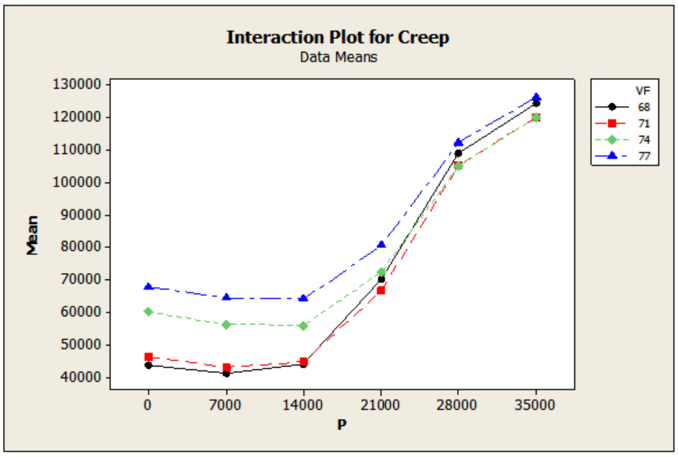

Fig. 13. Interaction plot for voids filled with asphalt versus pulse counts

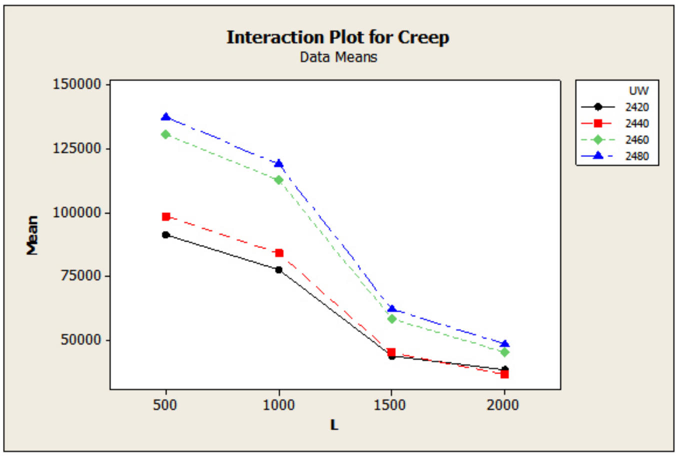

Fig. 16. Interaction plot for unit weight versus pulse width

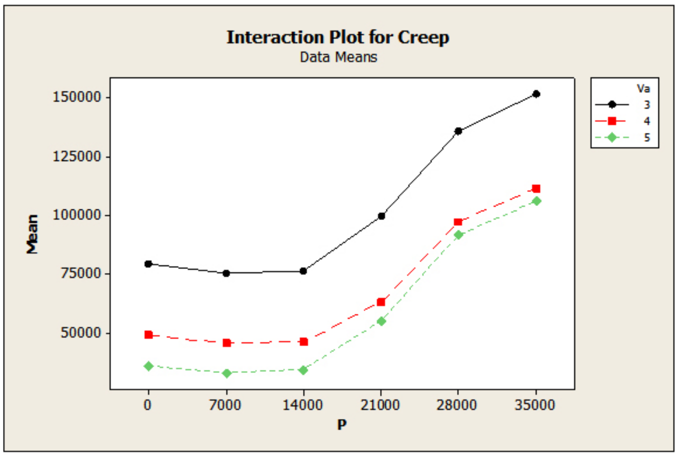

Fig. 14. Interaction plot for air voids versus pulse counts

In Fig. 13, as the voids filled with asphalt (VF) values of the specimens decrease (that is showing the effect of polypropylene modification) the strain accumulation decreases with increasing pulse counts again. This is quite clear from the interaction plot.

In Fig. 14, the changing pattern of strain accumulation can be visualised by the decrease in air void values and increase in pulse counts.

Fig. 15 stands for the rest period change patterns. For example, for 7000 pulse counts, the reader may realise that the 500 ms load – 500 ms rest loading pattern ends in a very destructive strain accumulation value when compared to 500 ms load – 2000 ms rest loading pattern. This is expected from the materials engineering point of view.

Fig. 16 is another interpretation of Fig. 15. This time unit weight values come into the scene and with the decrease of these values, that means with polypropylene modification, and increase in rest periods, strain accumulation obviously decreases.

In Fig. 17, the air void values increase coupled with the in-

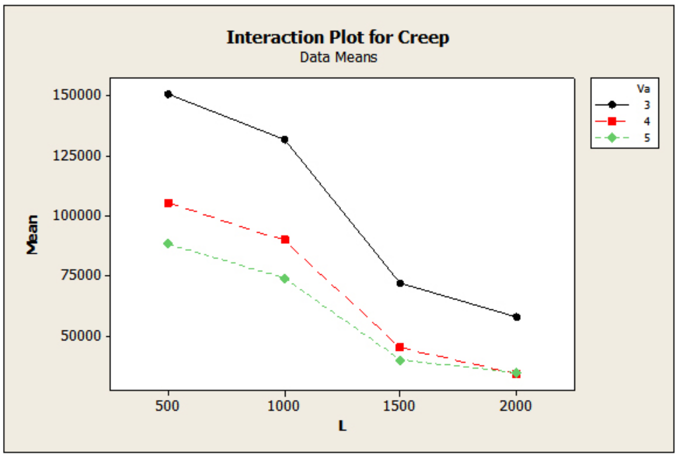

Fig. 17. Interaction plot for air voids versus pulse width

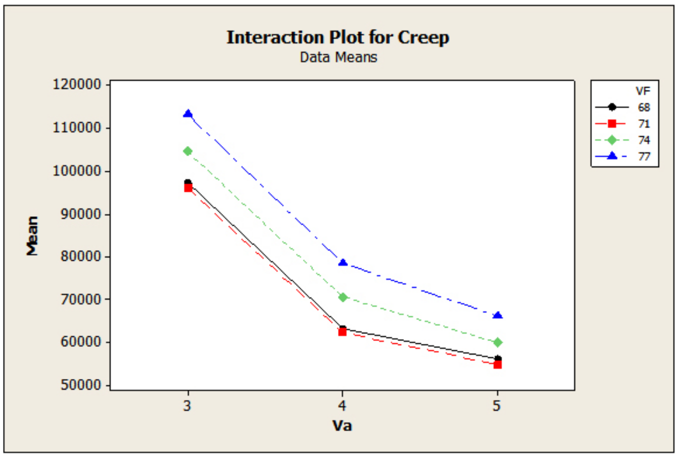

Fig. 18. Interaction plot for voids filled with asphalt versus air voids

crease in rest period patterns of the loading results in an acceptable strain accumulation decrease.

The decrease in VF (voids filled with asphalt) values which is a clear indication of polypropylene fiber modification together with the air voids increase is, this time, generating the decrease in strain accumulation.

A similar argument to the above discussions is valid in Fig. 19. Lighter specimens occurring because of the polypropylene modification arm in arm with lesser voids filled with asphalt values end up in a more desirable rheological behaviour.

Up to an acceptable point which is 16% in this case, the increase in the VMA (voids in mineral aggregate) values corresponding to polypropylene modification decreases the strain accumulation coupled with lighter specimens. From this point on, the increase in VMA values corresponds to a slight increase in strain accumulation as can be clearly expected for all patterns.

8.2 Three-dimensional parametric analysis results

At this point, some of the very representative three-dimensional plots are presented to show the various interactions between different testing parameters.

In Fig. 21, from the three dimensional interaction plot, the reader can visualise clearly that the increase in air voids coupled with the increase in pulse counts have ended up with a lesser strain accumulation.

Similar arguments are valid for Fig. 22. That means lighter specimens with longer rest periods have ended up with a lesser accumulated strain which is really desirable.

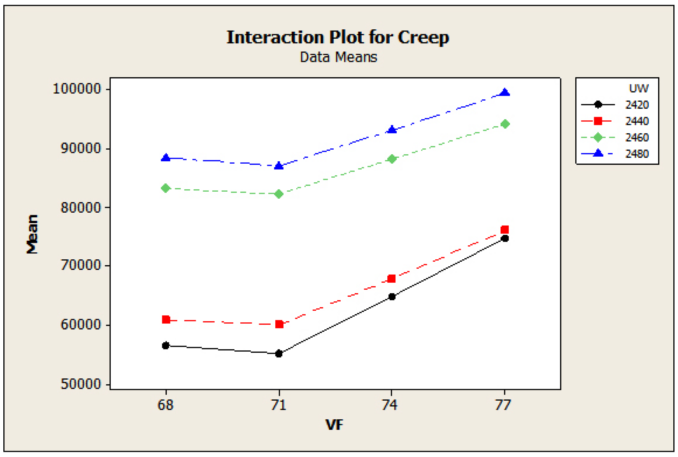

Fig. 19. Interaction plot for unit weight versus voids filled with asphalt

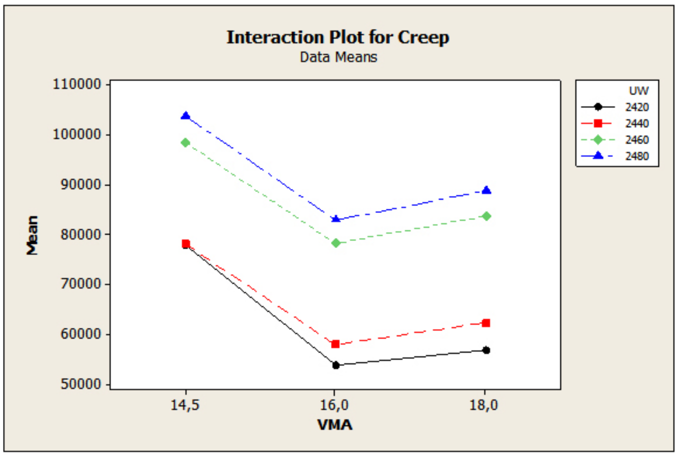

Fig. 20. Interaction plot for unit weight versus voids in mineral aggregate

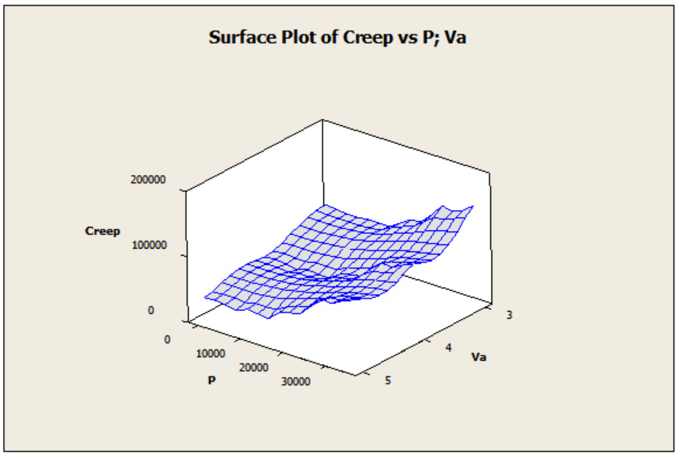

Fig. 21. Surface plot for strain accumulation versus pulse count and air voids

Higher air voids together with longer rest periods which is representing the effect of polypropylene modification plus slower speeds of the traffic (longer rest periods) end up with a more desirable pavement behaviour with considerably lesser strain accumulation.

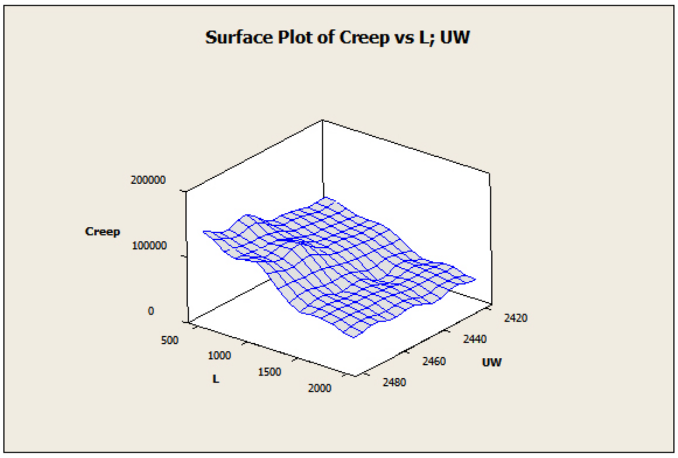

Fig. 22. Surface plot for strain accumulation versus pulse count and unit weight

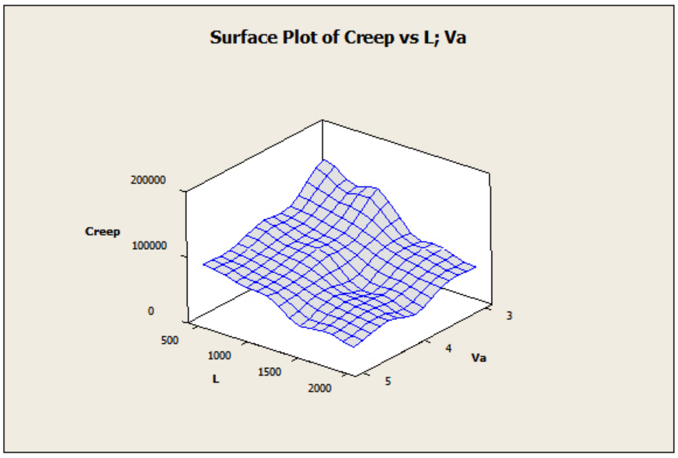

Fig. 23. Surface plot for strain accumulation versus pulse width and air voids

Fig. 24 shows the very positive effect of polypropylene modification together with lesser voids filled with asphalt values.

In Fig. 25 the general snapshot of the parametric study of mean effects of accumulated strain analysis can be visualized in a compact manner.

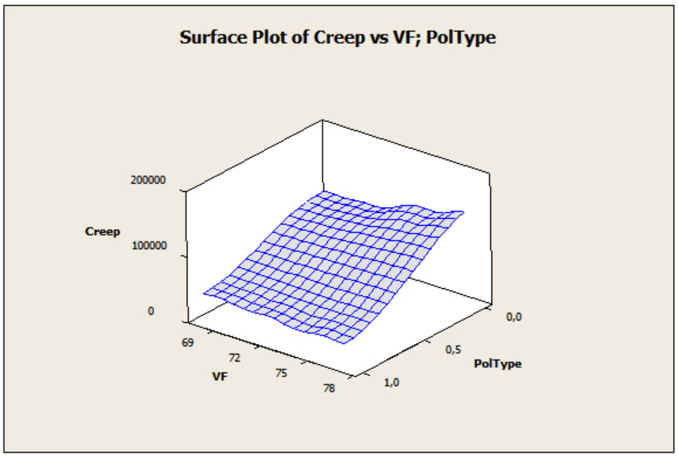

Fig. 24. Surface plot for strain accumulation versus voids filled with asphalt and polypropylene type

The reader must not lose sight of that the obtained results at the end of this and similar kind of studies is valid only for specific types of aggregate sources, bitumen, polymer modification techniques, aggregate gradation, mix proportioning, modification technique and laboratory conditions. Therefore it is not possible to generalise the findings that have been obtained throughout these studies for another specific case.

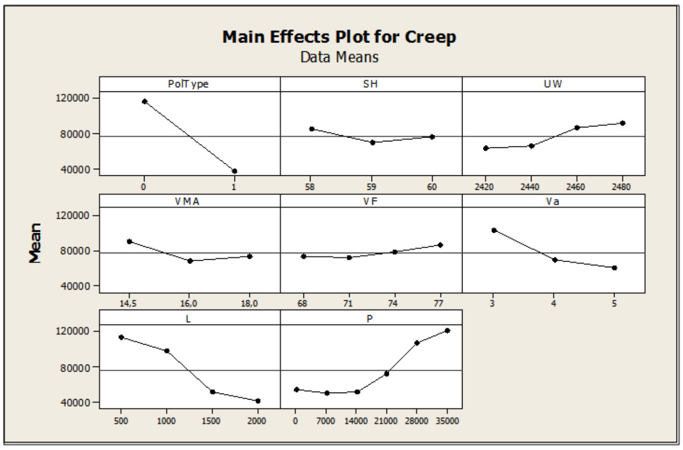

Fig. 25. Whole trends for the parametric study of main effects of accumulated strain (rutting potential) analysis

9 Conclusions

Wet basis M-03 type polypropylene fiber modification of dense bituminous mixtures is an efficient way to alter the mechanical properties and in this study, Marshall specimens, which are tested under repeated load creep loading by the use of UTM 5-P, have shown a considerable improvement in their service lives (5-12 times longer lives) by the aid of this modification. In addition to this fact, a novel approach for the prediction of mechanical properties such as accumulated strain development (rutting potential) at the end of repeated load creep tests carried out by UTM-5P utilizing neuro-fuzzy modelling has been proposed. The rutting potential can be explored by this means in a perfect manner as a main departure from the other published studies in this field. A very wide range of experimental studies covering the mechanical properties of asphalt concrete have been carried to obtain an experimental database which can be used for neuro-fuzzy training. To illustrate the applicability and effectiveness of neuro-fuzzy model, six physical properties of standard Marshall specimens such as polypropylene type, specimen height, unit weight, voids in mineral aggregate, voids filled with asphalt, air voids and two repeated creep test properties such as rest period and pulse counts were modelled in order to predict the rutting potential of asphalt specimens. As a result, neuro-fuzzy models have been proposed for strain accumulation values. The reader should bear in mind that the proposed model and parametric studies are valid for the ranges of the experimental database used for modelling. The reader must also not lose sight of that the obtained results at the end of this and similar kind of studies is valid only for specific types of aggregate sources, bitumen, polymer modification techniques, aggregate gradation, mix proportioning, modification technique and laboratory conditions. Therefore it is not possible to generalise the findings that have been obtained throughout these studies for another specific case. To obtain the main effects of each variable on accumulated strain, a wide range of parametric studies has been performed by using the neuro-fuzzy model. As a result, the proposed neuro-fuzzy model and formulation of the available accumulated strain development of Marshall specimens is quite accurate, fast and practical for use by other researchers studying in experimental pavement engineering field.

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