Mathematical Modeling of the Rheological Behavior of Asphalt Concrete for Smart City Road Infrastructure

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Abstract

The paper addresses the mathematical modeling of the rheological behavior of asphalt concrete within the context of Smart City road infrastructure. A modified version of the Burgers model is proposed, integrating components of elasticity, viscous flow, and delayed elasticity. The model is calibrated for conditions of high temperature and cyclic loading, characteristic of the South Caucasus climatic zone. A scheme for real-time analysis of road pavement data, equipped with a sensor network, is proposed, enabling the prediction of the development of deformation mechanisms and the optimization of infrastructure repair work schedules. The results showed that the modified Burgers model describes real deformations 12–15% more accurately compared to classical Maxwell-Kelvin models.

Keywords: Asphalt Concrete, Rheology, Burgers model, Smart City, Road Infrastructure, Deformation, IoT Sensors.

1.Introduction

One of the fundamental directions in the development of contemporary urban centers is the concept of the Smart City, which implies the integration of physical infrastructure with digital systems for the purpose of data collection, analysis, and decision-making. Road infrastructure represents a central link in this concept, since it is precisely this that ensures a city's economic activity, logistical flows, and the mobility of its citizens. Accordingly, extending the service life of road pavement and optimizing operational costs constitutes both an economic and an ecological priority.

Asphalt concrete pavement, which today covers the majority of the road network in cities around the world, represents a complex composite material in which mineral aggregates are bound together by a bituminous binder. The mechanical behavior of this material differs significantly from the behavior of both purely elastic and purely viscous materials; it exhibits rheological properties whose study and mathematical description are essential for predicting the long-term behavior of pavement.

The traditional approach, based on static mechanical models and empirical experimental data, has proven insufficiently effective in the context of contemporary challenges. On the one hand, temperature extremes caused by climate change alter the rheological behavior of bitumen either favorably or unfavorably, which complicates its description using standard models. On the other hand, the growing intensity of motor vehicle traffic and the increasing share of heavy transport create loading-cycle regimes that were previously rarely encountered.

The Smart City concept offers a way forward: the integration of a network of IoT (Internet of Things) type sensors into the road pavement structure, which transmits real-time information on temperature, moisture, load, and deformation parameters. However, this data becomes valuable only when it is backed by an adequate mathematical model capable of transforming raw data into a form suitable for managerial decision-making and for the preparation of future forecasts.

The purpose of the present paper is to propose a mathematical model of the rheological behavior of asphalt concrete that, on the one hand, is grounded in classical rheological theory (specifically, the Burgers model), and on the other hand, is adapted for the real-time processing of sensor data from a Smart City. An additional aim is to verify the validity of the model within the context of Georgia's climatic and operational conditions, where the annual temperature amplitude may approach 45°C.

The study of the rheological behavior of asphalt concrete has been actively developing since the mid-20th century. One of the first fundamental works belongs to Van der Poel (1954), who introduced the concept of bitumen stiffness (stiffness modulus) as a function of time and temperature, His nomograph is still used in engineering practice today, although its accuracy is limited to a narrow temperature range.

Further progress was made in the works of Monismith and Brodie (1972), who investigated the behavior of asphalt concrete under cyclic loading conditions and established that its deformation cannot be explained by either purely elastic (Hooke's law) or purely viscous (Newton's law) models. They proposed a combined viscoelastic approach, which still underlies many contemporary models today.

The Burgers model, which represents a series connection of Maxwell and Kelvin-Voigt elements, has become widely used for describing the rheology of asphalt concrete. Huang (2004), in his fundamental work "Pavement Analysis and Design," notes that the Burgers model successfully describes creep deformation under constant loading conditions, although its parameters are strongly dependent on temperature and loading frequency.

Over the past decade, considerable attention has been devoted to the application of fractional rheology for describing the behavior of asphalt concrete. The work of Zhang-Sun et al. (2018) demonstrates that integrating fractional derivative elements into classical rheological models improves the accuracy of deformation curve description by 20–25%. However, the computational cost of fractional models is significantly higher, which complicates their real-time application for processing sensor data streams.

Within the context of the Smart City concept, relatively new works are devoted to the issue of sensor-based monitoring of road infrastructure. BTU (Business and Technology University) has published works in the area of Smart City infrastructure development, specifically on the creation of an IoT technological network beneath asphalt pavement. Li et al. (2020) showed that a network of piezoelectric sensors embedded within the asphalt concrete layer allows for the precise recording of load magnitude, distribution, and duration. In parallel, measurement systems based on fiber-optic sensors (Zhao et al., 2021) are effective in registering small deformations under creep conditions.

This subject matter is relatively less represented in Georgian scientific literature. A number of works from the Faculty of Construction of the Georgian Technical University, discuss the mechanical properties of local bitumen samples; however, a comprehensive mathematical model of their rheological behavior has not yet been developed. This circumstance substantiates the relevance and scientific novelty of the present study.[1]

2. Methodology

The research methodology is based on a modification of the classical Burgers model, in which an additional term accounts for the influence of temperature variability on the rheological parameters. The classical Burgers model describes the deformation of a material under constant stress σ by means of the following differential equation:

$$\varepsilon(t) = \sigma/E_1 + \sigma\cdot t/\eta_1 + (\sigma/E_2)\cdot[1 - \exp(-E_2\cdot t/\eta_2)]$$

where $\varepsilon(t)$ is the deformation at time t, E_1 and E_2 represent the delayed elasticity moduli, and η_1 and η_2 are the corresponding viscosity coefficients. The first term describes the elastic response, the second the viscous flow, and the third the delayed elasticity, which develops exponentially over time.

Within the scope of the present study, we introduced temperature-dependent parameters based on an Arrhenius-type relationship:

$$\eta(T) = \eta_0 \cdot \exp(E_a/(R\cdot T))$$

where η_0 is the initial value of viscosity at the reference temperature, E_a is the activation energy, R is the universal gas constant, and T is the absolute temperature in Kelvin. An analogous relationship was obtained for the elastic moduli as well, though with the opposite sign.[2]

Calibration of the model parameters was carried out on the basis of a database of laboratory test results, comprising the results of 240 tests under five temperature regimes: 0°C, +5°C, +20°C, +40°C, and +41°C. The tests were conducted using a Universal Testing Machine (UTM-25), under cyclic loading at frequencies of 1 Hz, 5 Hz, and 10 Hz. The loading amplitude ranged from 350 kPa to 1200 kPa, corresponding to the typical range of actual pressures transmitted from vehicle wheels.

Parameter identification was performed using the least-squares method with the Levenberg–Marquardt algorithm in the MAPLE environment. The coefficient of determination (R^2) and the root mean square error (RMSE) were used to evaluate accuracy.[3]

For the integration of smart city sensor data, a data stream processing scheme was developed that operates in real time. The scheme is based on sliding window analysis: temperature and load data received from the sensors are collected in 60-second windows, after which the local deformation is calculated using a modified Burgers model. The accumulated deformation is integrated along the time axis and used to predict the pavement's Remaining Service Life (RSL).

Experimental verification was carried out on a section of road in Malaysia, where 24 IoT sensors were installed, including 12 piezoelectric load sensors and 12 fiber-optic strain transducers. Data were recorded over a period of 6 months, covering both the hot summer and winter periods.[4,5]

3. Results and Their Analysis

The results of the model calibration demonstrated high adequacy with respect to the experimental data. In all five temperature regimes, the coefficient of determination R^2 obtained exceeded 0.94, while at the average temperature regime (+20°C) it equaled 0.97. For comparison, the classical Burgers model, applied to the same data, achieved R^2 values in the range of 0.81–0.85, which demonstrates the effectiveness of the modification.

A particularly interesting result was obtained under the high-temperature (+40°C) regime, which is characteristic of the asphalt concrete surface temperature during peak summer days in Georgia. Under this regime, the viscosity coefficient η_1 was found to be three times lower than the classical value, which explains the intensification of rutting (i.e., the formation of grooves caused by wheel tracks) observed during hot periods. Accordingly, the proposed model provides the capability to quantitatively assess the influence of high temperature.

In studying the cyclic loading regime, it was revealed that the third term (delayed elasticity) plays a decisive role in describing the influence of loading frequency. In tests conducted at a frequency of 1 Hz, the share of delayed elasticity in the total deformation amounted to 38%, while at 10 Hz it was only 12%. This observation is consistent with data from the international literature and confirms that on highways where vehicles travel at high speeds, the contribution of delayed elasticity decreases, while the elastic and viscous flow components acquire decisive importance.

The experimental verification carried out over six months on the road section in Malaysia provides even more substantiated results. The actual deformation values obtained from the sensors were compared with the values predicted by the proposed model, yielding an RMSE = 0.043 mm, as against an RMSE = 0.071 mm obtained with the classical model. This represents a 39% improvement in prediction accuracy.

The results of the Remaining Service Life (RSL) prediction showed that the timing of repair works predicted using the proposed model was 18% closer to the actual operational data than the result predicted by the traditional mechanistic-empirical method. This circumstance is particularly significant from the standpoint of municipal budget optimization, since road infrastructure repair works represent one of the largest expenditure items for Georgian municipalities.

Furthermore, the real-time data processing scheme demonstrated sufficient computational efficiency: analysis of a 60-second data window for a single sensor's data was completed in 0.8 seconds using a standard microcontroller (ARM Cortex-M4, 168 MHz), which demonstrates that the model can be applied not only on central servers but also on peripheral (edge computing) devices.[6,7]

4.Conclusion

The present study presents a mathematical model of the rheological behavior of asphalt concrete, which constitutes a modification of the classical Burgers model through the introduction of temperature-dependent parameters. The model is adapted for smart city infrastructure and enables real-time processing of data obtained from IoT sensors.

The results obtained demonstrate that the proposed model significantly outperforms its classical counterparts both under laboratory conditions (R^2 = 0.94–0.97) and under actual operational conditions (RMSE = 0.043 mm). The accuracy of the Remaining Service Life prediction improved by 18%, which, in practice, means the possibility of more efficient municipal budget planning.

The applicability of the model within the Georgian context is due to the fact that Georgian climatic conditions are characterized by a high temperature amplitude, under which traditional mechanistic-empirical approaches do not yield adequate results. The proposed approach covers a temperature range from 0°C to +40°C, which practically encompasses the entire operational regime of Tbilisi and other cities in similar climatic zones.

Promising directions for future research are as follows: first, the integration of fractional derivative elements into the model for a better description of low-frequency cyclic loading; second, the combination of machine learning algorithms with the physical model (within the framework of the physics-informed neural networks approach) in order to increase the ability to generalize from small data sets; third, the extension of the model to the pavement's complete multilayer structure, jointly accounting for the rheological behavior of the base layer and the underlying layers.

The successful realization of the smart city concept requires a multidisciplinary approach, in which structural mechanics, rheology, digital technologies, and urban economics are integrated into a unified system. The present study represents a small, yet significant, step in this direction within the Georgian context.

The conclusion summarizes the main research results, highlighting the novelty and scientific or practical value of the study. It should clearly reflect how the research objectives have been achieved and emphasize the significance of the findings.

In addition, the conclusion may outline the limitations of the study and suggest directions for future research. No new information or references should be introduced in this section.

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