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THE EFFECT OF WEATHER AND CLIMATIC FACTORS ON TEMPERATURE DROPS IN BUILT-IN ASPHALT MIXTURES

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The asphalt standard (PN-S-96025:2000) introduces requirements concerning weather and climatic conditions with built-in Hot Mix Asphalt (HMA). This standard is limited to lack of rainfall, ambient temperature (10ºC – in layers up to 8.0 cm and 5ºC – in layers above 8.0 cm) and wind speed (up to 16 m/s). Unconditional adherence to these principles means the closure of the building season as early as the end of September. However, practice shows that work carried out at lower ambient temperatures can be successful. The answer to “Why is it done this way?” can be found by analysing heat flow in the layer of the mineral-asphalt mixture submitted to environmental influences, thus allowing the scale of the impact of particular factors on heat losses in HMA to be known, and, simultaneously, enabling appropriate decisions at the building site to be made.

Key words: roads, pavement, compaction, heat transfer

1. GENERAL REQUIREMENTS

Pavement layers made of Hot Mix Asphalt (HMA) should have appropriate physical and strength properties, an essential requirement to ensure maximum road lifetime. Manufactured HMA achieves these properties after building in, but above all, after compaction (in accordance with the standard PN-S-

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96025:2000) up to an index above 98% in relation to samples created in the laboratory. In order to be effective and economically viable, the concentration process should be carried out using appropriate equipment and within the determined range of temperatures, conditioned by the viscosity of the asphalt binder. The time thus needed to carry out the relevant work depends primarily on the weather and climatic conditions and the technology applied in the thickening work.

The above standard (PN-S-96025:2000) defines, in point 3.5, the principles to be fulfilled by a contractor when building in HMA. Unfortunately, due to the ambient temperature, the possibilities of carrying out the work would be limited to the summer season only. Are such strict criteria fully justified? Practice demonstrates that the desired properties may also be achieved at lower temperatures, thus allowing HMA to be built in correctly.

2. HEAT FLOW IN A HOT MMA LAYER

In a thickening HMA layer, the phenomenon of unstable thermal conduction occurs, meaning that the temperatures at every point of the layer differ not only from one another, but simultaneously change over time, taking on lower and lower values up to their equalization. The speed of this process depends to a great extent on possibilities of heat absorption by the environment surrounding the HMA through conduction, convection and radiation. These possibilities are described by the overall heat penetration coefficient in solid bodies (lower pavement structural layer, material of the working elements in road rollers), along with the overall heat penetration in fluids and the elements of the ambient environment (air, water). It should be added here that heat consumption by water used to wet the roller, at boiling point, is subject to different, more complex principles connected with the liquid-to-steam phase change heat, and will not be subject to detailed analysis at this stage.

The phenomenon of conduction in an unstable state is solved on the basis of Fourier's differential equation [1]. A classic way of solving this equation is the method of variable separation, which consists in looking for the solution in the form of the product of two functions, the function of time and space. Consequently, the equation (2.1) [1, 2, 3] is obtained. It allows the temperature in any place of a plate (pavement) to be defined, based on Biote (*Bi*) and Fourier (*Fo*) similarity numbers.

$$Y = \frac{T - T_{oś}}{T_p - T_{oś}} = \sum_{n=1}^{n=\infty} e^{-\delta_n^2 Fo} \frac{2\sin\delta_n}{\delta_n + \sin\delta_n \cos\delta_n} \cos\delta_n \frac{x}{s_m} \tag{2.1}$$

$$Fo = \frac{\lambda \cdot \tau}{\rho_p \cdot c \cdot s_m^2} \tag{2.2}$$

$$Bi = \frac{\alpha \cdot s_m}{\lambda} \tag{2.3}$$

where: T is the plate temperature at τ moment and at x distance from the plane lying on the plate axis [K]; T_p is the initial plate temperature at time $\tau = 0$, [K]; $T_{oś}$ is the mean temperature in which the body is placed, [K]; α is the heat penetration coefficient to the surroundings, [W/(m^2·K)]; s_m is the perpendicular distance of the body surface from the plane situated on the body axis, [m]; x is the distance of the considered point from the plane situated on the plate axis, [m]; λ is the plate heat conduction coefficient (the HMA layer), [W/(m·K)]; τ is the time from the moment of the heat movement initiation, [s]; ρ_p is the apparent density of the plate material, [kg/m^3]; c is the plate material specific heat, [J/(kg·K)].

The δ_n values correspond to the points of the function intersection $y_1 = ctg\delta$ and the function $y_2 = \frac{\delta}{Bi}$. A schematic diagram of heat conduction in a plate in an unstable state is shown in Fig 1.

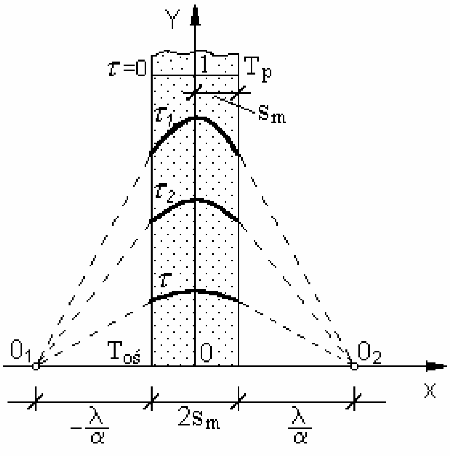

Fig 1. Plate self-cooling process in homogenous surroundings

The method shown above allows the determination of temperature drops in the cooled HMA layer, with the assumption, however, that this layer is situated in a homogenous medium. In reality, the plate is subject to the reactions of a range of factors, and the value of their reactions may be variable in time. Because of this, the calculations made will characterise, above all, the effect of individual environmental factors on their heat consumption from the built-in mineral-asphalt mixture.

3. HEAT PENETRATION TO SURROUNDINGS

3.1. Heat consumption by solid bodies

During the process of the HMA thickening, heat consumption takes place through both conduction and convection. Heat flow between solid bodies takes place by means of a conduction phenomenon which, in accordance with kinetic theory, occurs on the basis of the replacement energy of molecules being transmitted by molecules of higher energy to those of lower energy (the molecular phenomenon) inside a medium or from one medium to another through direct contact, where particular molecules in the unit do not show greater changes in their orientation [3]. A lack of connection continuity among the heat exchange media causes the heat exchange to take place on the basis of convection or, more generally, penetration.

A parameter describing the abilities of heat consumption by solid bodies, for example the lower constructional layer of the pavement or elements of thickening machines, is the overall heat penetration coefficient α_z (3.1).

$$\alpha_z = \frac{\lambda_z}{h_z} \tag{3.1}$$

where: λ_z is the material heat conduction coefficient (for example a lower-situated mineral-asphalt layer or steel, in the case of heat consumption by a steel road roller drum), [W/(m·K)]; h_z is the thickness of the layer consuming the heat, [m].

3.2. Heat penetration through liquid flowing round layers

The phenomenon of heat replacement with the surroundings in the form of fluid (gas, liquid) occurs by various forms of convection and by radiation. Heat penetration as a result of convection is due to the movement of the fluid at various temperatures (from a macroscopic perspective) with the simultaneous presence of the phenomenon of heat conduction in a thin boundary layer. In the direction perpendicular to the body surface, both the temperature of the fluid and the speed of its flow are different, which consequently decides about the transfer of both heat and mass momentum. Depending on the factor causing the fluid movement, forced convection (the flow mass speed is unequivocally defined) and natural convection (free) resulting from the action of the buoyant force can be distinguished, being the result of the density difference caused by the temperature difference in various areas of the fluid. In real conditions, these two forms of convection are most often present concurrently, which in accordance with [4] may be described as mixed convection. Therefore, the way to determine the heat quantity returned to the surroundings consists in calculating the value of the total heat penetration coefficient from the equation (3.2).

$$\alpha = \alpha_w + \alpha_s + \alpha_r \tag{3.2}$$

where: α_w is the heat penetration as the effect of the forced convection, [W/(m^2·K)], α_s is the heat penetration coefficient as a result of free convection, [W/(m^2·K)], α_r is the overall heat penetration coefficient by radiation, [W/(m^2·K)].

The quantity of heat exchange as a result of the forced and free convection is defined from the formula (3.3), using an overall value, which is the Nusselt number [1, 2, 3].

$$\alpha_{w,s} = \frac{Nu \cdot \lambda_p}{d} \tag{3.3}$$

where: d is the plate's typical dimension (thickness of the arranged layers of HMA), [m]; λ_p is the coefficient of the heat conduction in fluid, [W/(m·K)].

The determining of the Nusselt number quantity requires a knowledge of the fluid flow characteristic in the boundary layer, which may be laminar or turbulent.

In this case, it is necessary to know Reynold's (Re), Prandtl's (Pr) Grasshoff's (Gr) characteristic dimensionless numbers defined by the formulas (3.4), (3.4) i (3.6) [1, 3, 4].

$$\mathrm{Re} = \frac{w \gamma_p d}{\eta} \tag{3.4}$$

$$\mathrm{Pr} = \frac{c_p \eta}{\lambda_p} \tag{3.5}$$

$$\mathrm{Gr} = \frac{g\beta \Delta T d^3 \gamma_p^2}{\eta^2} \tag{3.6}$$

where: η is the fluid viscosity dynamic coefficient, [N·s/m^2]; w is the fluid flow speed in the non-disturbed stream, [m/s]; γ_p is the fluid density, [kg/m^3]; c_p is the specific heat at constant pressure, [J/(kg·K)]; g is the acceleration of the terrestrial gravity force equal to 9.81 [m/s^2]; β is the fluid cubical expansion coefficient, [1/K]; ΔT is the difference between the plate temperature (mineral-asphalt mixture) and the fluid temperature, surroundings (for example air) $\Delta T = T_S - T_{oś}$, [K].

It is assumed in the case of forced convection that in the range of quantities of the number $\mathrm{Re} < 8 \cdot 10^4 - 5 \cdot 10^5$ fluid movement takes place in a laminar way, whilst in the quantity $5 \cdot 10^5 - 10^7$ it takes the turbulent form. Therefore Nusselt's number is defined from the formulae (3.7) and (3.8) [2, 3, 4] accordingly:

$$\mathrm{Nu} = 0.664\,\mathrm{Re}^{\frac{1}{2}}\,\mathrm{Pr}^{\frac{1}{3}} \tag{3.7}$$

$$\mathrm{Nu} = 0.0366\,\mathrm{Re}^{\frac{4}{5}}\,\mathrm{Pr}^{\frac{1}{3}} \tag{3.8}$$

A parameter defining the form of movement in free convection may be the critical value of Grasshof's number or the product of the numbers Gr i Pr, named Reyleigh's (Ra) number, which is the more common form in literature. Thus, in the range of values $5 \cdot 10^2 < \mathrm{Gr\,Pr} < 2 \cdot 10^7$ the fluid movement near the plate returning the heat takes place in the laminar way, and in accordance with Michiejew [3] the heat consumption may be calculated from the formula (3.9), with the assumption, however, that the heat exchange when the fluid is heated takes place at the upper surface of the plate, whereas when the fluid cools, it takes place at the lower surface.

$$\mathrm{Nu} = 0.54\left(\mathrm{Gr\,Pr}\right)^{\frac{1}{4}} \tag{3.9}$$

In the range of values $2 \cdot 10^7 < \mathrm{Gr\,Pr} < 10^{13}$ the fluid movement in the boundary layer takes place in the turbulent manner and the quantity of the heat exchange is defined on the basis of the formula (3.10) [1].

$$\mathrm{Nu} = 0.135\left(\mathrm{Gr\,Pr}\right)^{\frac{1}{3}} \tag{3.10}$$

The heat losses due to radiation result from the difference in energy absorbed from solar radiation and emitted from the HMA. Quantification of this difference is obtained by determining the overall heat penetration coefficient by radiation from the formula (3.11) [1, 2].

$$\alpha_r = \frac{q}{\Delta T} = \frac{\varepsilon_1 I_S - \varepsilon_1 C_0 \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right]}{T_1 - T_{pow}} \tag{3.11}$$

where: I_S is the solar radiation density, [W/m^2]; ε_1 is the mineral-asphalt mixture emission ability; C_0 is the Stefan-Boltzmann constant, C_0=5.768 [W/(m^2·K^4) [1, 5, 6]; T_1 is the MMA layer surface temperature, [K]; T_2 is the open space temperature, T_2 = 230 [K] [1, 6]; T_{pow} is the air temperature, [K].

4. THE EFFECT OF FACTORS ON HOT MMA HEAT LOSSES

Heat exchange with the surroundings during the building in of hot MMA is an enormously complex process, because of the heat transfer in the thickened layer and the way the surroundings take up this heat. Consequently, the temperature in the HMA layer drops, thus, limiting the time needed to carry out an effective concentration process. Considerable temperature differences in the layer section or sudden, rapid HMA cooling can have a very negative effect on the quality of work executed and the parameters of the mineral-asphalt mixture.

In this elaboration, a number of calculations were executed for an HMA layer 5 cm thick (on the surface, inside and bottom of the layer) with 3.5 m width, assuming that the side edges and the lower surface are insulated. This is a theoretical case, whose aim is to raise awareness of the extent to which particular external conditions can affect temperature drops in the HMA layer. The calculations were made for two ambient temperatures 0ºC and 15ºC, at a wind speed of 0.2 and 15 m/s, constant relative humidity of ϕ = 80º% and an HMA initial temperature of 135ºC. The HMA physical properties used for the calculation were as follows: The heat conduction coefficient – λ_{MMA} = 0.698 W/(m·K), the specific heat – c_{MMA} = 0.921 kJ/(kg·K), the structural density – γ_{MMA} = 2.690 Mg/m^3. The results of the temperature drop calculations in the HMA layer are shown in Fig. 2–4.

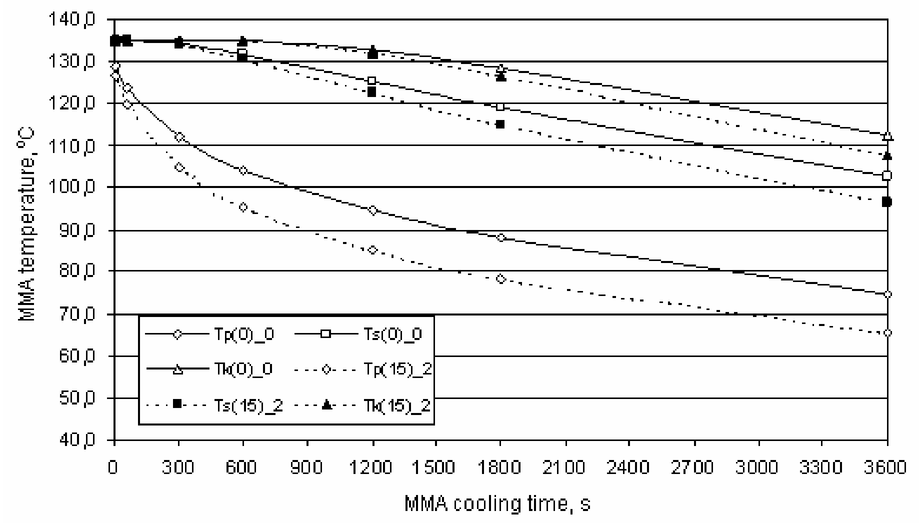

Fig. 2. Temperature in a 5 cm-thick **HMA** layer at ambient temperatures 0ºC and +15ºC,wind speed 0 and 2 m/s; Tp is the temperature on the layer surface, Ts the temperature inside the layer, Tk the temperature on the layer bottom; the value in brackets is the ambient temperature: (0) – 0ºC, (15) – 15ºC; the value after the dash indicate the wind speed:_0 – 0 m/s, _2 – 2 m/s

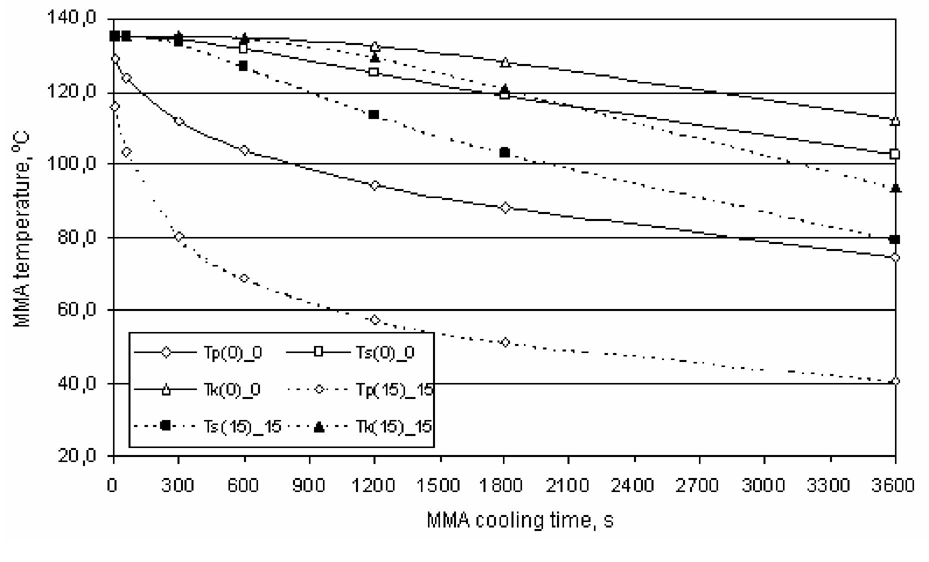

Fig. 3. Temperature in a 5 cm-thick **HMA** layer at ambient temperatures of 0ºC and 15ºC and the wing with the speed 0 and 15 m/s; markings as above

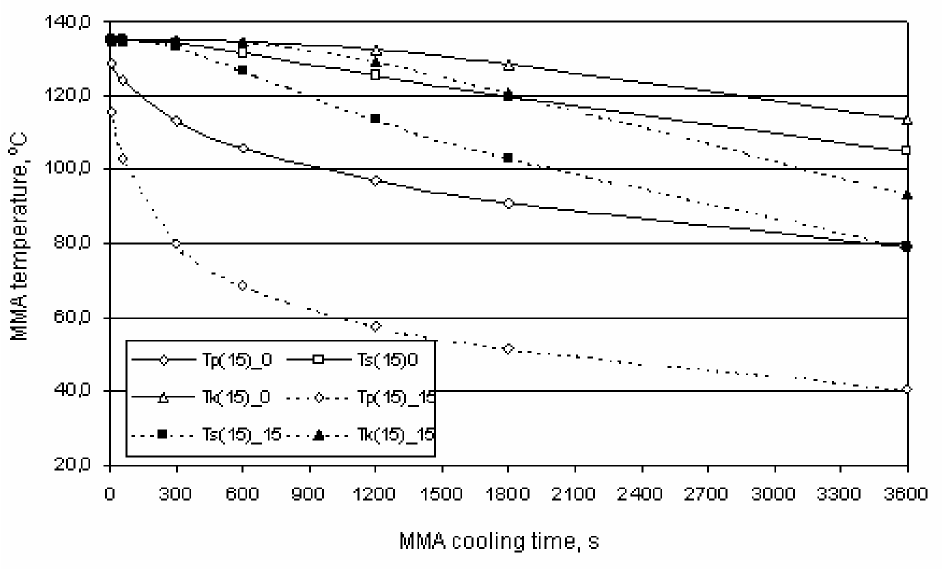

Fig. 4. Temperature in a 5 cm-thick **HMA** layer at ambient temperature 15ºC and wind speed 0 and 15 m/s; markings as above

5. CONCLUSIONS

Standard requirements (PN-S-96025:2000) introduce certain limitations with reference to weather and climatic conditions at HMA built-in. These conditions forbid work at wind speeds above 16 m/s and temperatures below 10ºC with a layer thickness of less than 8 cm (the minimum temperature over a 24-hour period not lower than 5ºC) and below 5ºC with layers above 8 cm (the minimum temperature over a 24-hour period not lower than 0ºC).

The theoretical model presented in this article enables the effect of particular factors on the HMA cooling speed to be assessed. In accordance with this, it may be argued whether the ambient temperature should limit road work so severely (the standard requirements), when this work needs to be carried out during the summer. From the calculation results it can be seen that it is not the temperature, but the wind speed which has the deciding effect on the HMA cooling. At a temperature of 15ºC and a wind speed of 2 m/s the temperature in the HMA layer decreases faster (especially in the surface layer) than in calm air with a temperature of 0^0C. Moreover, the form of the fluid flow itself is an important factor forming the temperature distribution in the layer (strong turbulence considerably increases the α coefficient value which, at a speed of about 6 m/s doubles and at 16 m/s increases as much as four times). Therefore, executing work at a wind speed of 8-16 m/s, which considerably affects the HMA cooling, should be supported with appropriate practical experience and theoretical analysis.

The autumn months are a difficult time of year to carry out bituminous work for another reason. This difficulty is, above all, caused by the presence of water which has a considerable effect on hot HMA heat losses. If the effect of technological water (the sprinkling of road roller steel drums) can be limited by the later use of road rollers or limiting their amount to a minimum, the water contained in the pores of the lower layer, however, may have very negative effects. This is a result, in principle, from the high heat consumption needed to convert water into steam, which affects the momentary temperature drop at the bottom of the layer. The temperature reduction affects the growth of the asphalt binder viscosity and simultaneously counteracts adherence among the layers, reducing the road construction load capacity. The heat consumption by the lower constructional layers (without the participation of water) is relatively small and corresponds to heat losses in calm weather.

In light of the negative effects of wind speed and moisture on the effectiveness of the HMA thickening process, a rational method to extend the construction season is undoubtedly the built-in HMA in thick layers (or two layers concurrently) and in as large widths as possible.

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