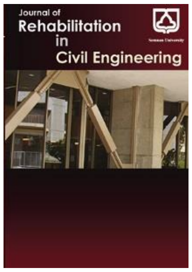
Journal of Rehabilitation in Civil Engineering 8-2 (2020) 92-113



journal homepage: http://civiljournal.semnan.ac.ir/

Laboratory Study and Investigation on Significance Level of Fatigue Phenomenon in Warm Mix Asphalt Modified with Nano-Silica

S.K. Badroodi[1], **M.R. Keymanesh**[2*], **Gh. Shafabakhsh**[3]

1. Department of Management, Payame Noor University, P.O. Box 25359-3650, Tehran, Iran
2. Department of Management, Payame Noor University, P.O. Box 25359-3650, Tehran, Iran
3. Faculty of Civil Engineering, Semnan University, Semnan, Iran

Corresponding author: *mrkeymanesh@pnu.ac.ir*

ARTICLE INFO

Article history:
Received: 19 March 2019
Accepted: 06 October 2019

Keywords:
Warm Mix Asphalt,
Fatigue, Self-Healing,
Reclaimed Asphalt Materials,
Nano-Silica,
Neural Network.

ABSTRACT

The present research aims to conduct laboratory assessment on fatigue phenomenon in warm mix asphalt modified with nano-silica and including reclaimed asphalt pavement materials by the aid of review on self-healing behavior and measurement of validity of laboratory results by modeling via neural artificial network in neutral network of SPSS software. For this purpose, 2% weight of sasobit and 3, 5 and 7 % weights of base bitumen-to-bitumen (85-100) were added and they were stirred up by high-cut mixer. Then, the specimens of four-point flexural test were made by the reclaimed bitumen samples. The quantities of 0, 70 and 100% of reclaimed asphalt materials were utilized for aging simulation process in warm mix asphalt to build four-point flexural tested slabs. The findings indicate that adding nano-silica may essentially affect rising self-healing level in warm mix asphalts. The current study intends to present a model based on neural artificial network technique to predict behavior of warm asphalt specimens including different nano-material contents and to compare them with the laboratory results for measurement of validity of the given model. The given results show high precision of the model at level of 0.951.

1. Introduction

1.1. Self-Healing in Asphalt Mixtures

The engineering materials were designed with self-healing property by entering diffused catalyst and microcapsules including healing factor in polymeric matrix for the first time at early 2001 [1]. The self-healing process starts in this way that the crack at the beginning will release healing factor among the crack by splitting the existing microcapsules in self-healing polymeric structure and this factor starts polymerization by contact to catalyst and healing factor and as a result this process approaches two ends of the fissure to each other and will lead to connection of two ends of crack [2]. Various researchers observed that self-healing mechanism might be divided into two classes in asphalt mixtures: a) Improvement of adhesion in connection between aggregates in asphalt mixture and b) Improved cohesion and adhesion of bitumen adhesive. Some researchers argue that as cracks are connected together due to Van der Waal's forces, the molecules are distributed from one direction to another so that the cracks are healed perfectly and resistance of asphalt reaches to the original level again [3]. Bitumen plays key role in asphalt self-healing process [4]. The main problem of self-healing process lies in this point that the self-healing process occurs very slowly in asphalt pavement at ambient temperature so that the rate of growth of cracks and failure is greater than self-healing ratio under normal condition and asphalt may not be repaired automatically in practice. Likewise, traffic flow may not be adequately blocked on the road to improve self-healing [5-7]. Self-healing is a driven process by low viscosity at high level and it depends on temperature and time of healing. Similarly, temperature and time of healing also depend on type of bitumen [8]. Hardness and resistance of bitumen materials are reduced as the bitumen materials are subject to redundant loading [9]. The micro-crack starting trends, expansion and macro-crack processes along loading cycles have been examined by several researchers [10]. Returning hardness to materials, rising lifetime of fatigue and returning resistance were observed for the first time in vitro by a fatigue test with relaxation periods in 1960. The results of analysis on effects of reclaiming agents (additives) on self-healing potential of asphalt materials were dispersedly reported. Lee et al. [11] compared healing of asphalt mixtures with different reclaiming agents e.g. SBR, SBS and GIL. They concluded that the asphalt mixture might show the best performance by SBS reclaiming factor with respect to fatigue, fractures and healing. The assessment conducted by Kim on effect of SBS reclaiming factor in healing and cracking properties indicated that SBS factor might have relatively small impact on rate of healing in asphalt mixtures [12]. In addition, Mr. Little deduced that adding SBS and Low Density Polyethylene (LDPE) might act as a filler system so that it could stop the healing potential in pure bitumen [13]. The negative effect of polymeric additive on healing may be interpreted with reliance on effect of polymer on bitumen composition structure. The polymeric networks are extended in bitumen by this factor and absorbing more compatible elements with bitumen by this factor is assumed as the reason for distension in the bitumen and therefore what remains form this process is the bitumen with higher asphaltene elements. The bitumen with higher density asphaltene is less likely susceptive for flow and healing process. Mr. Little also described possible effect of Hydrated Lime (HL) on healing potential in bitumen. Process of adding hydrated lime to bitumen with high aromatic property and the minimum asphaltene elements (AAM) showed the lower potential for healing. However, addition of hydrated lime to AAD bitumen as very dependent bitumen and another increased healing capacity by breaking high asphaltene. This process may be due to surface tension of hydrated lime or internal reactions with some fraction of more polar asphaltene in AAD bitumen that can increase flow and healing properties [13]. Bahia [14] tested two samples of non-modified bitumen, two modified adhesives with plastomer and to to modify samples with oxygen (oxidized). He concluded that the modified adhesive showed better HPI (healing properties of index) level than the original bitumen. The findings indicated that the modification technology could change healing performance.

1.2 Literature Review

The hot asphalt pavement may produce a lot of greenhouse gases because of performance at high temperature. Utilization from warm asphalt technology has been noticeably increased linearly with environmental protection and reduced energy consumption in recent years. There are various technologies for producing warm mix asphalt. Quantao Liu et al. (2017) compared healing behaviors induced by Warm Mixture Asphalt (WMA) made with Aspha-Min and conducted by steel fibers and Hot Mixture Asphalt (HMA) conducted by steel fibers by destruction-healing-destruction test. The results of tests indicated that the rate of self-healing was a little higher in WMA mixture made by Aspha-Min than in HMA mixture and also the inductive heat might extremely increase self-healing potential in WMA [15]. By analysis on effect of two additives including Sasobit and Evotherm in specifications of healing of fracture in warm asphalt (WMA), XIN Lu (2013) observed that these two additives did not highly change healing specification of breakdown in binder layer of asphalt, except sasobit might increase initial dynamic shear modulus and make fatigue life longer [16]. By evaluation of healing specifications of warm mix asphalt (WMA) including sasobit and Advera, Munir Nazzal et al. (2012) found that despite improvement in adhesive intrinsic healing, both additive might have adverse effect in cohesive intrinsic healing behavior in asphalt binder mixture and also sasobit reduced rate of fracture [17]. By evaluation of warm mix asphalt (WMA) including Nano-Hydrated Lime (NHL) and Regular Hydrated Lime (RHL), Aboelkasim Diab et al. (2013) indicated that instead of using Regular Hydrated Lime (RHL) with weight dose (20%) for reduction of fissure, Nano-Hydrated Lime (NHL) might be used with binder weight dose (5%) [18]. By comparison of warm mix asphalt (WMA) comprising of Nano-Hydrated Lime (NHL) and Regular Hydrated Lime (RHL), Abolekasim Diab et al. (2014) concluded that using Nano-Hydrated Lime (NHL) could be more efficient method in reducing fissures than by Regular Hydrated Lime (RHL) [19]. Jianchuan Cheng et al. (2013) explored effect of hydrated lime particles on humid sensitivity of warm mix asphalt (WMA). The results showed that the mixture including Sub-Nano Hydrated Lime (SNHL) might increase Indirect Tensile Strength (ITS) up to 8% and Tensile Strength Ratio (TSR) to 10% compared to the mixture with regular hydrated lime (RHL) content [20]. By evaluation of water-content additives in warm mix asphalt (WMA) e.g. Aspha-Min and Advera, Siyuan Xu et al. (2017) found that these two additives might weaken resistance of WMA mixture against humidity failure [21]. Through their assessment on two types of warm mix asphalts (WMA) out of which one was made by so-called technique (using sasobit) and the other included Zycosoil nano-material, Kavoosi et al. (2013) concluded that the given nano-material might play more effective role in rising humidity resistance in WMA mixture than by other parameters [22]. Zalnejad et al. (2015) reviewed effect of different levels of nano-silica in improvement of physical, rheological and mechanical characteristics of warm mix asphalt (WMA) with 2% sasobit content. The results of tests showed that performance of WMA mixture was improved by rising percent of nano-silica that included little increase in resilient modulus of mixture, improvement in response of pavement to traffic load at 25°C, reducing depth of crack in loading cycles, decreased hardness of the modified sample versus control specimen, longer lifetime of fatigue in asphalt concrete and reduced depth of fissure [23]. By their laboratory investigation in warm mix asphalt (WMA) reinforced by jute natural fibers and synthetic poly-olefin-Aramid (FORTA) fibers, Aliha et al. (2017) found that WMA mixture with FORTA fiber content showed better resistance to growth of crack than WMA mixture including jute fibers [24].

1.3. Statistical Models

Five methods are available to enter variables in regression model. These techniques have been already designed in computerized programs and researchers allow computerized program during adaption of these techniques to run automatically analysis. These methods are as follows:

1) Enter Method: In this technique, all independent variables enter in the analyses together.

2) Stepwise Method: Stepwise method enters variables in analysis one by one. Namely, firstly a variable enters the analysis with the highest correlation coefficient to the dependent variable. In this method, order-preference for entering variables is not available to researcher.

3) Remove method: This technique removes. The remove method is similar to enter method, but it is not frequently used in multivariate regressions because it does not perform analysis of variance.

4) Backward method: In this method, all independent variables initially enter in the model similar to enter method, but unlike enter method the less effective variables are excluded from the equation one after another until it reaches to the maximum level.

5) Forward method: Firstly, simple correlation is calculated among each of independent variables with the dependent variable and then an independent variable enters in analysis with the highest correlation to the dependent variable [25].

Enter Method has been utilized in the present research.

1.4. Research Objective

The current research aims to conduct laboratory results for fatigue phenomenon in warm mix asphalt modified by nano-silica and with the contents of reclaimed asphalt materials by the aid of self-healing behaviour using neural artificial network by means of SPSS software. The addition of nano-silica increases the bursting at mid-temperatures, which can be due to the very high level of nanosilica, which, by placing in the bitumen network, artifies the bitumen network and increases the asphalt mix's resistance to intermittent loading [26]. In this research, we try to investigate the effects of nano silica and the healing phenomenon on recovered semi-warm asphalt mixtures.

2. Methodology

2.1. Consuming Materials

2.1.1. Aggregate Materials

The grading of stone materials used in this study is the average continuous grading level for warm mix asphalt relating to Topeka layer (stone-filled sheet asphalt) in accordance with Journal No 101 of technical and general specifications of routes. The limits of this grading are given in Table 1.

Table 1. Continuous grading of warm mix asphalt for pavement layer.

Screen size	19mm (3.4inch)	12.5 mm (1.2inch)	9.5 mm (3.8inch)	4.75 mm (No 4)	2.36 mm (No 8)	0.3 mm (No 50)	0.075mm (No 200)
Rejected percent	100	95	-	59	43	13	6

The used materials are of limey type in this study and their specifications are presented in Table 2.

Table 2. Characteristics and specific weight of stone materials.

Type of materials	Apparent specific weight (gr/cm^3)	Breakdown in both fronts (%)	Los Angeles erosion (%)	Water absorption (%)
Limey	2,69	95	21.3	1.68

2.1.2. Bitumen

The bitumen used in this study is of bitumen Penetration degree (85-100) type made in Isfahan J-oil refinery. The characteristics of the bitumen are given in Table 3.

Table 3. Specifications of bitumen used in building of specimens.

Characteristic	**Quantity**	**Standard**	**Allowed range**
Permeation degree (deci-mm)	86	ASTM D-5	85-100
Softness point (C°)	50	ASTM D36	45- 52
Flaming point (C°)	225	ASTM D-92	Min 225
Rotary low viscosity at 135degrees η (Pa.S)	3.25	ASTM D-4402	Max 3
Ductility (cm)	100	ASTM D-113	Min 100
Purity degree (%)	99.5	ASTM D2042-76	Min 99
Weight loss (%)	0.05	ASTM D-6	Max 0.8

2.1.3. Reclaiming Additive (Nano-Silica)

The characteristics of nano-silicon dioxide are shown in Table. The nano-silicon dioxide or silica is the most abundant material found in crust of earth. This compound has structure similar to diamond with chemical formula (SiO_2). The chemical compounds and physical properties of nano-silica are described in Table 5.

Table 4. Constituent compounds of nano-SiO_2.

SiO_2	Ti	Ca	Na	Fe
≤ 99%	< 120ppm	< 20ppm	< 50ppm	< 200ppm

Table 5. Physical properties of nano-SiO2.

Diameter (nm)	Surface volume ratio (m^2/g)	Density (g/cm^3)	Melting point (°C)
20-30	130-600	2.1	1’600

2.2. Laboratory Plan and Method of Production of Specimens(Materials and Methods)

The optimal percent of bitumen was determined by the aid of Marshal's tests and asphalt specimens were made with optimal bitumen percent under various controlled and modified conditions. Wet mixture method was utilized for preparation of the reclaimed bitumen. Initially, 1000g of bitumen (85-100) was heated to reach to 135°C until melting flow point. Then, it was put under high-cut mixer device (homogenizer) at speed 4000rpm. The amount of 2% of sasobit was gradually added to the bitumen and then it was mixed by homogenizer device and specimen became cold during 15min and the reclaimed bitumen was prepared for producing asphalt samples. Likewise, the reclaimed bitumen was prepared and used with 0, 3, 5 and 7% of weight of bitumen. Similarly, the amounts of 0, 70 and 100% of reclaimed asphalt materials were used as alternate for regular materials in building of asphalt slabs in order to analyse aging effect in fatigue phenomenon. The relaxation time is deemed as one of parameters that are effective in self-healing performance of asphalt mixture which has been examined in several studies. Among the foremost items existing in relaxation time one is time period and another item is number of their use. Reduction of dynamic shearing modulus (G*) consists of the main effect for using relaxation periods in fatigue performance in bitumen adhesives. Two relaxation periods have been designated with 24h time in this study after first and second loadings. The four-point bending test device performs the fatigue strength test according to the AASHTO T 321-07, EN 12697-24 and T 0739-2011 standards. The main objective of this test is to provide a model for predicting the fatigue life of asphalt, which is carried out through standard samples in the form of a beam. This machine can apply repetitive bending loads on the asphalt samples and can measure the applied load and the deformation. The fatigue test is performed by placing the asphalt beam under a four-point repetitive loading at a specific strain level. In general, the fatigue beam test is performed by the fixed stress and fixed strain methods.

3. Results and Discussions

Percent of additives has been selected with respect to analysis of previous studies. *R* denotes quantity of replacement with the recycled materials, *N* stands for amount of consuming nano-silica and *S* expresses exerted constant strain level in terminology of specimens in these figures.

The fatigue age has been compared in asphalt specimens with and without different quantities of recycled materials including various quantities of nano-silica under constant strain levels 400μm and 800μm in Figs 1 and 2. As it seen, the specimens with 5% contents of nano-silica have shown longer fatigue age.

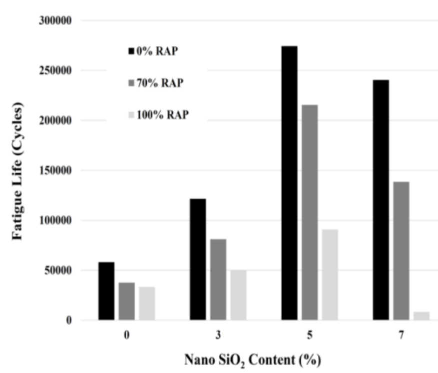


Fig.1. Comparison of fatigue age in asphalt specimens with and without various quantities of recovered materials with different contents of nano-silica under constant strain level 400μm.

The self-healing quantity has been indicated for asphalt specimens with and without various quantities of recycled materials including optimal content of nano-silica under constant strain level (400µm and 800µm) in Figs 3 and 4.

As it observed in Figs 3 and 4, following to rising age of asphalt specimens, the rate of elastic stiffness is reduced in them. This is visible in all samples with any content of reclaimed materials. As the necessary period is allocated to the specimen for self-healing, it is seen that noticeable lost percent of this elastic stiffness will be returned to the initial condition. The samples were relaxed for 24h in these specimens after first and second loadings.

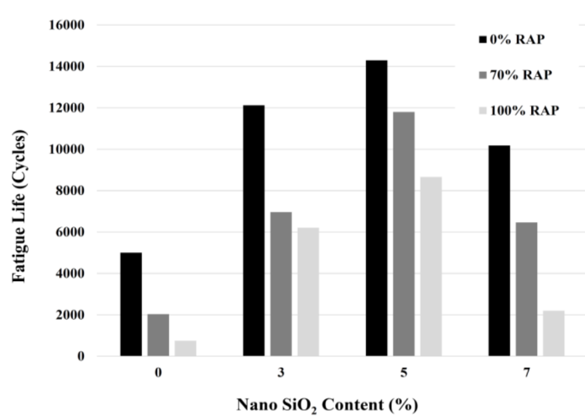


Fig. 2. Comparison of fatigue age in asphalt samples with and without different quantities of recovered materials including different contents of nano-silica under constant strain force 800µm.

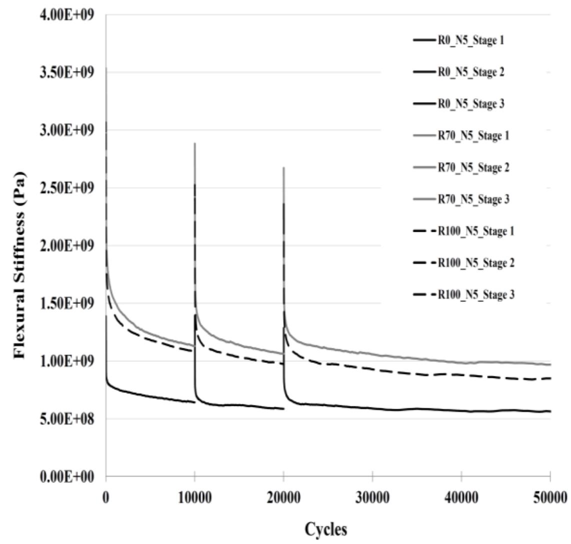


Fig. 3. Comparison of self-healing level in asphalt samples with and without different quantities of recycled materials including different contents of nano-silica under constant strain force 400µm.

The given mechanism occurred for bitumen materials at three stages that would lead to recovery of intrinsic and mechanical adhesive property of bitumen partially or wholly along the breaking surface (crack). These three stages take place in two phases: First phase is viscoelastic self-healing that is related to creation of joint and reconnection among surface of aggregates and bitumen adhesive. The second phase includes viscose self-healing that is time-dependent and it is related to creation of bond in bitumen materials where if there is adequate time it may occur perfectly and it may lead to relatively full recycling and or perfect recovery of lost mechanical properties. Regardless of putting additives, bitumen materials include self-healing property alone as well and it may increase age of pavement servicing along with relatively intrinsic failure property such as the created cracks in servicing age.

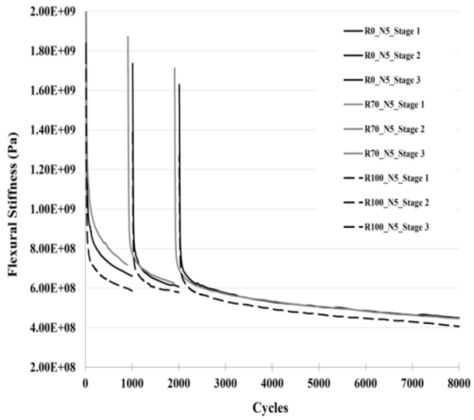


Fig. 4. Comparison of self-healing level in asphalt samples with and without different quantities of recycled materials including different optimal contents of nano-silica under constant strain force 800µm.

With respect to Figs 3 and 4, it is seen that elastic stiffness is added in specimens as quantity of Reclaimed Asphalt Pavement (RAP) materials is increased.

Due to aging, Reclaimed Asphalt Pavement (RAP) materials possess high hardness. However the used additives e.g. sasobit and nano-silica could prevent from more stiffness of bitumen and lead to correction of warm asphalt mixture behaviour. Due to creation of lesser cumulative failure quantity under strain level (400µm), it is seen higher percent of self-healing has been achieved at this strain level. Self-healing rate will be reduced by rising strain and whereas self-healing trend is a function of failure accumulation rate so it can be mentioned higher strain level has accelerated failure accumulation trend and it reduces self-healing potential for asphalt molecules within a short period of time.

The self-healing percent of reclaimed specimens has been compared with their initial states with respect to the rates of their elastic modulus in Figs. 5 and 6. The healing effect has been expressed as hardness improvement compared to initial hardness. It is seen by looking at the results that the reclaimed specimens noticeably recover their elastic stiffness to the great extent. It is observed according to fatigue age trend that the samples including 5% contents of nano-silica have shown higher self-healing percent.

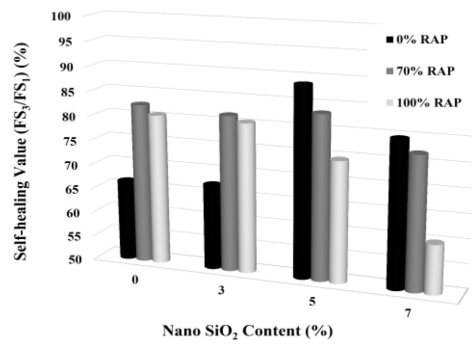


Fig. 5. Comparison of self-healing level in asphalt samples with and without different quantities of recycled materials including different optimal contents of nano-silica under constant strain force 400µm.

By comparing self-healing level in asphalt samples with and without different quantities of reclaimed materials including various quantities of nano-silica under constant strain levels of 400µm and 800µm, it is observed that the self-healing level is extremely increased at strain lower levels because of adequate time for recovery of strains and healing of micro-cracks.

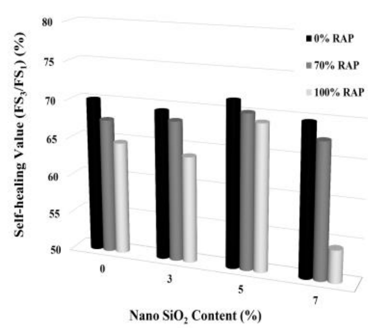


Fig. 6. Comparison of self-healing level in asphalt samples with and without different quantities of recycled materials including different optimal contents of nano-silica under constant strain force 800µm.

3.1. Presentation of Fatigue and Self-Density Model and Analysis of Effect of Parameters on it Using Statistical SPSS (18) Software

This study intends to approximate fatigue model. In order to be able to determine the effect of each phenomenon independently, we used the Enter Method modeling method To this end, initially dependent variable (fatigue and self-density) and independent variables (percent of nano-silica and RAP percent) are defined for samples in SPSS (18) statistical software for the model and bivariate Pearson method was employed to calculate correlational coefficients to control correlation among dependent and independent variables. Determination of rate of coordination in variance of two variables is deemed as the objective for bivariate correlation study. For this purpose, appropriate parameters are employed according to calibration scales for variables. Whereas the interval scale is used with normal bivariate distribution to measure variables in most of bivariate correlation studies thus calculated correlation coefficient in such studies includes Pearson's momentum correlation coefficient or briefly known as Pearson's correlation coefficient. Overall, dependent variable should be correlated with independent variable at higher than level 0.5 and at the same time independent variables should be significant at level lesser than 0.5. The effective variables in prediction of statistical model are described in the following table where two types of numerical and descriptive (coded) variables in modelling.

Table 6. Effective variables in the model.

<table>
<tr><td rowspan="2">Variable</td><td rowspan="2">Abbreviated title</td><td colspan="6">Encoding</td></tr>
<tr><td colspan="2">1</td><td colspan="2">2</td><td colspan="2">3</td></tr>
<tr><td>Fatigue</td><td>Fatigue</td><td colspan="6">Without code</td></tr>
<tr><td>Self-density</td><td>Healing</td><td colspan="6">Without code</td></tr>
<tr><td>Nano-silica</td><td>N</td><td>0%</td><td colspan="2">3%</td><td colspan="2">5%</td><td>7%</td></tr>
<tr><td>RAP</td><td>R</td><td colspan="3">0</td><td colspan="2">70</td><td>100</td></tr>
<tr><td>Strain</td><td>S</td><td colspan="3">400</td><td colspan="3">800</td></tr>
</table>

After determination of variables for modelling, it is necessary to collect related statistics and data about variable for modelling. The conducted tests in laboratory are assumed as information reference. In those studies for which regression analysis is employed usually prediction of one or more criterion variables is deemed as goal among one or more prediction variables. The multiple-regression method is employed if this goal is to predict one criterion variables between several prediction variables at the same time. The multivariate regression model is utilized if it is intended to predict several target criterion variables out of prediction variables or their subset. The multiple regressive studies aim to find prediction variables in order to forecast variance of criterion variable separately and or jointly. The prediction variables enter in regressive analysis by different methods. Here three basic techniques are discussed:

a) Enter method; b) Stepwise method, and c) Hierarchical method (AHP)

All prediction variables enter analysis at the same time in enter method.

In stepwise method, the first prediction variable enters the analysis based on the highest 0-order correlation coefficient with criterion variable. Then, other prediction variables enter the analysis according to separated (partial) and -separated (semi-partial) correlation coefficient. After entry of any new variable in this method, separated and -separated correlation coefficient is revised as the last input variable for all variables which have already entered and if it has lost significance by entry of new variable, it is excluded from the equation. Generally order preference for entry of variables is not available for the researcher in stepwise method.

The order preference of entry of variables is considered by researcher based on a theoretical or empirical framework in hierarchical method. In other words, researcher personally makes decision about order preference of entry of variables in analysis. Such a decision is made before starting analysis that can be based on three major principles in the following:

- Cause and effect relationship

- Relationship of variables in the previous studies

- Structure of research plan (e.g. in factorial plans, main effects are firstly analysed and their mutual impacts): Whereas analytic hierarchical process (AHP) method is done with respect to a special theoretical or empirical framework thus it is particularly important in studies. It should be noted that it is necessary to be familiar with statistical and regressive analytical techniques for such type of studies.

Therefore modelling is done in this study using poison regression method. Statistical model aims to find a relationship among prediction function for effective factors in fatigue and self-density (healing) and fatigue-dependent parameters X $_j$, (j=1,2,..,n) and a set including q parameters that denote nano effect, RAP and related strain rate is allocated to them. Thus, two separate analyses are done in two modes. Independent variables should not highly correlated with each other where one of them is related to effect of nano- parameters and RAP and strain level on fatigue and another factor is concerned with analysis on the given parameters in self-density (healing). Hence, fatigue and self-density are separately considered as dependent variables while other parameters are assumed as independent variables.

Poison’s regression model is included in discrete models and it is used when the consequences are rare. Given statistics of this study is non-negative integer therefore this method could model the results well.

The general form of the model is as follows.

$$P(Y_i) = \frac{\mu_i^{Y_{ie-\mu_i}}}{Y_i!} \quad (1)$$

The relationship among fatigue and self-density effect (i=1, 2, 3,…,n) and q-parameter (Xil,Xil,…,Xiq) is expressed as follows.

$$\ln(\mu_i) = \beta_0 + \sum_{j=1}^{q} X_{ij}\beta_j (2)$$

$$\mu_i = E(Y_i) = e^{\beta_i x_i} (3)$$

Yi: Independent variable with Poison's distribution and mean μ_i, *Xi*: Independent variables for intersection (i)

3.1.1. Output of Poison's Regression Model

The results show that the variables are placed at significance level higher than 0.05 and adjusted R^2-value resulting from fatigue is 0.951 and self-density (healing) denotes goodness of fit for the model. The given results from Poison's model are presented in the following table.

Table 7. Results of Poison's regression model in fatigue

Model Information

Dependent Variable	Fatigue
Probability Distribution	Poisson
Link Function	Log

Table 7. (continued)

Case Processing Summary

	N	Percent
Included	24	29.6%
Excluded	57	70.4%
Total	81	100.0%

Table 7 (continued)

Categorical Variable Information

			N	Percent
Factor	N	0%	6	25.0%
		5%	6	25.0%
		5%	6	25.0%
		7%	6	25.0%
		Total	24	100.0%
	R	0%	8	33.3%
		70%	8	33.3%
		100%	8	33.3%
		Total	24	100.0%
	S	400	12	50.0%
		800	12	50.0%
		Total	24	100.0%

Table 7. (continued)
Parameter Estimates

Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test		
			Lower	Upper	Wald Chi-Square	df	Sig.
(Intercept)	8.134	.0042	8.126	8.142	3755150.218	1	.000
[N=1.00000]	-1.089	.0031	-1.095	-1.083	121186.584	1	.000
[N=2.00000]	-.381	.0025	-.385	-.376	23862.899	1	.000
[N=3.00000]	.416	.0020	.412	.420	42335.288	1	.000
[N=4.00000]	0[a]	.	.	.	.	.	.
[R=1.00000]	1.304	.0025	1.299	1.309	267182.484	1	.000
[R=2.00000]	.917	.0026	.912	.923	120061.356	1	.000
[R=3.00000]	0[a]	.	.	.	.	.	.
[S=1.00000]	2.745	.0035	2.738	2.752	613388.451	1	.000
[S=2.00000]	0[a]	.	.	.	.	.	.
(Scale)	1[b]						

Dependent Variable: fatigue
Model: (Intercept), N, R, S

a. Set to zero because this parameter is redundant.

b. Fixed at the displayed value.

Table 8. Results of Poison's regression model in self-density (healing).
Model Information

Dependent Variable	Healing
Probability Distribution	Normal
Link Function	Identity

Table 8. (continued).
Case Processing Summary

	N	Percent
Included	24	29.6%
Excluded	57	70.4%
Total	81	100.0%

Table 8. (continued).
Categorical Variable Information

			N	Percent
Factor	N	0%	6	25.0%
		5%	6	25.0%
		5%	6	25.0%
		7%	6	25.0%
		Total	24	100.0%
	R	0%	8	33.3%
		70%	8	33.3%
		100%	8	33.3%
		Total	24	100.0%
	S	400	12	50.0%
		800	12	50.0%
		Total	24	100.0%

Table 8. (continued).
Parameter Estimates

Parameter	B	Std. Error	95% Profile Likelihood Confidence Interval		Hypothesis Test		
			Lower	Upper	Wald Chi-Square	df	Sig.
(Intercept)	59.732	.5401	58.673	60.790	12232.704	1	.000
[N=1.00000]	3.827	.5774	2.695	4.958	43.930	1	.000
[N=2.00000]	3.680	.5774	2.548	4.812	40.627	1	.000
[N=3.00000]	8.093	.5774	6.962	9.225	196.506	1	.000
[N=4.00000]	0[a]	.	.	.	.	.	.
[R=1.00000]	4.335	.5000	3.355	5.315	75.169	1	.000
[R=2.00000]	6.250	.5000	5.270	7.230	156.250	1	.000
[R=3.00000]	0[a]	.	.	.	.	.	.
[S=1.00000]	9.777	.4082	8.977	10.577	573.499	1	.000
[S=2.00000]	0[a]	.	.	.	.	.	.
(Scale)	1[b]						

Dependent Variable: Healing
Model: (Intercept), N, R, S

a. Set to zero because this parameter is redundant.

b. Fixed at the displayed value.

Significance level that is called *p* or *p*-value is shown in statistical reports as (sig.value) in SPSS. It is a scale or criterion known as significance basis and at the same time is well-known as the first-type error. If the results of difference analysis or relation between variables are smaller than 5%, we can say there is very little random probability for such a difference or relationship and it can be concluded that the given difference or relationship is significant and if this rate is greater than 5% thus there is very high probability for random result and as a result there is no significant relationship or difference among variables. According to statistical view, the null hypothesis may be rejected based on observed data provided it is true. More simply, the random level of observed difference depends on null hypothesis. As this probability is a smaller number, we can more trust in reality of observed difference. Therefore, significance level is zero in statistical tests of this study and there is higher probability for reality of observed difference and it indicates reality of prediction model. The following figures show diagram of dispersion of statistical results in both loading modes in which Xaxis denotes observed results and Y-axis indicates the predicted values.

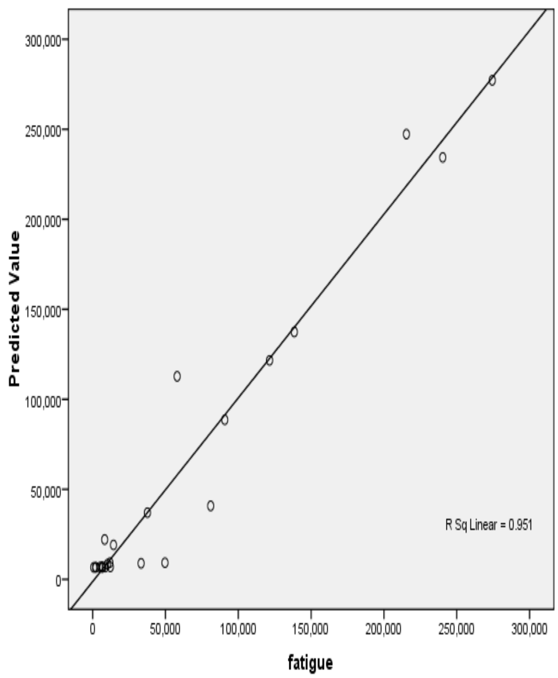


Fig .7. Diagram of dispersion of fatigue laboratory results.

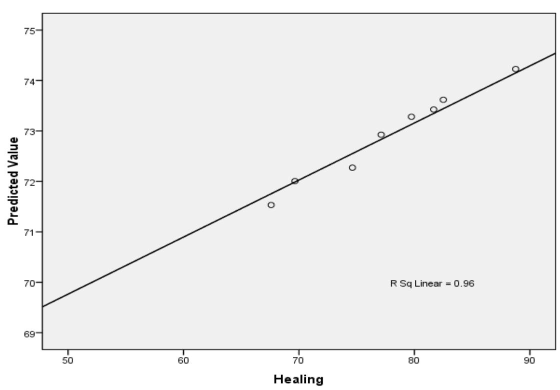


Fig .8. Diagram of dispersion of laboratory results for self-density (healing).

3.1.2. One-Way Analysis of Variance (ANOVA)

It is one of the most frequently used analyses that are utilized in all difference sciences. More simply, it can be implied if there are two or more groups and it is intended to compare scores of a single variables in these groups, this test should be employed.

3.1.2.1. Defaults of One-Way Analysis of Variance (ANOVA)

1. Here fatigue and self-density effect are the dependent variable that should be at interval or relative level.

2. Independent variable (here is percent of nano-silica, RAP percent and strain rate) should be nominal or ordinal.

3. Data should be normally distributed for dependent variables (Kolmogorov-Smirnov analysis).

Mean square results from dividing sum of squares by intergroup degree of freedom and F-ratio is the foremost component in these tables and it results from dividing of intergroup mean square by intragroup mean square. Tables for ANOVA are visible for both loading modes in the appendix. However, F-value in the given tables is statistically significant at level ($P<0.0001$).

3.1.3. Optimization by Neural Network in SPSS

The Artificial Neural Network (ANN) is a mathematical structure that creates mapping among a group of input numbers with a group of output numbers so that *n* output members are obtained from *m* input members. Neural networks are the systems which have inspired from structure and performance of human's brain. Artificial neural networks are composed of elements called neural cells. Any artificial neural cell includes a series of inputs and outputs and a lot of nodes or processing units. The processing unit is a type of mathematical function that is called transform function. Transform function or sigmoid may affect network inputs based on their type and then produce output for neural cell. Mechanism of neural networks is in series and parallel orders. As a result, a group of parallel neural cells, each of which as a specific input produces a group of outputs after processing function. These outputs may be in turn used as inputs for another group neural cells that are connected to the group of primary cells in series. Overall, a group of parallel neural cells forms a layer. Neural networks are assumed as superior tools because of their power, flexibility and ease of use in many uses relating to prediction processes by data analysis. The forecasting neural networks are utilized in cases when the process of complicated. While neural networks need to fewer defaults and modelled structure, it is useful to perceive a general concept of network architecture. Multilayer perceptron network or radius-oriented function is a function of predictors which are also called as independent variables or inputs and it minimizes target variables in outputs. MLP network and RBF, which are used here, include a function of measurements that minimize prediction error for failure toughness. The following figure also expresses the existing relationship among structure of this function. This structure that is well-known as feed-forward architecture in which the internal relations of network are moved forward from the input layer to the output layer without return. The feed-forward neural network is the first and simplest type of artificial neural network. Data are moved in this path only in one direction at this information network that is forward. In fact, data start from input node (neuron) and are passed through hidden layers (if any) toward output nodes. As it mentioned, there is no loop or distance in this network. One can compare the main characteristic of designed neuron model that is composed of weighted input signals by a threshold value and thereby to make decision about the output. If sum of weighted signals is lesser than threshold point, this neuron produces zero outputs unless it produces 1 as output. One-layer perceptron is the simplest type of neural network that is composed of a layer of output neurons. The inputs of this network are attributed directly to the outputs by an array of weights. As a result, this network lacks hidden layer. This network may be assumed as the simplest type of feed-forward neural network. Sum of product of any weight to the input is calculated in any neuron with correspondent subscript. If calculated sum of values in above process is greater than threshold level for any neuron (0 as usual), the neuron is activated and receives active value (1 usually) otherwise it accepts passive value (-1 as usual). The neurons with this method have been utilized in this study. A perceptron can be made using any value for active and passive modes as long as threshold value is placed between two values. Most of perceptron systems include output values from 1 or -1 or threshold value of zero (0).

The multilayer neural network may compute a continuous output instead of step function. A common option which is called logistic function (logic) is expressed as follows:

$$f(x) = 11 + e + x\left\{/\text{displaystyle } f(x) = \left\{/\text{frac}\{1\}\{1 + e\hat{}\{-x\}\}\right\}\right\} \qquad (4)$$

Logistic function is also known as sigmoid function was selected in this section. The single-layer network is equalized with logistic regression model by this choice. The model is widely used in statistical model. The variable of this function includes continuous derivative and also variable of the given derivative is obtained according to the function. This property caused this function to be utilized in feed-forward method. The relationship among derivative of this function with the function is as follows:

$$\acute{f}(x) = f(x)\left(1 - f(x)\right)\{/displaystyle\ \acute{f}(x) = f(x)\left(1 - f(x)\right)\} \qquad (5)$$

With respect to the statistical model used in this study that was in linear regression form, it was characterized that the given function had also linear performance. The following figures indicate diagram of neural network for fatigue and self-density effect.

In this figure:

➢ Input layer comprises of predictor.

Input layer includes invisible nodes or units. The value of any hidden unit is a function of predictor. The precise structure of function depends on two factors: type of network and controllable characteristics by the user.

➢ Output layer includes reactions (responses).

Structure of these networks shows a summary of data of neural network in diagrams.

➢ Description

The data relating to neural network, including dependent variables, indicate number of input and output units, quantity of units and hidden layers and activator functions of them.

➢ Diagram

Diagram shows the network as an unchangeable chart.

➢ Synaptic weights

It indicates coefficients that have been approximated to show relationship among units of a layer and the next layer.

➢ Performance of network

It indicates the results which are utilized for showing goodness of model.

➢ Summary of model

It presents a summary of results of neural network perfectly and separately.

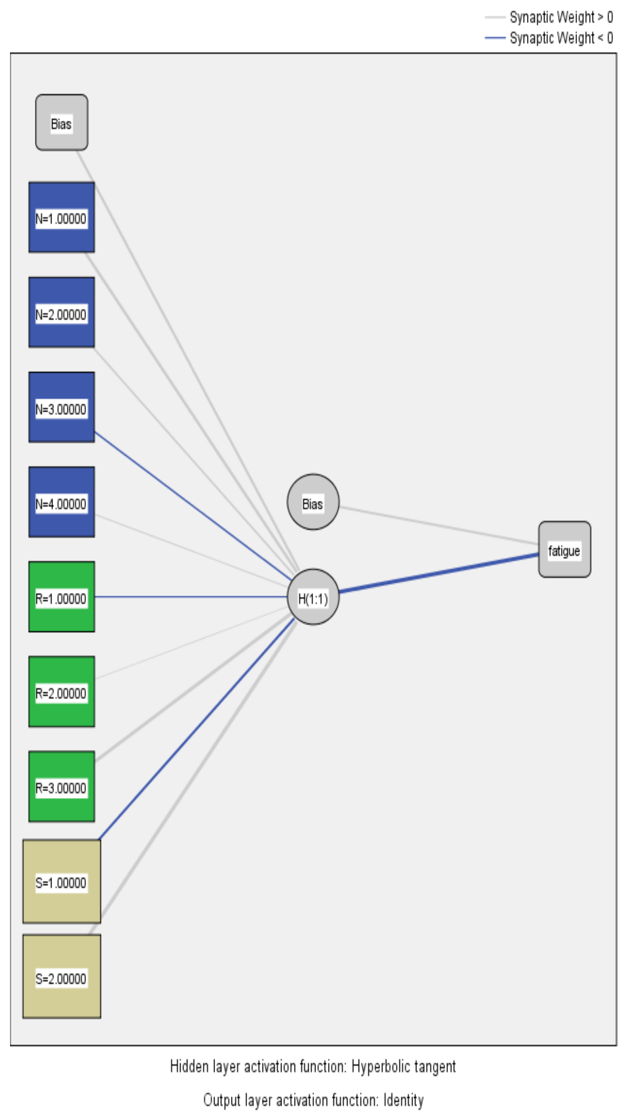


Fig .9. Feed-forward architecture of fatigue.

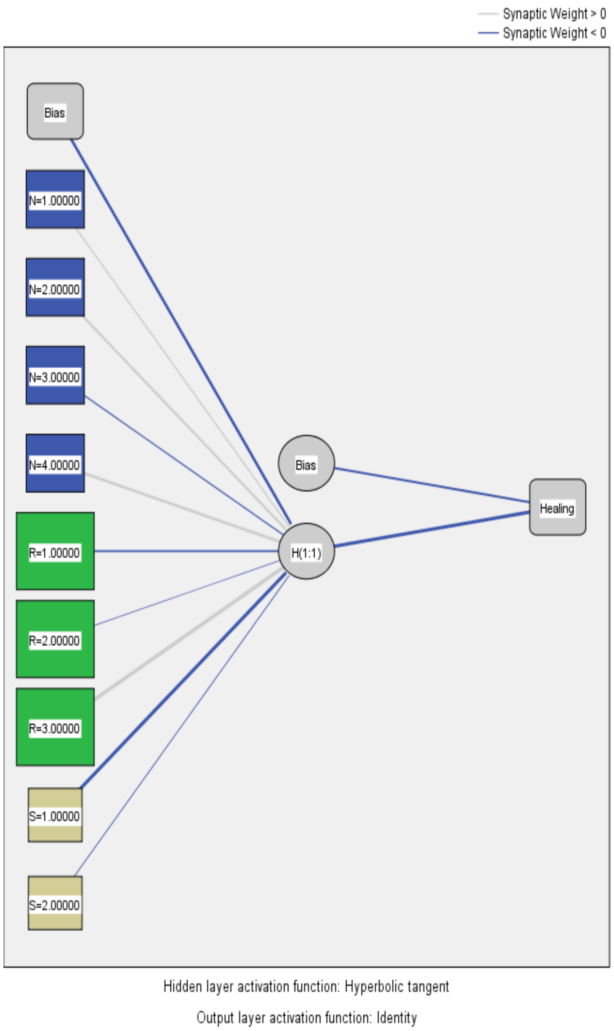


Fig .10. Feed-forward architecture of self-density (healing)

- Results of classification

They present a classification table for any absolute dependent variable in partial and whole form. Any table shows number of cases which have been properly or improperly classified in each of related classifications to dependent variable. Total percent of those modes, which have been properly classified, is also reported. This classification is also visible in the following table.

3-1-4- Analysis of importance of independent variable

It is a sensitive analysis that calculates importance of any predictor in determination of neural network. Finally, a table is presented with a diagram that indicates

importance and normalized importance of any predictor.

Table 9. Importance of independent variables in fatigue.

Independent Variable Importance

	Importance	Normalized Importance
N	.300	75.7%
R	.303	76.5%
S	.397	100.0%

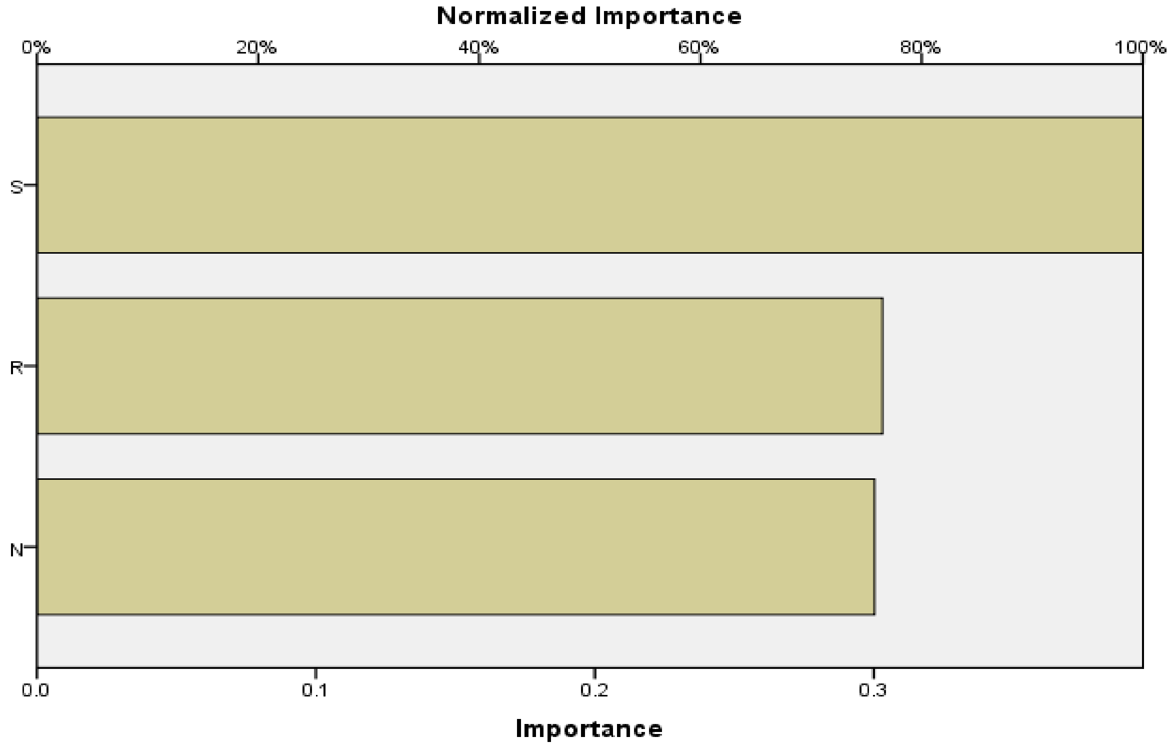


Fig. .11. Diagram of importance analysis for independent variables in fatigue

Table.10. Importance of independent variables in self-density (healing).

Independent Variable Importance

	Importance	Normalized Importance
N	.274	54.4%
R	.503	100.0%
S	.223	44.4%

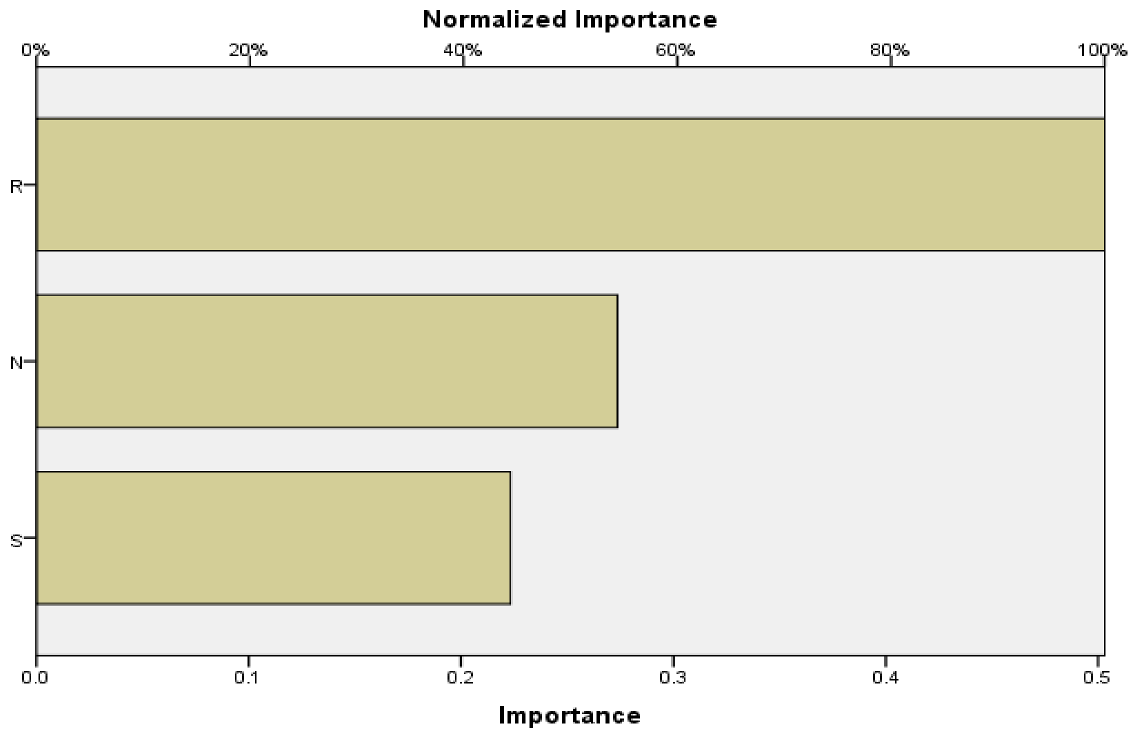


Fig.12. Diagram of importance analysis of independent variables in self-density (healing).

Thus, with respect to analysis in these networks, data structure may be designed by the aid of programming knowledge that can act similar to a neuron. The edges with positive weight may stimulate or activate subsequent passive node and the edges with negative weight may deactivate or control the next connected node (if it was already active). Given the diagrams it is seen in both modes that neurons are significantly related to dependent variable and importance degree has been expressed for each of independent variables in fatigue respectively based on strain, RAP and effect of nano-silica and also in self-density with RAP, nano-silica and strain.

4. Conclusion

The present research aims to conduct laboratory assessment and analysis on significance level of fatigue phenomenon in the warm mix asphalt (WMA) modified with nano-silica and content of reclaimed asphalt pavement materials by the aid of review on self-healing behaviour. The foremost findings of current research are as follows:

- Reclaimed Asphalt Pavement (RAP) materials are highly hard due to aging process. However the used additives e.g. sasobit and nano-silica could prevent from further hardness of bitumen and led to improvement of behaviour of warm mix asphalt.

- Considering the observation of laboratory results ‹By comparison among self-healing in asphalt specimens with and without various quantities of reclaimed materials including different contents of nano-silica under constant strain levels (400µm and 800µm), it is observed that due to adequate opportunity to recover strains and to heal micro-cracks, rate of self-healing is extremely increased at lower strain levels.

- Using analysis of results, we concluded that this model has been built for various testing processes based on artificial neural network technique to predict behaviour of warm asphalt specimens with different percent of nano-materials and comparing it with the laboratory results to validate the given model. The adjusted R^2-value resulting from the model at fatigue level (0.951) denotes goodness of fit for this model.

- Self-healing rate is reduced by rise of strain and whereas self-healing trend is a function of failure collection level, it can be implied that higher strain level has accelerated failure collection level and reduced self-healing potential among asphalt molecules within short period of time.

- With respect to the statistical model used in this study that was linear regression, it was identified the given function had also linear performance.

- With respect to the analysis in neural networks and by the aid of programming knowledge, a data structure may be designed so that it can act similar to a neuron. The edges with positive weight may stimulate or activate subsequent passive node and the edges with negative weight may deactivate or control the next connected node (if it was already active). Given these diagrams it is seen in both modes that the neurons had significant relationship with dependent variable and importance degree has be expressed for each of independent variables in fatigue respectively as strain, RAP and effect of nano-silica and for self-density implied with RAP, nano-silica and strain.

- Due to the use of sasobit in recycled asphalt and the structure of this type, the effect of healing on recycled samples was more evident than typical samples.

REFERENCES

[1] White, S. R., Sottos, N. R., Geubelle, P. H., Moore, J. S., Kessler, M., Sriram, S. R., ... & Viswanathan, S. (2001). Autonomic healing of polymer composites. *Nature*, *409*(6822), 794.

[2] Shan, L., Tan, Y., & Kim, Y. R. (2013). Establishment of a universal healing evaluation index for asphalt binder. *Construction and Building Materials*, *48*, 74-79.

[3] Little, D. N., & Bhasin, A. (2007). Exploring mechanism of H ealing in asphalt mixtures and quantifying its impact. In *Self healing materials* (pp. 205-218). Springer, Dordrecht.

[4] Fischer, H. (2010). Self-repairing material systems―a dream or a reality?. *natural Science*, *2*(8), 720-726.

[5] Qiu, J., Van de Ven, M., Wu, S., Yu, J., & Molenaar, A. (2012). Evaluating self healing capability of bituminous mastics. *Experimental mechanics*, *52*(8), 1163-1171.

[6] Dai, Q., Wang, Z., & Hasan, M. R. M. (2013). Investigation of induction healing effects on electrically conductive asphalt mastic and asphalt concrete beams through fracture-healing tests. *Construction and Building Materials*, *49*, 729-737.

[7] Uchida, K., Kurokawa, T., Himeno, K., & Nisizawa, T. (2002). Healing

characteristics of asphalt mixture under high temperature conditions. *JOURNAL OF PAVEMENT ENGINEERING, JSCE*, *7*, 29p1-29p11.

[8] Bonnaure, F. P., Huibers, A. H. J. J., & Boonders, A. (1982). A laboratory investigation of the influence of rest periods on the fatigue characteristics of bituminous mixes (with discussion). In *Association of Asphalt Paving Technologists Proceedings*(Vol. 51).

[9] Daniel, J. S., & Kim, Y. R. (2001). Laboratory evaluation of fatigue damage and healing of asphalt mixtures. *Journal of Materials in Civil Engineering*, *13*(6), 434-440.

[10] Menozzi, A., Garcia, A., Partl, M. N., Tebaldi, G., & Schuetz, P. (2015). Induction healing of fatigue damage in asphalt test samples. *Construction and Building Materials*, *74*, 162-168.

[11] Lee, N. K., Morrison, G. R., & Hesp, S. A. (1995). Low temperature fracture of polyethylene-modified asphalt binders and asphalt concrete mixes (with discussion). *Journal of the Association of Asphalt Paving Technologists*, *64*.

[12] Kim, B., & Roque, R. (2006). Evaluation of healing property of asphalt mixtures. *Transportation Research Record*, *1970*(1), 84-91.

[13] Little, D. N., Lytton, R. L., Chairl, B., Williams, D., & lTexas, A. M. (1998, August). An analysis of the mechanism of microdamage healing based on the application of micromechanics first principles of Fraci1jre and healing. Lino Lakes, MN: Association of Asphalt Paving Technologists.

[14] Bahia, H. U., Zhai, H., Bonnetti, K., & Kose, S. (1999). Non-linear viscoelastic and fatigue properties of asphalt binders. *Journal of the Association of Asphalt Paving Technologists*, *68*, 1-34.

[15] Shafabakhsh, G. H., Ani, O. J., & Talebsafa, M. (2015). Artificial neural network modeling (ANN) for predicting rutting performance of nano-modified hot-mix asphalt mixtures containing steel slag aggregates. *Construction and Building Materials*, *85*, 136-143.

[16] Liu, Q., Yu, W., Wu, S., Schlangen, E., & Pan, P. (2017). A comparative study of the induction healing behaviors of hot and warm mix asphalt. *Construction and Building Materials*, *144*, 663-670.

[17] Lu X. (2013). Investigation of the Fracture Healing and Mechanism of Asphalt Binders. A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, Washington state university, Department of Civil and Environmental Engineering.

[18] Nazzal, M., Kaya, S., & Abu-Qtaish, L. (2012). Evaluation of WMA healing properties using atomic force microscopy. In *7th RILEM international conference on cracking in pavements* (pp. 1125-1134). Springer, Dordrecht.

[19] Diab, A., You, Z. P., & Wang, H. N. (2013). Using modified creep and recovery tests to evaluate the foam-based warm mix asphalt contained nano hydrated lime. In *Advanced materials research* (Vol. 646, pp. 90-96). Trans Tech Publications.

[20] Diab, A., & You, Z. (2014). Rheological characteristics of nano-sized hydrated lime-modified foamed warm mix asphalt. In *Pavement Materials, Structures, and Performance* (pp. 79-89).

[21] Cheng, J., Shen, J., & Xiao, F. (2011). Moisture susceptibility of warm-mix asphalt mixtures containing nanosized hydrated lime. *Journal of Materials in Civil Engineering*, *23*(11), 1552-1559.

[22] Xu, S., Xiao, F., Amirkhanian, S., & Singh, D. (2017). Moisture characteristics of mixtures with warm mix asphalt

technologies–A review. *Construction and Building Materials*, *142*, 148-161.

[23] Kavussi, A., Qorbani, M., Khodaii, A., & Haghshenas, H. F. (2013). Quantification of parameters affecting moisture resistance of warm mix asphalt using response surface methodology. In *IJPC—International Journal of Pavements Conference, Sao Paulo, Brazil*.

[24] Zalnezhad H., Galooyak S.S., Farahani H., Goli A. (2015). Investigating the Effect of Nano-Silica on the Specification of the Sasobit Warm Mix Asphalt. Petroleum & Coal, 57(5).

[25] Jafari Haghighatpour,P., Kaymanesh, M, Aliha, M., (2018)," Design of Optimized Asphalt Mixture Against Pure Mode Ш Fracture ",Ph.D. Thesis, Payame Noor University(PNU), Tehran- Iran

[26] Ameri, M., Hasani nia, M., Ziari, H., (2014)," Evaluation of fatigue strength of nano-silica-modified asphalt concrete", Transportation EngineeringYear Sixth Number II.