

Presenting asphalt mixtures flow number prediction model using gyratory curves

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Abstract

Pavement permanent deformations due to lack of shear strength in mixture are a major reason of rutting. Any simple test to determine mixtures resistance to permanent deformation isn't distinguished in the 1st level of SUPERPAVE mix design method and prevalent methods for evaluating mixture rut resistance are expensive and time-consuming. Two aggregate types, gradations, asphalt cements and filler types were used in this research to present a prediction model for rutting based on flow number. A mathematical model to estimate flow number of dynamic creep test was developed using model parameters and gyratory compaction slope. The model is validated using Neural Network and Genetic Algorithm and makes it possible to evaluate mixtures shear strength while optimum asphalt content is being determined in laboratory. So not only there is no need to expensive test instruments of rutting or dynamic creep but a remarkable time saving in mix design procedure is achievable.

Keywords: Rutting, Gyratory, Dynamic creep, Flow number, Shear stress curve.

1. Introduction

Increasing loading cycles on pavement leads to cumulative raise in permanent deformation and rutting as a surface depression in wheel path which can cause hydroplaning, reduce pavement drainage capacity, make moisture based deterioration growing rate faster, pavement thickness decreases in rutted zone and finally increase fatigue cracking in flexible pavements [1]. Mentioned parameters introduce rutting as an expensive flexible pavement deterioration mechanism [2]. Rutting could be recognized as a result of mixture volume decrease (pavement consolidation due to traffic (figure 1)), asphalt permanent deformation in constant volume (Plastic deformations due to normal shear stress in mixture (figure 2)) or a combination of them [3]. Another type of rutting is known which is due surface layer abrasion. Surface permanent deformation have the most share among various rutting causes, so considering it in mix design procedure seems essential [3,4].

Various laboratory methods are introduced to evaluate pavement permanent deformation which direct shear, repeated

shear at constant height, dynamic shear modulus test, creep and rutting test. Austria, France, Hungary, Romania and Switzerland use LCPC (Laboratoire Central des Ponts et Chaussées) and Finland, Sweden and Australia use Dynamic creep for rutting evaluation.

The pressure of 300 kPa is applied to specimen in a cycle with 500ms loading and 1500 ms rest at 50°C in dynamic creep test. Drawing specimen cumulative permanent deformation curve versus loading cycles will produce the illustrated curve of figure 3 with three main stages. It is proved that the cycle in which territory phase is started (Fn) (Flow Number) is related to mixture rutting resistance directly [6,7].

This is a time-consuming test and UTM (Universal Testing Machine) which is used as the creep test instrument is expensive and needs skillful operator. So developing a method to distinguish asphalt mixture shear strength in a non-expensive and fast method is necessary.

2. Problem Definition

2.1. Research Target and Essence

Compaction as the most important issue on aggregates structure and positioning has considerable effect on mixtures rut and permanent deformation resistance [9]. It is proved that aggregates rotary or transitive in asphalt mixture due to inadequate compaction will cause permanent deformation

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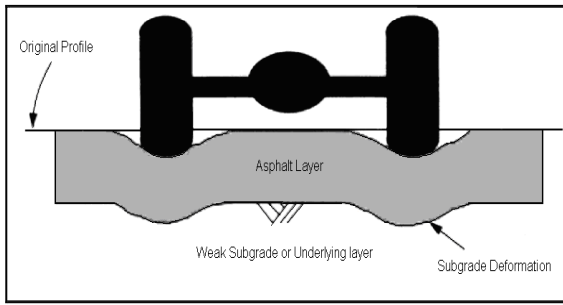


Fig. 1 Rutting due to bottom layers consolidation [5]

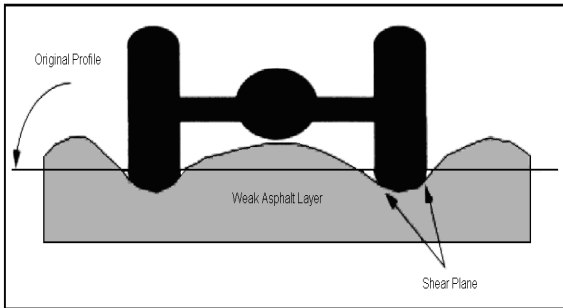


Fig. 2 Rutting due to lack of shear strength in asphalt mixture [5]

along shear planes [10]. On the other hand a weakness point of marshal method which is most applied method of compaction and mix design in Iran is compacting method which doesn't provide a fair simulation according to the researches [11]. Hence gyratory compaction machine (GCM) is used in SUPERPAVE mix design method after 40 years research on rotational compaction method by SHRP. This mix design method involves three levels which are divided by load and traffic. The first level is considered for traffic less than 10^6 ESALs (Equivalent Single Axle Loads) which composes of volumetric analysis and simple tests. Being simple and economical issues make this level interesting for engineers, but lack of performance tests is remarkable here. Simple methods for evaluating asphalt mixture workability should be developed to complete this level.

Asphalt mixtures with various aggregates, asphalt cements, gradation and filler were prepared and a model to predict flow number and consequently rutting resistance were developed after determining OAC for each group and performing dynamic creep test. As a result of this study mixture rutting

potential is predictable in a short time with low cost in laboratory simultaneously with preparing them.

2.2. Literature Review

Lack of a test in 1st level of SUPERPAVE mix design to predict rutting of asphalt mixtures lead a lot of researches focus on this issue in FHWA (Federal Highway Administration), NCHRP (National Cooperative Highway Research Program) and FAA (Federal Aviation Administration) [12]. Other studies in this field using GCM output information will be stated in the following part.

2.2.1. Studies on Compaction Slope of SGC (Superpave Gyratory Compactor)

The idea of using SGC compaction slope was developed for the first time in 2000 [13]. Later studies stated that compaction slope is only an aggregates internal friction property [14]. But according to Mohr-Coulomb formula, shear stress (τ) is a function of cohesion (C) and internal friction angle (Φ). Although other studies proofed SGC compaction slope effect on rutting, but this parameter can't be used singly to predict asphalt shear strength performance.

$$\tau = C + \sigma_n \times \tan(\phi) \quad (1)$$

2.2.2. Studies Considered a Part of Compaction Slope Curve

Researches define various indexes for asphalt rutting resistance with studying volumetric mass versus curve. TDI (Terminal Densification Index) which is assumed as compaction curve integral from 4% to 2% voids was one of them. DEI (Densification Energy Index) was defined as 8% to 4% voids in mentioned curve and CEI (Compaction Energy Index) as compaction start to 8% voids integral (Figure 4). Studies showed models based on these indexes were affected by aggregates positioning in molds greatly and wide tests showed this models aren't reliable. [15,16].gyration

2.2.3. Studies on Shear Parameters in Compaction

Gyratory shear strength, gyration number corresponding to maximum shear and gyratory shear slope were defined using gyratory shear curve. Researches performed in Florida and Michigan Universities although there is a relation between APA (Asphalt Pavement Analyzer) rut depth and these parameters but presented models didn't show good relation and aren't applicable [17].

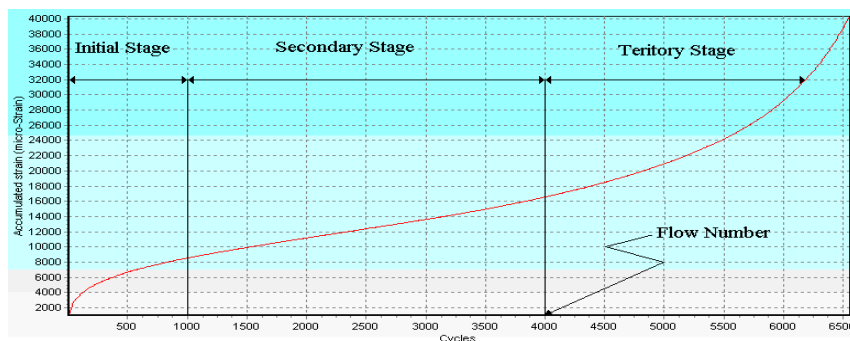


Fig. 3 Three stages of cumulative strain curve versus loading cycles in dynamic creep test [8]

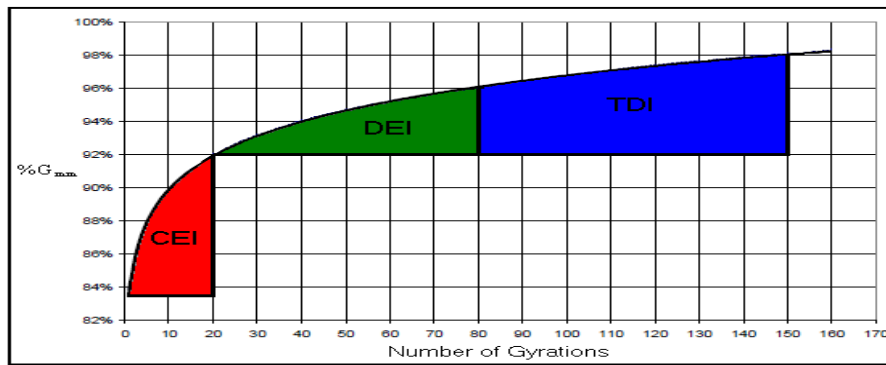


Fig. 3 Energy indices in density variations vs. gyratory gyration number curve [18]

2.3. Research Assumptions

Although asphalt rutting is derived from cumulative deformation of base and subbase layers consolidation, abrasion and permanent deformation in asphalt layer but the main reason of rutting is asphalt permanent deformation [4]. This parameter was studied in this research under 50°C temperature. To consider design requirements asphalt mixtures were prepared using OAC ($\pm 0.5\%$). Materials were similar from shape and aggregate texture issues and all specimens were prepared in a constant situation.

3. Methodology

3.1. Materials Selection and Tests

RudehenAsbcheran mine (east of Tehran) and Rivand mine (Sabzevar) were used for limestone and silica aggregates source respectively. Minimum Percentage of Fracture, Maximum Abrasion, Maximum Water Absorption, Minimum Adhesion in Bitumen-Aggregate System, Minimum Sand Equivalent and Minimum Sulfate Soundness Value tests results were in the

standard range. Saveh mine rock powder and Qom limestone powder passed from 0.075mm sieve were used as two filler types in specimen preparation procedure. PI and Hydrometry test results located in standard range either. Asphalt cement was supplied from Pasargad Oil Company in tow types of AC60-70 and AC85-100. Penetration, SayboltForol Viscosity, Softening Point, Ignition Point, Specific Gravity, Weight Loss and Ductility performed for both types and results passed Code234 (Iranian Pavement Code) requirements [19]

3.2. Optimum Asphalt cement Content

3.2.1. Gradation

Middle range of number 4 and 5 continuous gradations were used according to table 1.

3.2.2. OAC Determination and Specimen Naming

According to various types of aggregates, gradation, filler and asphalt cement, 288 specimens were prepared for OAC using marshal method and finally 16 optimum asphalt contents were determined as table 2. Combination of two letters and two numbers was used for specimen naming. Left to right, first

Table 1 Aggregates gradation for Binder and Topka layers [4]

| Sieve Specification | | | Number 4 Continuous Gradation | | | Number 5 Continuous Gradation | | |
|---------------------|--------|--------|-------------------------------|-----------------|------------|-------------------------------|-----------------|------------|
| Sieve | | | Passed Range | Passed | Remained | Passed Range | Passed | Remained |
| mm | Number | Inches | Weight (%) | Ave. Weight (%) | Weight (%) | Weight (%) | Ave. Weight (%) | Weight (%) |
| 19 | - | (3/4) | 100 | 100 | 0 | - | - | - |
| 12.5 | - | (1/2) | 90-100 | 95 | 5 | 100 | 100 | 0 |
| 9.5 | - | (3/8) | - | - | - | 90-100 | 95 | 5 |
| 4.75 | 4 | - | 44-74 | 59 | 36 | 55-85 | 70 | 25 |
| 2.36 | 8 | - | 28-58 | 43 | 16 | 32-67 | 49/5 | 20/5 |
| 1.18 | 16 | - | - | - | - | - | - | - |
| 0.6 | 30 | - | - | - | - | - | - | - |
| 0.3 | 50 | - | 5-21 | 13 | 30 | 7-23 | 15 | 34/5 |
| 0.15 | 100 | - | - | - | - | - | - | - |
| 0.075 | 200 | - | 2-10 | 6 | 7 | 2-10 | 6 | 9 |

Table 2 Determined OAC for 16 various asphalt mixture combination

| Limestone Specimen Specification | A4P6 | A4P8 | A5P6 | A5P8 | A4A6 | A4A8 | A5A6 | A5A8 |
|----------------------------------|------|------|------|------|------|------|------|------|
| OBC | 5.81 | 5.70 | 5.92 | 5.80 | 6.16 | 5.90 | 6.24 | 6.00 |
| Silica Specimen Specification | S4P6 | S4P8 | S5P6 | S5P8 | S4A6 | S4A8 | S5A6 | S5A8 |
| OBC | 5.05 | 4.96 | 5.24 | 5.02 | 5.40 | 5.15 | 5.45 | 5.25 |

character shows aggregate type (S for silica base aggregate and A for limestone base aggregate), second character is a number shows gradation number (4 for gradation number 4 and 5 for gradation number 5), third character is the filler type (P for rock powder and A for limestone powder) and the fourth character is the asphalt cement type (6 for AC60-70 and 8 for AC85-100).

3.3. Preparing Specimens for Tests

3.3.1. Choosing Gyration Number

Gyratory Compaction Machine was used for compacting specimens. 8, 95 and 150 gyrations were chosen for N_{ini} , N_{des} and N_{max} respectively according to table 3 for ESALs equal to 106.

3.3.2. Determining Number of Specimens for Research

To perform rutting test, due to various parameters, 144 specimens were prepared totally with OAC, 0.5% less and 0.5% more asphalt cement content with SGC. To validate test results 3 specimens were made for each similar condition.

3.1. Gyratory Parameters

3.4.1. Gyratory Shear Stress Modeling Parameters

Shear stress versus gyration number is one of the SGC output curves. To gain more parameters from gyratory output curves and since it is proved shear stress is related to rutting inversely, gyratory shear stress were modeled versus gyration number as independent parameter. Following logarithmic model seemed to be the best model after testing all models:

$$G_s = K_1 \ln(N) + K_2 \quad (2)$$

In which G_s is gyratory shear stress in a specific gyration of N while K_1 and K_2 are gyratory shear stress semi-log curve slope and y-intercept respectively.

In other words graphs such as figure 5 were drawn for all 144 specimens and the result of modeling is shown in table 4. As it is clear in this table more than 95.14% of models have more than 75% correlation coefficient.

Maximum shear (S_m) is the other variable which can be determined using presented model except K_1 and K_2 .

Table 3 N_{ini} , N_{des} and N_{max} in SGC [4]

| ESALS 10^6 | Maximum Design Temperature Average | | | | | | | | | | | |
|-----------------|------------------------------------|----------|-------|-----------|----------|-------|-----------|----------|-------|-----------|----------|-------|
| | < 39 °C | | | 39-40 °C | | | 41-42 °C | | | 43-44 °C | | |
| | N-initial | N-design | N-max | N-initial | N-design | N-max | N-initial | N-design | N-max | N-initial | N-design | N-max |
| <0.3 | 7 | 68 | 104 | 7 | 74 | 114 | 7 | 78 | 121 | 7 | 82 | 127 |
| 0.3-1 | 7 | 76 | 117 | 7 | 83 | 129 | 7 | 88 | 138 | 8 | 93 | 146 |
| 1-3 | 7 | 86 | 134 | 8 | 95 | 150 | 8 | 100 | 158 | 8 | 105 | 167 |
| 3-10 | 8 | 96 | 152 | 8 | 106 | 169 | 8 | 113 | 181 | 9 | 119 | 192 |
| 10-30 | 8 | 109 | 174 | 9 | 121 | 195 | 9 | 128 | 208 | 9 | 135 | 220 |
| 30-100 | 9 | 126 | 204 | 9 | 139 | 228 | 9 | 146 | 240 | 10 | 153 | 253 |
| >100 | 9 | 143 | 235 | 10 | 158 | 262 | 10 | 165 | 275 | 10 | 172 | 288 |

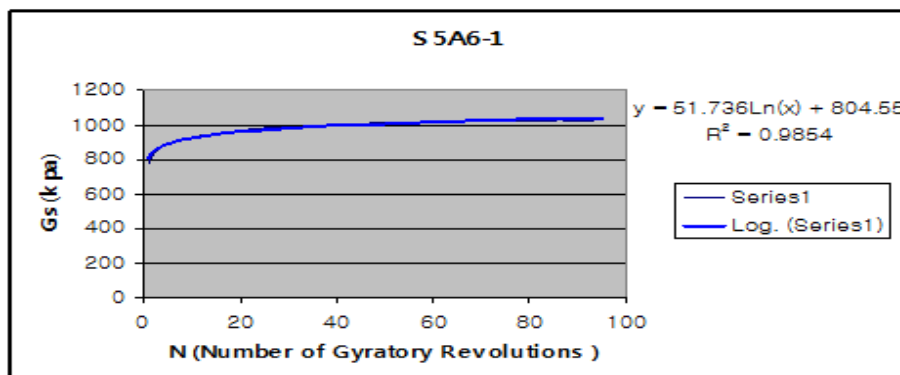


Fig. 5 Shear stress modeling versus gyration number (for one of the limestone specimens, gradation number 4, rock powder as the filler and 60-70 asphalt cement)

Table 4 Determining Correlation Coefficient of presented model for all gyratory shear stress curves (144 specimens)

| R ² Range | Correlation Coefficient (R) | | | | | | Total |
|----------------------|-----------------------------|-------|-------|-------|-------|------|-------|
| | 100-95 | 95-90 | 90-85 | 85-80 | 80-75 | <75 | |
| Number of Specimens | 84 | 29 | 9 | 10 | 5 | 7 | 144 |
| Percent | 58.33 | 20.14 | 6.25 | 6.94 | 3.48 | 4.86 | 100 |

3.4.2. Compaction Slope Parameter

Specimen height is the other parameter measured by gyratory per cycle. Since specimen height is distinguished in each cycle, compaction slope can be determined using eq. 3 considering constant specimen weight and specimen cross section. Studies showed compaction slope is related to aggregates internal friction directly, so it can affect shear strength of mixture [20].

$$K = \frac{(\%G_{mm,Ndes} - \%G_{mm,Nini})}{[\log(N_{des}) - \log(N_{ini})]} * 100 \quad (3)$$

In which:

$$\%G_{mm,Ndes} = \frac{G_{mb}}{G_{mm}} \quad (4)$$

$$\%G_{mm,Nini} = \%G_{mm,Ndes} * \frac{h_{des}}{h_{ini}} \quad (5)$$

- $\%G_{mm,Ndes}$ and $\%G_{mm,Nini}$: Asphalt mixture maximum specific gravity percent at initial gyration and design gyration respectively,
- h_{ini} and h_{des} : Specimen height in N_{ini} and N_{des} during compaction respectively,
- G_{mb} and G_{mm} : Bulk and maximum specific gravity respectively.

3.4.3. Other Parameters

Other parameters like air voids in initial and design gyration (Va_{ini} and Va_{des}), gyration number in which maximum shear stress is given ($N-S_m$), Voids in mineral aggregates (VMA), height and density variations were determined for each specimens which only K , K_1 and S_m introduced as effective parameters in sensitivity analysis. (table 5)

3.5. Creep Test

Three creep tests were performed for each combination at 50°C, under 300 kpa pressure with 500 ms loading and 1500 ms rest using UTM-5 and flow number of each combination were determined [21]. The results could be seen in table 6.

4. Presenting Experimental Model

4.1. Developing a Model using SPSS19

Predicting a variable behavior using other variables behaviors is the target of regression. It means to recognize the relation between effective parameters (x) and affected parameters (y) and to ensure a meaningful correlation between variables and finally to estimate a variable using another one. Correlation Coefficient (R^2) is a parameter which illustrates a relation between model results and actual

Table 5 Analysis of variance (SPSS 19 Output)

| ANOVA | | | | | |
|------------|----------------|-----|-------------|---------|------|
| Model | Sum of Squares | df | Mean Square | F | Sig. |
| Regression | 5.809E8 | 2 | 2.904E8 | 436.047 | .000 |
| 1 Residual | 87258037.990 | 131 | 666091.893 | | |
| Total | 6.682E8 | 133 | | | |

results. Two assumptions are considered in regression as H_0 and H_1 :

$$\begin{cases} H_0: R = 0 \\ H_1: R \neq 0 \end{cases} \quad (6)$$

The aim is to reject H_0 assumption which sig F change coefficient is used for validation. Whatever this coefficient is less, R^2 meaningfulness is more and so the model is more validated. This coefficient should be less than 0.05 since reliability is considered as 95% in this model. Statistical analysis results of 144 data series in SPSS 19 is listed in table 7 and the model was gained as following:

According to tables 8 and 9, final model was presented as equation 7:

$$F_n = 743.562 K - 94.115 K_1 \quad (7)$$

In which:

F_n = Flow number from dynamic creep test

K = Gyratory Compaction Slope from Eq3

K_1 = Gyratory Shear Stress Curve Slope (Eq2)

As it can be understood from table 7, R for this model is 0.932 which is meaningful in 95% reliability level.

4.2. Validating the model using ANN

ANN (Artificial Neural Network) is a simulation of brain nerve and has learning, generalization, and decision making power like human's brain. In designing the network, after defining a dynamic system mechanism, the model is trained and system mechanism is saved in model memory, so this memory is used to estimate new cases. Neural networks have been used in various aspects of pavement engineering such as estimating asphalt dynamic and elasticity modulus [22,23], asphalt cement properties effect on asphalt features [24] and Mixture Compaction Quality Control [25].

A neural network is composed from several processors which are called neurons or nodes. Each neuron is connected to other neurons with oriented lines having specific weight. Weight shows the amount of information used by network to solve the problem. Neurons are organized in groups called layers. Generally there are two layers to connect network with out of it as input layer (to get input data) and output layer to transfer answers out of network. Other layers between these two layers are called hidden layers. Network input and output layer number depends on dependent and independent variables of the desired relation respectively. The model in this paper has two independent variables and one dependent variable, so the network has two input neurons and one output neuron (figure 6).

Figure 7 shows input (I) and output (O) and a hidden neuron structure. B and w parameters could be set up and f function type is selected by designer so the neuron output is desired. Determining b and w for total network is called network training. Network output is compared with actual observations and error is calculated in training process.

Table 6 Gyratory compactor and creep test results for 144 specimens

| | Limestone Specimen Specification | Difference with OAC | F _n | K | K ₁ | K ₂ | Maximum Shear (Sm) | Silica Specimen Specification | F _n | K | K ₁ | K ₂ | Maximum Shear (Sm) |
|---|----------------------------------|---------------------|----------------|--------|----------------|----------------|--------------------|-------------------------------|----------------|------|----------------|----------------|--------------------|
| 1 | A4P6 | | 1225 | 10.560 | 61.387 | 787.630 | 1049 | 1 | S4P6 | 320 | 8.281 | 54.606 | 803.12 |
| 2 | A4P6 | -0.5 | 2000 | 8.620 | 44.936 | 647.320 | 839 | 2 | S4P6 | 620 | 7.909 | 54.593 | 835.41 |
| 3 | A4P6 | | 1300 | 10.747 | 64.181 | 774.380 | 1046 | 3 | S4P6 | 2704 | 6.906 | 38.522 | 911.16 |
| 1 | A4P6 | | 5100 | 8.034 | 40.065 | 676.750 | 893 | 1 | S4P6 | 664 | 8.632 | 60.530 | 825.94 |
| 2 | A4P6 | 0.0 | 5250 | 10.161 | 28.635 | 845.770 | 977 | 2 | S4P6 | 1872 | 7.676 | 37.358 | 923.89 |
| 3 | A4P6 | | 5000 | 10.713 | 40.814 | 839.350 | 1026 | 3 | S4P6 | 788 | 8.718 | 56.609 | 835.55 |
| 1 | A4P6 | | 7375 | 8.869 | 47.824 | 815.980 | 1062 | 1 | S4P6 | 684 | 8.945 | 58.899 | 843.50 |
| 2 | A4P6 | 0.5 | 6900 | 7.743 | 44.735 | 658.330 | 870 | 2 | S4P6 | 756 | 7.423 | 46.943 | 874.27 |
| 3 | A4P6 | | 6500 | 10.061 | 44.325 | 838.820 | 1047 | 3 | S4P6 | 860 | 8.332 | 47.344 | 853.31 |
| 1 | A4P8 | | 1475 | 11.216 | 69.459 | 742.240 | 1049 | 1 | S4P8 | 490 | 7.453 | 48.512 | 856.06 |
| 2 | A4P8 | -0.5 | 1250 | 11.363 | 69.312 | 738.510 | 1058 | 2 | S4P8 | 640 | 7.955 | 51.713 | 838.22 |
| 3 | A4P8 | | 1550 | 11.127 | 65.995 | 769.230 | 1074 | 3 | S4P8 | 544 | 8.098 | 53.093 | 836.63 |
| 1 | A4P8 | | 3850 | 10.573 | 54.222 | 821.510 | 1052 | 1 | S4P8 | 1036 | 8.280 | 49.258 | 843.15 |
| 2 | A4P8 | 0.0 | 3300 | 10.897 | 49.539 | 816.900 | 1032 | 2 | S4P8 | 1584 | 7.850 | 43.737 | 876.39 |
| 3 | A4P8 | | 5500 | 10.604 | 50.411 | 829.960 | 1047 | 3 | S4P8 | 2480 | 7.798 | 40.790 | 884.45 |
| 1 | A4P8 | | 2550 | 10.805 | 59.273 | 783.790 | 1052 | 1 | S4P8 | 2664 | 7.816 | 33.519 | 900.33 |
| 2 | A4P8 | 0.5 | 4750 | 11.105 | 58.485 | 810.780 | 1058 | 2 | S4P8 | 2400 | 7.989 | 34.831 | 912.03 |
| 3 | A4P8 | | 4875 | 10.805 | 59.273 | 783.790 | 1052 | 3 | S4P8 | 2160 | 8.220 | 44.317 | 867.48 |
| 1 | A5P6 | | 3200 | 10.468 | 25.534 | 781.18 | 909 | 1 | S5P6 | 424 | 7.927 | 48.384 | 843.71 |
| 2 | A5P6 | -0.5 | 2900 | 10.723 | 39.783 | 690.46 | 864 | 2 | S5P6 | 668 | 7.469 | 49.990 | 851.30 |
| 3 | A5P6 | | 3500 | 10.835 | 48.797 | 651.37 | 861 | 3 | S5P6 | 764 | 7.517 | 48.195 | 852.17 |
| 1 | A5P6 | | 4125 | 10.710 | 42.101 | 698.30 | 876 | 1 | S5P6 | 744 | 7.883 | 47.150 | 861.43 |
| 2 | A5P6 | 0.0 | 1625 | 10.584 | 43.333 | 698.03 | 887 | 2 | S5P6 | 888 | 7.605 | 47.644 | 857.71 |
| 3 | A5P6 | | 5750 | 10.166 | 48.614 | 704.55 | 942 | 3 | S5P6 | 900 | 7.380 | 46.585 | 858.58 |
| 1 | A5P6 | | 3250 | 10.819 | 45.744 | 661.46 | 869 | 1 | S5P6 | 2440 | 7.473 | 37.069 | 895.56 |
| 2 | A5P6 | 0.5 | 3560 | 9.016 | 47.100 | 564.90 | 776 | 2 | S5P6 | 1824 | 7.134 | 32.490 | 906.45 |
| 3 | A5P6 | | 3875 | 9.906 | 48.275 | 639.55 | 891 | 3 | S5P6 | 3488 | 7.038 | 31.084 | 911.38 |
| 1 | A5P8 | | 2550 | 10.217 | 38.543 | 663.54 | 825 | 1 | S5P8 | 672 | 7.445 | 57.682 | 835.79 |
| 2 | A5P8 | -0.5 | 2375 | 9.161 | 59.753 | 756.67 | 1016 | 2 | S5P8 | 396 | 7.265 | 53.960 | 859.17 |
| 3 | A5P8 | | 4750 | 8.083 | 23.693 | 723.37 | 830 | 3 | S5P8 | 512 | 7.656 | 56.813 | 842.73 |
| 1 | A5P8 | | 5625 | 7.171 | 24.845 | 711.25 | 836 | 1 | S5P8 | 1020 | 7.460 | 51.417 | 853.31 |
| 2 | A5P8 | 0.0 | 4125 | 9.798 | 54.522 | 773.04 | 1008 | 2 | S5P8 | 1608 | 7.652 | 46.923 | 872.31 |
| 3 | A5P8 | | 3125 | 10.155 | 32.938 | 681.47 | 825 | 3 | S5P8 | 1616 | 7.844 | 50.780 | 868.75 |
| 1 | A5P8 | | 1425 | 10.422 | 36.944 | 667.57 | 824 | 1 | S5P8 | 2232 | 7.201 | 36.618 | 905.04 |
| 2 | A5P8 | 0.5 | 4875 | 5.335 | 38.374 | 795.48 | 819 | 2 | S5P8 | 6112 | 7.177 | 38.223 | 903.16 |
| 3 | A5P8 | | 5125 | 6.232 | 35.887 | 764.24 | 822 | 3 | S5P8 | 4400 | 7.520 | 44.138 | 895.43 |
| 1 | A4A6 | | 444 | 6.119 | 39.965 | 778.64 | 959 | 1 | S4A6 | 564 | 8.026 | 50.107 | 827.97 |
| 2 | A4A6 | -0.5 | 538 | 6.282 | 44.871 | 787.96 | 984 | 2 | S4A6 | 326 | 7.435 | 46.117 | 832.25 |
| 3 | A4A6 | | 238 | 5.855 | 44.249 | 773.68 | 971 | 3 | S4A6 | 426 | 7.723 | 50.088 | 811.04 |
| 1 | A4A6 | | 450 | 6.419 | 46.253 | 780.63 | 987 | 1 | S4A6 | 888 | 8.312 | 54.104 | 809.26 |
| 2 | A4A6 | 0.0 | 235 | 6.137 | 48.104 | 783.91 | 998 | 2 | S4A6 | 544 | 7.693 | 46.870 | 830.14 |
| 3 | A4A6 | | 538 | 6.188 | 43.421 | 784.84 | 975 | 3 | S4A6 | 1392 | 7.938 | 44.122 | 849.20 |
| 1 | A4A6 | | 906 | 6.716 | 44.815 | 776.91 | 983 | 1 | S4A6 | 1408 | 8.073 | 46.509 | 847.04 |
| 2 | A4A6 | 0.5 | 714 | 6.673 | 45.196 | 788.27 | 992 | 2 | S4A6 | 1312 | 7.832 | 39.271 | 859.24 |
| 3 | A4A6 | | 1816 | 6.419 | 42.104 | 799.94 | 992 | 3 | S4A6 | 3000 | 7.905 | 38.328 | 865.18 |
| 1 | A4A8 | | 1176 | 9.123 | 51.139 | 772.79 | 998 | 1 | S4A8 | 324 | 6.868 | 44.123 | 829.01 |
| 2 | A4A8 | -0.5 | 1372 | 8.877 | 49.526 | 794.28 | 1005 | 2 | S4A8 | 356 | 6.971 | 50.617 | 804.45 |
| 3 | A4A8 | | 1824 | 8.614 | 53.073 | 794.55 | 1029 | 3 | S4A8 | 688 | 7.483 | 56.506 | 803.21 |
| 1 | A4A8 | | 1680 | 9.744 | 52.217 | 803.84 | 1026 | 1 | S4A8 | 486 | 7.695 | 52.007 | 807.22 |
| 2 | A4A8 | 0.0 | 2144 | 9.742 | 48.769 | 807.65 | 1013 | 2 | S4A8 | 3616 | 7.386 | 31.991 | 862.23 |
| 3 | A4A8 | | 812 | 10.258 | 58.466 | 769.10 | 1023 | 3 | S4A8 | 344 | 7.767 | 44.967 | 818.20 |
| 1 | A4A8 | | 2440 | 10.225 | 46.158 | 801.24 | 993 | 1 | S4A8 | 900 | 8.264 | 45.079 | 856.14 |
| 2 | A4A8 | 0.5 | 2448 | 6.204 | 44.110 | 799.73 | 992 | 2 | S4A8 | 948 | 8.313 | 36.983 | 846.30 |
| 3 | A4A8 | | 840 | 6.811 | 46.144 | 787.61 | 992 | 3 | S4A8 | 732 | 8.417 | 44.112 | 833.02 |
| 1 | A5A6 | | 1524 | 8.543 | 53.748 | 770.26 | 1008 | 1 | S5A6 | 296 | 6.739 | 51.736 | 804.55 |
| 2 | A5A6 | -0.5 | 2024 | 8.157 | 55.907 | 785.50 | 1029 | 2 | S5A6 | 324 | 6.780 | 52.890 | 801.58 |
| 3 | A5A6 | | 1424 | 8.900 | 58.416 | 780.06 | 1037 | 3 | S5A6 | 350 | 6.532 | 52.481 | 814.92 |
| 1 | A5A6 | | 1416 | 9.648 | 58.161 | 775.22 | 1029 | 1 | S5A6 | 440 | 7.541 | 46.088 | 828.54 |
| 2 | A5A6 | 0.0 | 2480 | 9.622 | 53.063 | 802.01 | 1028 | 2 | S5A6 | 600 | 7.364 | 44.679 | 833.53 |
| 3 | A5A6 | | 3928 | 9.256 | 45.210 | 872.15 | 1065 | 3 | S5A6 | 560 | 7.895 | 52.836 | 812.41 |
| 1 | A5A6 | | 4024 | 8.632 | 40.233 | 832.11 | 1017 | 1 | S5A6 | 728 | 8.487 | 48.941 | 804.52 |
| 2 | A5A6 | 0.5 | 2544 | 9.064 | 41.651 | 830.60 | 1005 | 2 | S5A6 | 824 | 7.312 | 46.536 | 830.80 |
| 3 | A5A6 | | 3376 | 8.979 | 47.587 | 813.47 | 1013 | 3 | S5A6 | 1076 | 7.557 | 42.811 | 846.27 |
| 1 | A5A8 | | 2640 | 8.427 | 50.076 | 789.29 | 1007 | 1 | S5A8 | 314 | 6.701 | 46.173 | 810.62 |
| 2 | A5A8 | -0.5 | 1888 | 8.665 | 55.004 | 789.63 | 1029 | 2 | S5A8 | 380 | 6.786 | 51.148 | 789.57 |
| 3 | A5A8 | | 2744 | 8.038 | 53.134 | 798.62 | 1029 | 3 | S5A8 | 378 | 7.298 | 50.725 | 793.20 |
| 1 | A5A8 | | 1640 | 9.026 | 46.620 | 821.98 | 1016 | 1 | S5A8 | 728 | 8.685 | 55.412 | 791.73 |
| 2 | A5A8 | 0.0 | 2312 | 8.931 | 48.718 | 814.79 | 1022 | 2 | S5A8 | 724 | 7.788 | 48.103 | 819.08 |
| 3 | A5A8 | | 3392 | 8.909 | 52.352 | 802.56 | 1031 | 3 | S5A8 | 740 | 8.096 | 51.413 | 809.47 |
| 1 | A5A8 | | 2776 | 9.547 | 38.051 | 824.58 | 983 | 1 | S5A8 | 2128 | 8.447 | 51.536 | 814.41 |
| 2 | A5A8 | 0.5 | 2344 | 9.217 | 34.710 | 835.80 | 984 | 2 | S5A8 | 1264 | 8.699 | 53.506 | 812.96 |
| 3 | A5A8 | | 3344 | 9.325 | 40.075 | 819.42 | 986 | 3 | S5A8 | 1144 | 9.188 | 54.484 | 793.68 |

Table 7 Parameters statistical analysis in SPSS 19 results

| | Descriptive Statistics | | | | | | |
|----------------|------------------------|-------|---------|---------|---------|----------------|------------|
| | N | Range | Minimum | Maximum | Mean | Std. Deviation | Variance |
| Flow Number | 144 | 7140 | 235 | 7375 | 1954.76 | 1604.082 | 2573077.54 |
| K | 144 | 6.03 | 5.34 | 11.36 | 8.3890 | 1.37017 | 1.877 |
| k ₁ | 144 | 77.83 | -8.37 | 69.46 | 46.7772 | 9.99775 | 99.955 |

Table 8 Model statistical specification summary (SPSS 19 output)

| Model Summary | | | | | |
|---------------|-------|----------|-------------------|----------------------------|------------------------------------|
| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate | Change Statistics Sig. F Change |
| 1 | 0.932 | 0.869 | 0.867 | 816.145 | .000 |

Table 9 Model independent variable coefficient (SPSS 19 output)

| Coefficients | | | | | | | | |
|--------------|----------------|-----------------------------|------------|---------------------------|---------|-------|--------------------------------|-------------|
| Model | | Unstandardized Coefficients | | Standardized Coefficients | T | Sig. | .95% Confidence Interval for B | |
| | | B | Std. Error | Beta | | | Lower Bound | Upper Bound |
| 1 | k | 743.562 | 39.843 | 2.816 | 18.662 | 0.000 | 664.743 | 822.382 |
| 2 | k ₁ | -94.115 | 6.993 | -2.031 | -13.459 | 0.000 | -107.948 | -80.282 |

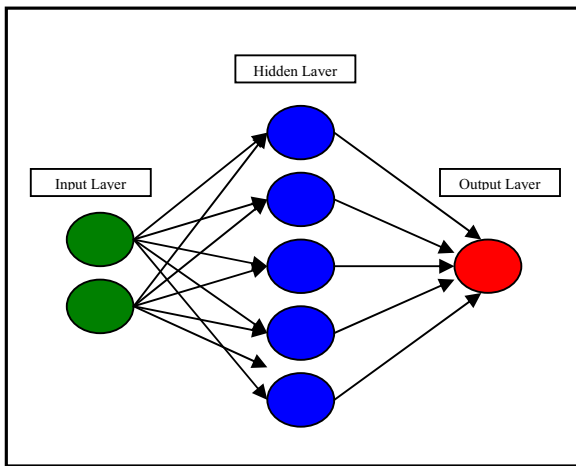


Fig. 6 ANN layers

Coefficients are modified based on this error. Whatever root mean square error (RMSE) is closer to zero, error is less, so the model is better.

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (x_i - y_i)^2}{n}} \quad (8)$$

R^2 is the statistical index to validate output accuracy which

whatever closer to 1, more precise the model is.

$$R^2 = \left(\frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \right)^2 \quad (9)$$

MATLAB 2008 software was used for coding the network. About 67% of data were used for training the network after normalizing by equation 10 and remained data were used for validation.

$$X_n = (x - x_{min}) / (x_{max} - x_{min}) \quad 0 \leq X_n \leq 1 \quad (10)$$

4.2.1. Neural Network results for presented model

Considering two neurons in input layer and one in output and using 5, 10, 15 and 20 neurons in median layers, results were obtained as table 10 and figure 8. R^2 were determined as 0.9122 in best structure in validation phase as it is stated in table.

4.3. Validating model Using GA

Genetic Algorithm (GA) is a method of optimizing and validating models which using a natural inception performs based on evolution principle (Survival of the fittest). GA applies survival fittest rule on a set of solutions to obtain better answers. Independent variables are determined in each phase of evolution so that less difference is achieved between real value of dependent variable and estimated value (Figure 9). MATLAB 2008 software was used for coding and Excel 2007 for comparing the results in this study.

4.3.1. GA results for presented model

As it is illustrated in figure 10, 0.835 is obtained as determination coefficient for this model.

Table 10 Neural network run output (for 5, 10, 15 and 20 neurons in a hidden layer)

| Neural Network Structure | Training Phase | | Validation Phase |
|--------------------------|----------------|---------|------------------|
| | R^2 | RMSE | R^2 |
| 2-5-1 | 0.8231 | 0.0162 | 0.7061 |
| 2-10-1 | 0.8117 | 0.0120 | 0.7861 |
| 2-15-1 | 0.8927 | 0.0102 | 0.8366 |
| 2-20-1 | 0.9270 | 0.00705 | 0.9122 |

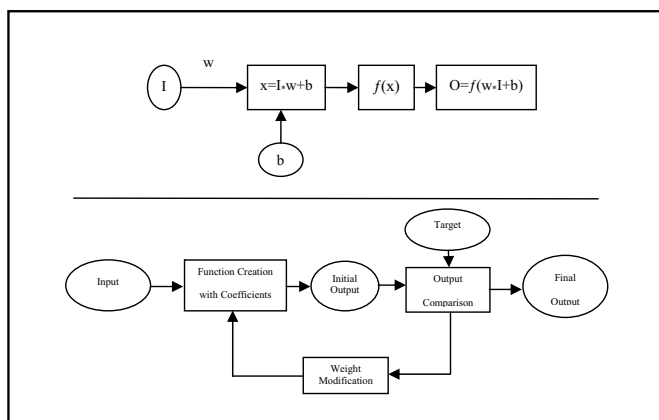


Fig. 7 Neural network architecture

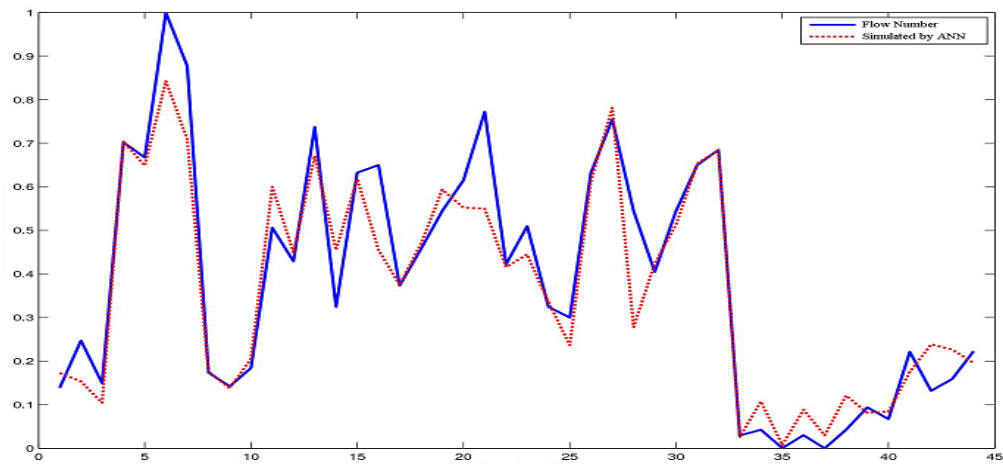


Fig. 8 Standardized flow number curve of model and real values in 1-20-2 structure of validating phase

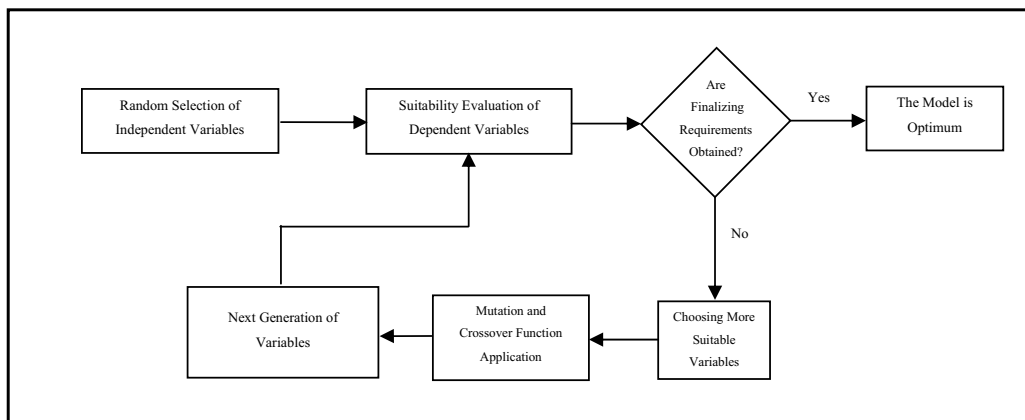


Fig. 9 Applied GA flowchart

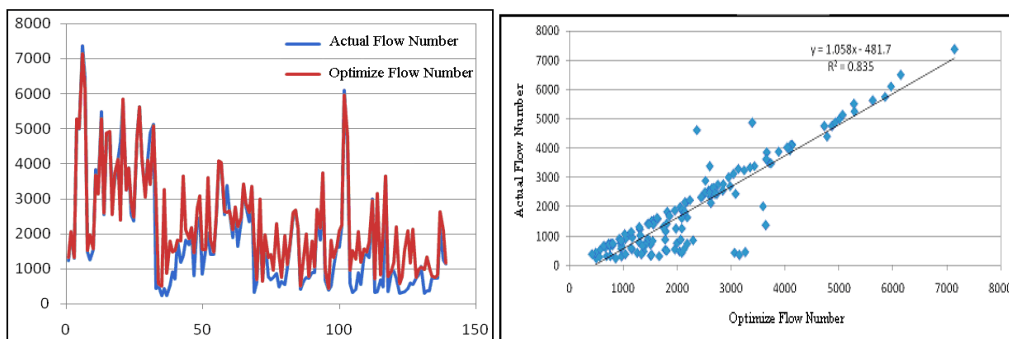


Fig. 10 a. Estimated and real values comparison of model number 1 during evolution and b. Regression on real and estimated values of model

5. Discussion and Conclusion

One of the most important consequences of this study is GSM shear stress modeling versus gyration number. It was proved that logarithmic model results in the best trend. This curve has two main phases. The first phase can be named as compaction phase, has an intense slope. Shear stress variation in this phase is more than condensation phase, as the second phase of the curve. Voids variation of first phase is more than

that of the second one too. Using the GSM compaction slope and equation slope the model for predicting flow number was developed. It should be noted the model is developed in 50°C and with OAC. Other conclusions are as following:

- In compaction phase, particle movement in various directions will cause asphalt compaction initially. But in second phase aggregates rotation and slippage lead to volume reduction and specimen density increase. So mixture voids are more in compaction slope in compare with condensation phase

considerably.

- Average compaction slope for specimens prepared with gradation #4 is more than #5 prepared specimens. Compaction slope is an index of aggregates internal friction. So #4 gradation which has more coarse aggregates has more compaction slope than #5 gradation.

- Shear stress variation in compaction phase is more than condensation phase. The reason will be for materials more impacts and a resistance to mixture volume change in this phase.

- Compaction slope coefficient is positive in the developed model. So specimens with higher compaction slope have more flow number and are resisted to rutting more. This is due to high resistance because of more internal friction and structural form. This is in accordance with other consequences about compaction slope.

- Shear stress curve negative coefficient in this model states asphalt mixtures with higher shear stress gradient in compaction phase are resisted to rutting more. In other words the more the shear stress in the compaction slope in compare with condensation phase is, the less the shear strength of mixture is.

- Using developed model, flow number can be estimated simultaneously during specimen preparation for determining OAC and evaluate rutting index before preparation, so a considerable save will be held in time and costs.

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