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Optimizing asphalt mix design process using artificial neural network and genetic algorithm

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HIGHLIGHTS

- Conventional asphalt mix design is a time consuming iterative process requiring significant amount of materials.
- Significant information is available in a database on historical mix designs.
- This paper presents a procedure that was followed to successfully develop Artificial Neural Network (ANN) and Genetic Algorithm (GA) models that utilized the database and automate selection of aggregate gradation and binder content to produce asphalt mixtures that comply with applicable specification requirements.

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ABSTRACT

Selection of aggregate gradation and binder content for asphalt mix design, which comply with specification requirements, is a lengthy trial and error procedure. Success in performing mix design rely largely on experience of the designer. This paper presents development of an automatic mix design process with the ability to both predict and optimize asphalt mix constituents to obtain desired mix properties. A successful automatic process requires the use of local past experience translated into a design aid tool, which then predicts properties of asphalt mix without actually testing the mix in laboratory. In the proposed approach, simple multilayer perceptron structure Artificial Neural Network (ANN) models were developed using 444 Marshall mix design data. The ANN models were able to predict both air voids and theoretical maximum specific gravity of asphalt mix to within ±0.5% and ±0.025, respectively, for 99.6% of the time. After that, the ANN models were called by a non-linear constrained genetic algorithm to optimize asphalt mix, while satisfying the Marshall requirements defined in the formulation as constraints. Durability of the optimized mix is ensured by introducing a constraint on adequacy of asphalt film thickness. The developed mix design aid tool is compiled into a computer software called Asphalt Mix Optimization (AMO) that can be used by road agencies as a mix design tool. A case study is presented to demonstrate the ability of the model to optimize aggregate gradation and minimize binder content in asphalt mix. The computed ANN outputs and the optimized gradation were found to compare well with laboratory measured values. Although, Marshall compacted mixes were used in demonstrating the approach, this method is general and can be applied to any mix design procedure.

1. Introduction

Asphalt mix design entails proportioning of aggregates and binder in a design recipe to obtain desirable mechanical and volumetric properties for the mixture produced. The mechanical and volumetric properties significantly influence the performance and durability of asphalt mix. Influences of aggregate on properties of bituminous mix are well known and their requirements are specified by client bodies around the world. The initial efforts in finding optimal gradation were based on the principle that maximizing the density would result in a denser gradation, leading to a better performing mix [12,22]. However, it has been reported in several studies that the maximum density results in low Voids in Mineral Aggregate (VMA) and, therefore, low Binder Content (P_b) and Air Void (Va). McLeod [19] proposed to use volumetric relationship in asphalt mix design, instead of following maximum density.

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The effect of aggregate gradation on volumetric parameters, strength and permanent deformation in asphalt mixes have been extensively studied by various researchers. Researchers have stressed on the importance of packing characteristics of aggregate gradation based on relative volume of different parts of gradation [2,27,23]. The approach is based on the fact that change in packing of coarse and fine aggregate directly relate to aggregate interlocking and void in aggregate in compacted asphalt mix.

Although the current gradation design methods provide some indications on volumetric and mechanical properties, essentially they are empirical and require a trial and error process to establish an optimum blend. Further, the methods may be useful in comparing different gradations but cannot accurately predict volumetric and mechanical properties of asphalt mixes without testing them in laboratory. Recently, in an effort to accurately estimate volumetric and mechanical properties of asphalt mixes, some researchers have adopted more computational approach, which considers particle to particle interaction [24,16]. These approaches are based on discrete element method, which uses force functions to define particle to particle interaction. Limitation of such models is the significant increase in the computational effort when smaller particles (<1.18 mm) are included in the analysis. Moreover, the ability of these models to reach equilibrium is often significantly reduced on including the small particles in the analysis.

It is evident that selection of aggregate gradation for asphalt mix design, which would comply with volumetric and mechanical requirement is complex and rely mainly on experience. Random selection based on trial and error to obtain an optimum gradation is nearly impossible. This is because asphalt mix formulation depends on several factors such as specific gravity, texture, shape and absorption properties of locally used aggregates and binder. Therefore, it is important that the local past experience be translated into a design aid tool. Ozturk and Kutay [20] used laboratory data collected from 1817 Superpave mix designs to develop a novel Artificial Neural Network (ANN) model ANN-AM. The objective of their study was to use mix design data in training ANN which can then be used as a virtual Superpave mix design tool. Aggregate gradation, specific gravity, PG grade, P_b, initial, design and maximum gyrations were used as input in the model to predict Va, VMA and Voids Filled with Bitumen (VFB) at different gyration levels. The objective of the current study is to first train an ANN model for Marshall mix design and then demonstrate that such a model can be used to develop an automated scheme to obtain optimized asphalt mix with desire properties.

In recent years, artificial intelligence tools have gained traction to learn surrounding conditions and provide successful responses. In pavement engineering, ANN has been used to interpret complex data obtained from field, laboratory or computer simulations. ANN has mostly been applied in three major areas in pavement engineering, i.e. evaluation of structural condition of pavement, forecasting distress condition of pavement and estimation of asphalt mix properties. In structural evaluation, ANN has been mainly used to interpret Falling Weight Deflectometer (FWD) data through an inverse scheme to predict modulus value of pavement layers [13,17]. Apart from estimating deflections for FWD analysis, researchers have also demonstrated application of ANN in estimating stresses, layer thickness and joint load transfer in pavement. In function evaluation, ANN has been used to predict deterioration of pavement performance in terms of roughness, rut depth and cracking [14,5,28,18]. ANN has also been used for crack detection, classification and determination of severity. In asphalt mix evaluation, ANN has been successfully used to estimate asphalt mix properties such as indirect tensile strength, density and dynamic modulus [15,6,11].

1.1. Objective

The goal of the present study is to develop an automatic design tool, which uses local experience of road agencies to aid in optimizing asphalt mix. Therefore, the procedure followed was (i) to obtain mix properties from construction projects and use them in developing ANN models and (ii) develop an optimization scheme using Genetic Algorithm and automate mix design procedure.

Although Superpave has gained prominence as the state-of-the-art method for asphalt mix design, there are still many road agencies around the world where Marshall mix design is still the most prevalent asphalt mix design method. Therefore, in this study Marshall mix design data for mixes intended to be used for pavement construction projects were collected and used in developing the model. Another advantage of the developed model is that it would be helpful for agencies that have experience with Marshall mix performance, but plan to move towards Superpave mix design. In such cases, the ANN models can assist the designer to predict Marshall Properties for Superpave design mixes that have aggregate and binder properties that are within the limits of the databased used in developing the ANN models.

Based on the existing literature and despite successful demonstration of possible advantageous ANN implementation in pavement engineering, it has not been adopted in practice. The main obstacles in adopting ANN in practice is lack of background information and complex architecture of ANN models. Therefore, one of the objective of this study is to develop ANN model that uses simple architecture and readily available asphalt mix properties as inputs.

2. Research approach and database

A model that is capable of satisfactorily estimating volumetric properties through simple input parameters can be used to conduct a virtual mix design. Further, the model can then be called by an optimization scheme to produce mixes with optimized characteristics (objectives). This is because the model would be able to evaluate different asphalt mix scenarios generated by varying the model inputs.

Although this paper presents models developed for Marshall mix design, the approach described here is general and can be applied to any other mix design method. In Marshall mix design, four asphalt mix parameters, i.e. stability, flow, bulk specific gravity (G_{mb}) and theoretical maximum specific gravity (G_{mm}) are measured in laboratory and used in further analysis for acceptance or rejection of the mix. Initially, this study considered these four mix design parameters as the target variables. However, it was later realized that a much better ANN model for Va can be developed compared to G_{mb}. Finally, it was decided to use Va as a target variable instead of G_{mb} and then Va along with G_{mm} were used to calculate G_{mb}. Therefore, four separate ANN models were developed to predict the four targeted variables. The input variables used in all the four models were the same, which were obtained from the 444 Marshall Mix data.

In subtropical hot desert climate regions like the one in the present study, bleeding is one of the major concern. Therefore, there is a natural tendency in the pavement industry in regions with such climate to use lower binder content. Selection of lower binder content to avoid any potential bleeding may jeopardize durability of asphalt mixes in these regions. Studies have shown that durability is directly related to bitumen film thickness (FT_b). Therefore, to ensure that sufficient durability is achieved in the mix, in addition to Marshall mix design parameters, minimum FT_b requirement is also included in the model.