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Short Communication

Modeling of asphalt concrete via simulated annealing

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ABSTRACT

In this study, 65 asphalt core specimens taken from D100/11 state highway section in Turkey were examined for their physical properties in the laboratory. Analysis of data was conducted to determine the effects of the varying environment temperature and varying length of exposure to these temperatures on the stability of the asphalt core samples using destructive, Marshall, method. The asphalt core samples were determined using SPSS statistical program for modeling. Simulated annealing was implemented to determine a set of unknown parameters which best matched the asphalt concrete model predictions with experimental data. This modeling procedure can be used as a guideline for experiments to improve the stability of the asphalt concrete. The stability of the asphalt concrete is taken as the main objective function with respect to voids of volume, saturated unit volume weight, air dry unit volume weight, environment temperature, and exposure time.

1. Introduction

The stability of the asphalt concrete determines the performance of the highway pavement. Low stability in an asphalt concrete may lead to various types of distress in asphalt pavements. Cracking is a major form of distress and degradation in asphalt pavement layers that may be brought about by low stability of asphalt concrete [8] and [9]. In this study, the stability of the asphalt concrete is the main objective function with respect to voids volume, saturated unit volume weight, air dry unit volume weight, environment temperature, and exposure time. The objective function was formed with multi-linear regression analysis as a mathematical model.

Optimizing the stability of the asphalt concrete can be complex and a time consuming process since there are large numbers of design variables and constraints. The simulated annealing (SA) can be efficiently applied to complex problem with large numbers of design variables and constraints. Any efficient optimization algorithm explores to investigate new and unknown areas in search voids and exploit to make use of knowledge found at point previously visited to help find better solution point. The SA can provide a remarkable balance between exploration and exploitation of the search space. From this point of view, this study provides use of the SA to seek a global optimum solution to problem in hand. The SA algorithm imitates the process of annealing in metals as they cool from liquid to solid states. The algorithm is based on the idea of exploring the solution space by moving around in the neighborhood structure for the global optimum point. It does not require the evaluation of gradient of the objective function.

2. The simulated annealing

In this section of the paper, the fundamental intuition of the SA and how it processes are given briefly. The SA was proposed by Kirkpatrick et al. [3] to deal with complex non-linear combinatorial optimization problems. They showed the analogy between simulating the annealing of solid as proposed by Metropolis et al. [4]. The SA is an iterative improvement algorithm for a global optimization. It is inspired from thermodynamic to simulates the physical process of annealing [1] and [5] of molten metals. It obtains the minimum value of energy by simulating annealing which is a process employed to obtain a perfect crystal by gradual cooling of molten metals [6] in order to keep the system of melt in a thermodynamic equilibrium at given temperature. Thus, it exploits an analogy between the way in which a metal cools and freezes into a minimum energy crystalline structure. At high temperature, the atoms in the molten metal can move freely with respect to each other as the cooling proceeds, the atoms of metal become more ordered and the system naturally converges towards a state of minimal energy. This formation of crystal mostly depends on the cooling rate. If the metal is cooled at very fast rate, the atoms will form an irregular structure and the crystalline state may not be achieved. The Metropolis algorithm provides an efficient simulation of a collection of atoms in equilibrium at given temperature. The SA makes use of the Metropolis et al. [4] algorithm which pro-

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vides an efficient simulation according to a probabilistic criterion stated as:

$$P(\Delta E) = \begin{cases} 1, & \text{if } \Delta E \langle 0 \\ e^{(-\Delta E/T)}, & \text{otherwise} \end{cases} \quad (1)$$

where if $\Delta E \langle 0$, the probability, P, is one and the change – the new point- is accepted, $e^{(-\Delta E/Tk)}$; Each set of points of all atoms of a system is scaled by its Boltzmann probability factor. ΔE is the change in the energy value from one point to the next, k is the Boltzmann's constant, T is the current temperature as a control parameter. Even at a low temperature, there is a chance for the system being in a high-energy state.

Thus, if $\Delta E \langle 0$, the probability, P, is one and the change – the new point – is accepted. Otherwise, the modification is accepted at some finite probability. Each set of points of all atoms of a system is scaled by its Boltzmann probability factor $e^{(-\Delta E/Tk)}$, where "ΔE" is the change in the energy value from one point to the next, "k " is the Boltzmann's constant and "T" is the current temperature as a control parameter. Even at a low temperature, there is a chance for the system being in a high-energy state. Thus, there is a corresponding chance for getting out of a local energy minimum in favor of a better solution, a global one. The general procedure for employing the SA as follows;

Step 1: Start with a random initial solution, X, and an initial temperature, T, which should be high enough to allow all candidate solutions to be accepted and evaluate the objective function. The initial temperature is problem specific and depends on the scaling of the objective function.

Step 2: Set $i = i + 1$ and generate new solution ($X_i^{new} = X_i + rSL_i$), where "r" is random number and "SL_i" at each move should be decreased with the reduction of temperature. Evaluate "$F_i^{new} = F(X_i^{new})$.

Step 3: Choose accept or reject the move. The probability of acceptance (depending on the current temperature) if $F_i^{new} \langle F_{i-1}$, go to Step 5, else accept F_i as the new solution with probability$e^{(-\Delta E/T)}$, where $\Delta E = F_i^{new} - F_{i-1}$ and go to Step 4.

Step 4: If F_i was rejected in Step 3, set $F_i^{new} - F_{i-1}$. Go to Step 5.

Step 5: If satisfied with the current objective function value, F_i, stop. Otherwise, adjust the temperature ($T^{new} = Tr_T$) where r_T is temperature reduction rate called cooling schedule and go to Step 2. The process is done until freezing point is reached. The major advantages of the SA are an ability to avoid becoming trapped in local optimum. This is due to nature ability of the SA allowing deteriorations with a large probability in the objective function.

3. The problem statement

In this study, ultrasound was used as nondestructive method in order to determine the stability of the asphalt core samples. As destructive method, Marshall Stability test method was used. Whereas the results of the Marshall Stability test method are definitive, the results of the ultrasound method are not. The results of the ultrasound method could be used for only prediction of the stability of the asphalt concrete samples.

Preparation of the asphalt core samples was carried out at two stages. At the first stage, the samples were prepared for experiments and, the samples were examined for their physical properties at the second stage. For the experiments, five specimens taken out of 65 samples randomly and kept at 290.15 °K (17 °C) in the laboratory environment were used as reference samples to compare the stability, depressions and ultrasound values of the other samples exposed to varying temperatures for varying waiting length of periods. The other 60 samples were separated into three main groups according to temperature. In other words, for each temperature of 303.15, 313.15, and 323.15 °K (30, 40, and 50 °C), twenty samples were chosen. Then, each of the twenty samples was divided into four categories according to the waiting times of 5400, 10.800, and 16.200 s. (1.5, 3, 4.5 and 6 h) due to simulate the summer days weather condition and five specimens were used for each waiting time. The number of the groups, including the reference group, was 13 in total. For determination of the physical properties of the samples, diameter of the specimens was 0.1016 m and they were cut 0635 m long with core cutting machine.

The relationship among stability, resistance to plastic flow, ultrasound velocity, temperature, waiting time, and physical properties for the asphalt core samples were determined using SPSS statistical program. The correlation analysis was conducted to determine the significance level and the relationship among all variables as seen in Table 1.

The results regarding the relationship between stability and other variables were as follows: temperature −0.887, saturated unit volume weight −0.522, air dry unit volume weight −0.515, waiting time −0.482, resistance to flow −0.218, and voids volume 0.302. Multi-linear regression and analysis of variances were used to predict the stability based on the physical properties, environment temperature, and exposure time. The correlation coefficient square, 0.934, between the predicted the stability and the experimental results was almost perfect [7].

The obtained results from the multi-linear regression analysis are formulated as model in the following:

$$F(x_i) = -485.962 - 14.122x_1 + 32989.52x_2 - 30452.284x_3 - 104.604x_4 - 100.169x_5 \quad (2)$$

where x_1 is voids volume, x_2 is saturated unit volume weight, x_3 is air dry unit volume weight, x_4 is environment temperature, and x_5 is exposure time. Descriptive statistics of basic physical properties were given in Table 2.

The parameters used in experiment strongly influence the quality of the structure and basic geometric properties of the approximating function. If they are not defined properly, the accuracy of the result will not be satisfactory and the objective is hard to be accomplished. The efficiency of applying the SA to the problem in hand can be explained by intensive exploration and exploitation of the search voids. It is desirable to utilize optimization techniques to evaluate and select the design variables that can be used to maximize the stability of the asphalt concrete subject to a set of constraints. The SA offers solutions such as the design constraints that are hard to handle by analytical methods can be easily incorporated into the algorithm. The optimization problem is formulated as:

$$F_{obj} = F(x_i) \quad (3)$$

The vector of design variables, x_i, is voids volume x_1, saturated unit volume weight x_2, air dry unit volume weight x_3, environment temperature x_4, and exposure time x_5.

Ranges of each design variable is as follows:

$$0.74 \leqslant x_1 \leqslant 50.18 \quad (4)$$

$$2.40 \leqslant x_2 \leqslant 2.67 \quad (5)$$

$$2.38 \leqslant x_3 \leqslant 2.66 \quad (6)$$

$$17 \leqslant x_4 \leqslant 50 \quad (7)$$

$$0 \leqslant x_5 \leqslant 6 \text{ or } 1.5 \leqslant x_5 \leqslant 6 \quad (8)$$