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Benchmark Studies of Compaction of Asphalt Concrete Mixes using Punched Molds

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Abstract: Paving asphalt concrete is a rather complex multiphase material, whose properties largely depend on those of bitumen. Bitumen-containing rocks are heterogeneous; i.e., are characterized by the presence of interface between different phases (solid, liquid and gas). The results of studies have demonstrated that asphalt concrete exhibits almost all the properties that are typical of elastic, viscous and plastic bodies depending on conditions and character of loads. For this very reason, it is classified as a visco-elastoplastic material; one of its main factors being viscosity of bitumen or the asphalt binding agent. The properties of asphalt concrete are variable and depend on a number of factors, such as the magnitude and nature of load, the ratio between mix components and primarily on temperature. The existence of a large number of parameters affecting the production technology makes it impossible to accurately describe the compaction process under complex loading types. In this case, most of the studies should be carried out at the experimental level in order to determine the qualitative indicators. The task of determining the deflected mode of material under punched operative parts executing a certain type of force impact. The effect of complex loading of the material being compacted on accumulation of irreversible deformations has been successfully assessed both theoretically and experimentally.

Key words: Asphalt concrete mix · Intensification of compression · Punched molds · Asphalt concrete pavement · Density

INTRODUCTION

The production process of the top layer of the pavement consists in distribution of asphalt concrete mix and its compaction until the standard values are obtained. The second stage is the final technological procedure that determines the future reliability and durability of the pavement. One of the methods to enhance the efficiency of using compaction machines is to use road rollers that allow one to vary the contact pressure value under the operative organ of the road roller within a broad range in accordance with changes in strength properties of the material being compacted [1].

The significant aspect is that the oriented bitumen film is retained between the particles of the mineral framework, since overloading can make this layer sink, resulting in damaging the contact zone of breakstone grains [2]. Hence, the untimely transition to heavier compacting machines may cause deterioration of the layer without reducing its density. The retention of oriented bitumen allows one to preserve the asphalt concrete mix in general [3]. Strength and durability of the asphalt concrete compacted to the design density values at relatively low temperatures are typically higher than those of asphalt concrete that has the same density but has been compacted at a high temperature [4].

The studies demonstrate that the road rollers do not fully comply with the requirements of the road-making process. However, there is the potential to improve their operation and technological processes due to "smart" control over the compacting force impact [5].

MATERIALS AND METHODS

Asphalt concrete mix (ACM) consists of certain ratio of sand, bitumen, mineral powder and break stone, which are mixed until homogeneous under heating. Despite the apparent simplicity of the components, no mathematic model of compaction of the ACM has been used thus far.

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It can be attributed to a large number of constantly changing factors that affect the quality and course of the compaction process: air and mix temperature, layer thickness, duration of contact between the roller and the compacted layer and the need to increase roller pressure on ACM after each passage.

The compaction process is governed by 3 key factors: duration of contact between a mold and the mix, thickness of the top layer of asphalt concrete pavement and mold pressure on ACM. The selected number of levels p along with the number of factors k determine the number of possible experiments N, which is equal to

$$N = P^k \quad (1)$$

The experiment where all the possible combinations of the factor levels is known as full factorial experiment (FFE). The 2^3 design has been selected, which allows one to calculate 8 (N = 8) coefficients of the regression equation, where the effects of inter-factor interactions are taken into account:

$$Y=b_0+b_1x_1+b_2x_2+b_3x_3+b_{12}x_1x_2+b_{13}x_1x_3+b_{23}x_2x_3+b_{123}x_1x_2x_3 \quad (2)$$

According to the results of using the FFE 2^3 design, the values of these factors in the central point of the experiment corresponded to their optimal values. Thus, the values of the parameters being estimated belong to the confidence interval; reliable results have been obtained.

Main Body: It has been ascertained by analyzing the existing compaction theories that it is impossible to predict the pattern of the deflected mode of material being compacted under a complex force impact from the operative parts. The absence of a single compaction theory makes researchers to come up with approximated calculation methods that are of a particular character. The designs providing that the compacted material undergoes all possible types of loads, including shear stress, vacuumization of the asphalt concrete mix resulting from loads caused by ordinary and torsional vibration of the rollers, have a significant effect on forming the operative parts of compaction machines [6]. The development of the design of high-performance machines for compacting asphalt concrete mixes keeps the path from intensification and multiplication to the integration of the conventional operative parts into a single one that uses the nonconventional type of force impact on the material being compacted.

Maintaining the required transport and performance characteristics of the motor roads is performed during the construction and depends on quality of the material used, manufacturing environment, the technology used and parameters of the power-assisted units of the machines. A large number of methods assessing the density of both soils and asphalt bitumen mixes during the compaction are based on measuring deformation of the layer and deformation modulus. Deformation and degree of compaction typically develop according to the exponential law (or one close to it). The density (deformation) curve approaches a certain limit characterizing the limit density for these conditions. The deformation capacity is usually assessed from the deformation modulus, which is determined as the ratio between the force applied to a mold and the deformation that caused it.

$$E = \frac{P}{\lambda \times d_{mold}} \quad (3)$$

where P is the force acting on the mold; d_{mold} is the diameter of the mold; and $\ddot{e}$ is mold subsidence.

The scheme of loading of a mold is shown in Fig. 1. This scheme was used to design modulus meters and other devices employed to measure the deformation modulus and subsequently the contact pressures during the passage of the rollers of the compacting roller machine. The scheme shown in Fig. 1 can be modified by representing the mold as a punched plate as shown in Fig. 2.

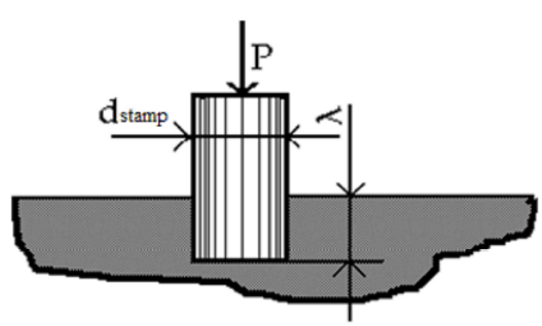
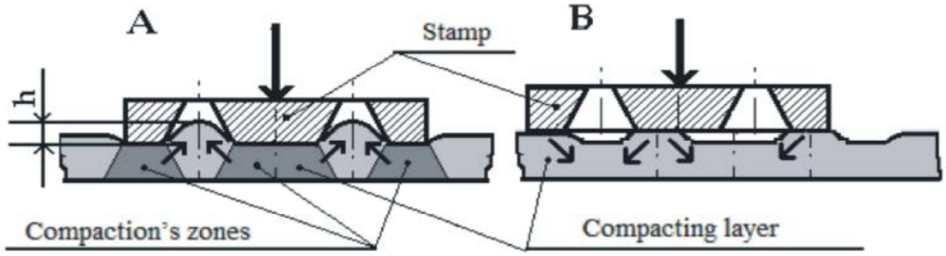
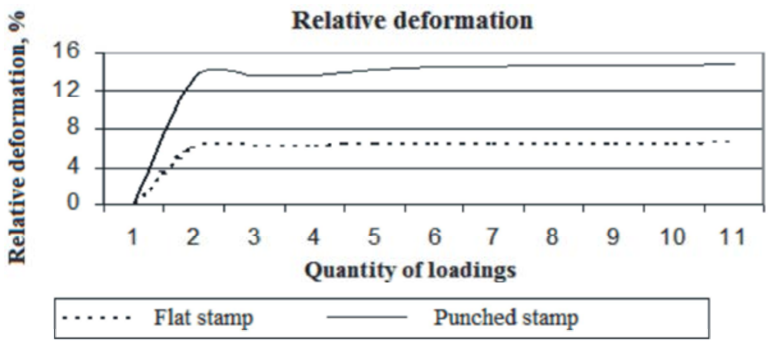


Fig. 1: The scheme of loading of a solid mold.



A	A
A	B
Compaction's zones	Compaction zones
Stamp	Mold

Fig. 2: Scheme of loading of the layer by a punched mold. A) initial scheme of loading; B) subsequent loading, with a certain shift of the mold with respect to the initial position.



Flat stamp	Punched mold
Punched stamp	Flat mold
Quantity of loadings	Number of loadings

Fig. 3: Deformation of the layer as a function of the number of loadings under a flat and a punched mold.

For this loading process, some material will be extruded from the layer into the holes. If the next cycle is performed with a shift of the mold, the compaction zones will shift as well. However, height *h* will decrease each time, since some of the layer has already underwent loading and has been partially compacted. If loading of the mold is lower than the ultimate load, it is obvious that *h* approaches zero; i.e., termination of any significant *h* value can mean the termination of density gain. However, the final load value should not be higher than the ultimate load. The value related to the equation [7] is proposed as the final load:

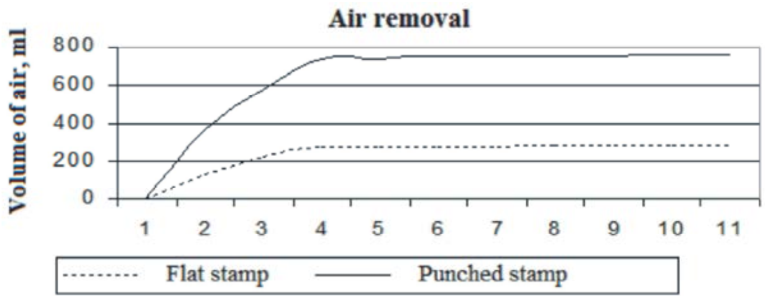
$$\sigma_c = (0.8\text{-}0.9)\ \sigma_{ult}, \quad (4)$$

where σ_c are the contact pressures on the mold surface; σ_{ult} is the ultimate strength of the layer.

The experiments with punched molds that have been conducted over the past few years have proven the high potential of this direction [8]. The diameter of holes, percentage of punched areas and operation modes of the vibrator were to be determined at the first stage. The following parameters can be controlled in laboratory benchmark experiments:

- load duration from 0.1 to 6 s;
- pressure on the compacted mix being equivalent to the weight of a light-, medium-and heavy-weight roller machines;
- thickness of the compacted mix from 50 to 100 mm.

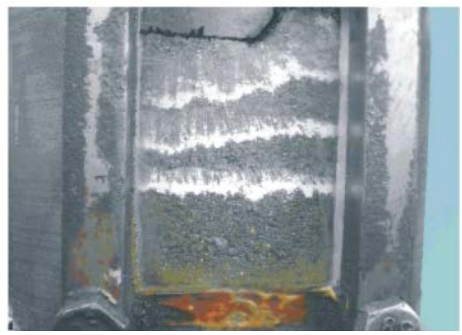
The values obtained in the benchmark experiments allow one to simulate the real conditions occurring under the rollers of the roller machines. Moreover, the amount of air forced away from the mix each time after the mold is loaded is determined. The average relative deformation under the punched mold is always 20-25% higher than that under a flat mold (Fig. 3). Taking into account that the final 2-3 % of density gain occurs during half of all the passages of the roller machine, the resulting effect is significant.



Flat stamp	Punched mold
Punched stamp	Flat mold

Fig. 4: Air removal when a flat and a punched molds are used

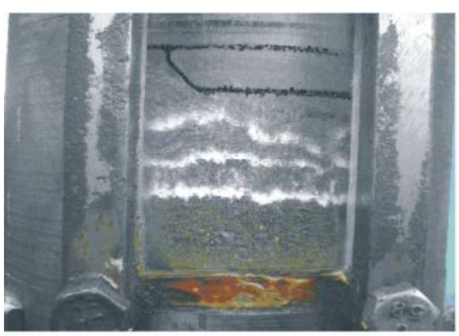
1. Beginning of mix compaction by a punched mold.



2. The mold is rotated by an angle of 10° (the onset of "wave" motion)

3. The mold is rotated by an angle of 20°
(intense filling of the mold holes with ACM)

4. The mold is rotated by an angle of 30°
(the interlayer distance decreases)



5. The mold is rotated by an angle of 40°
(ACM particle continue to approach)

6. The mold is rotated by an angle of 50°
(the maximum compaction of ACM)

Fig. 5: Deformation of asphalt concrete mix

In all cases without exception, the air volume and intensity of its removal under the punched operative part were considerably (2-3 times) higher (Fig. 4).

A window made of acrylic glass (20 mm thick) was mounted on an experimental bench setup to directly observe the process of deformation of the compacted material. This makes it possible to assess the qualitative pattern of deformation of the compacted layer and provide quantitative evaluation of some parameters. At this stage, we focused on interpreting the qualitative pattern of the processes going on (Fig. 5).

- Beginning of mix compaction by a punched mold.
- The mold is rotated by an angle of 10° (the onset of "wave" motion)
- The mold is rotated by an angle of 20° (intense filling of the mold holes with ACM)
- The mold is rotated by an angle of 30° (the interlayer distance decreases)
- The mold is rotated by an angle of 40° (ACM particle continue to approach)
- The mold is rotated by an angle of 50° (the maximum compaction of ACM)

An effect (that can be referred to as the "perforation effect") was revealed during the study. Benchmark experiments allowed us to answer one of the key questions-what is the mechanism of the perforation effect?-and to quantitatively estimate this effect. An assumption was made that the effect emerges due to the improved conditions for removal of air entrapped in the asphalt concrete layer.

Summary: When considering all possible rheological models describing the behavior of the condensed material, no models can be found that would describe the behavior of the material as air is squeezed out of the open and closed pores. It seems to be unreasonable to replace the resistance against squeezing of air with viscous resistance (Newton body). Air viscosity is manifold lower than that of the liquid phase of the asphalt concrete mix (bitumen). However, the degree of compaction entirely depends on air volume in ACM [9].

Basically, the solidification element starts functioning when air is partially or almost completely removed from a certain local area of the compacted layer and no density gain occurs any longer. The redistribution of bitumen over the inter-grain space has no significant effect on density [10]. If bitumen amount is optimal and the granulometric composition of the mineral portion has been selected correctly, one can expect that the main portion of bitumen will be converted to the structurized state. In turn, this will increase the general strength of the compacted layer.

The solutions regarding the time of air flow from a closed volume in the super-and subcritical area in the form of nonlinear and differential equations, respectively, are given in literate devoted to the hydro-pneumatic actuator. It is difficult to solve these equations, since all the factors are variable, while the differential equation, due to its complexity, can be solved using the grapho-analytical method only. In this context, it is unreasonable to consider the work of a modified model with the Prager body at this stage. Examination of this model can be subject to an individual study of the behavior of ACM under conditions of complex loading. However, the modified model offers an integral method for studying compaction of ACM, which consists in comparative tests on measuring the volume of air released from the compacted material under various types of multiplicative action (vertical and torsional vibration, reversal loading, punched operative parts). It seems that this method can be used to assess the efficiency of various types of working equipment of multiplicative action.

CONCLUSIONS

A stressed state emerges under a punched mold; according to the theory of plasticity, this state causes the emergence of slide lines in the deformed materials. The theoretic consideration of this problem is limited, since it is difficult to determine the actual situation directly under the hole. Shear stress emerges in space under the hole with the intensity proportional to load under the mold. The directions of this stress coincide with the slide lines. The stress is a source of relocations and decomposition in the layer, as well as squeezing it into a hole. All these factors (relocations, decomposition) cause a multiplicative effect on the compacted material, which increase the removal of the gas phase due to a drastic decrease in resistance. One can eventually assume that the trajectory of a single particle of the mineral framework, with allowance for the character and directions of the slide lines, is the helical motion with continuously changing kinematic parameters.

It was found that the perforation effect can be estimated to be ~40% of the total effect at the initial stage and ~60% at the final stage of the compaction process. In other words, if the operative part is punched, the increase in intensity is noticeable and rather significant all other conditions being identical (including the identical pressure on the compacted layer). This is indicative of the fact that at identical sizes of the rollers of the roller machine, a punched roller machine is expected to be more lightweight. The calculations based on Eq. (1), which take into account the increase in compacting load due to a decrease in the contact surface area, demonstrate that the compacting effort increases for the most admissible punching value and corresponds to a twofold increase in weight of the roller machine at the final stage of the compaction process.

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