

## THE HEAT EXCHANGE IN THE EDGE AREA – THE PROBLEM OF HOT MIX ASPHALT COMPACTION

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**Abstract.** The temperature of asphalt mix during its laying is not homogenous. Edges are a particular place. An intensive collection of heat occurs there through horizontal (upper and bottom) surfaces and lateral surface. An additional factor is the thermal layer created on the surface of the layer which multiplies the potential to collect the heat by the surroundings. The theoretical calculations carried out and confirmed by laboratory tests and measurements on the road allow foreseeing the speed of temperature drops for these areas. This facilitates the correct planning of the process of compaction, and by the same obtaining the required density of mix.

**Keywords:** hot mix asphalt, heat exchange, convection, conducting, layer edge.

### 1. Introduction

The compaction of hot mix asphalt (HMA) allows to shape accordingly its physical and resistance properties (Bražiūnas *et al.* 2010; Dubois *et al.* 2010; Mrawira, Luca 2006; Rafiei *et al.* 2012). The effectiveness of the process depends upon the input of compaction and the temperature of mix (Houman 2012; Kassem *et al.* 2012; Kennedy *et al.* 1984; Williams *et al.* 2009; Willoughby *et al.* 2001). Changes in the temperature of HMA while laying it out are dependent on the speed of heat flow in the layer (expressed by  $\lambda$  ratio) and the capacity to collect it by the surrounding environment (characterised by the  $\alpha$  ratio). The description of the phenomenon described in the literature concerns only areas near the center of the layer (Mahoney *et al.* 2000; Mieczkowski 2006; Timm *et al.* 2001). The obtained

results not used for the evaluation of heat loss directly on its edge, because of omitting additional surface of heat flow (side edge). Within the edge the heat exchange takes place in two directions what causes quicker cooling of HMA. In consequence, difficulties occur in obtaining the required compaction, and by the same, void content increases in the layer what leads to the occurrence of damage in a form of shortage (Fig. 1). The cause of the heat exchange process shall find its reflection in the operation of compacting machine which shall allow to shape properly the asphalt mix (AM) structure in these areas and to limit the destructive impact of atmospheric factors (water, frost, UV) (Bell *et al.* 1984; Bražiūnas *et al.* 2010; Choubane *et al.* 1998; Harvey, Tsai 1996; Hughes 1989; Linden *et al.* 1989; Scherocman 1984; Tarefder, Yousefi 2012; Willoughby *et al.* 2001).



Fig. 1. Damage on the asphalt surface in the area

## 2. Heat exchange on hot HMA layer edge

Heat flow in HMA layer is described by Fourier's differential equation, which is presented as a product of two functions: time and space (1, 2) (Hobler 1986). The adopted model has some limitations related to the direction of the heat flow. It was assumed that the heat movement takes place in one direction, i.e. through the horizontal upper and bottom surface.

$$T_{(x)} = T_{os} + Y(T_p - T_{os}), \quad (1)$$

$$Y = \sum_{n=1}^{n=\infty} e^{-\delta_n^2 Fo} \frac{2 \sin \delta_n}{\delta_n + \sin \delta_n \cos \delta_n} \cos \delta_n \frac{x}{s_m}, \quad (2)$$

where  $T_{(x)}$  – temperature in the layer at  $\tau$  moment and in the  $x$  distance from the plane lying in the axis of the layer, K;  $T_p$  – initial temperature of the layer in time  $\tau = 0$ , K;  $T_{os}$  – temperature of the centre in which the body is held, K;  $\delta_n$  values of intersection points of function  $y_1 = \text{ctg} \delta$  and function  $y_2 = \frac{\delta}{Bi}$ ;  $Bi = \frac{\alpha s_m}{\lambda}$  – Biot number;  $Fo$  – Fourier number;  $s_m$  – perpendicular distance of the body's surface from the plane lying in the body axis, m;  $x$  – distance of the considered point from the plane lying in the layer axis, m;  $\alpha$  – ratio of heat penetration into the environment, W/(m<sup>2</sup>K);  $\lambda$  – coefficient of heat conducting of HMA layer, W/(mK).

In the area of layer edge, heat collection takes also place through the lateral surface, which causes an intensification

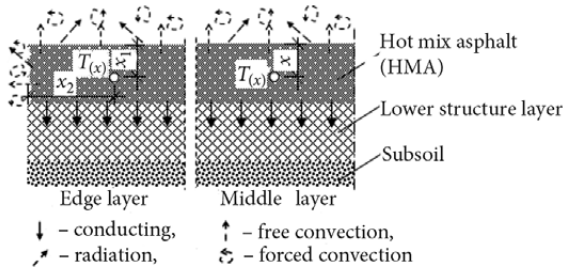


Fig. 2. Types of heat exchange in the area of the edge layer and in the centre of the layer

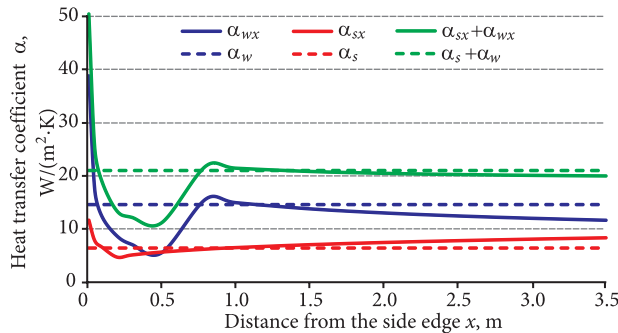


Fig. 3. Example of the values of local coefficients of heat penetration at forced convection ( $\alpha_{wx}$ ) and free convection ( $\alpha_{sx}$ ) and the mean ones for the layer adopted for calculations ( $\alpha_w$  – forced convection,  $\alpha_s$  – free convection)

of the process. This required an amendment to the model based on the Newton's principle. In accordance with it, the bodily shape is created from infinite or half-finite bodies (with the condition of their perpendicularity being maintained) (Hobler 1986). In the case where the HMA layer is cooled, this is a sort of simplification, resulting from different values of the coefficient of heat penetration ( $\alpha$ ) on the both surfaces of exchange. However, the differences are big enough to disqualify the method adopted. The effect of the additional heat collection by the lateral edge in the adopted model was taken into account in the manner of  $Y$  parameter determination. In the edge area, it is determined as the product of  $Y_{x1}$  and  $Y_{x2}$  (3) components, with the heat flow in the layer through both the surfaces taken into account. The chart picture of the thermal phenomena, occurring in the centre of the layer (in the place away from the edge) and in the area of the edge, has been presented in Fig. 2.

$$Y = Y_{x1} \cdot Y_{x2}. \quad (3)$$

Eq (3) takes into account HMA layer cooling through horizontal surfaces  $Y_{x1}$  and vertical edge  $Y_{x2}$ . This corresponds to the process of cooling of a body composed of two half-infinite bodies. In the case of the first body, the  $s_m$  parameter corresponds to one half of the width of the parameter laid out, however, in the second one, it is one half of the layer width. The effect of cooling the layer as a consequence of heat collection through the lateral (vertical) surface shall be noticeable only in a relatively small distance from the edge. The increase in  $x_2$  distance limits the influence of  $Y_{x2}$  parameter on value  $Y$  ( $Y_{x2} \rightarrow 1$ ), and cooling the layer for these spots takes place practically through horizontal surfaces. This has a physical justification and reflects the possibilities for heat to flow from the layer centre to its outer edge. In the case of  $Y_{x2}$ , this distance is so large that the collection of heat by the external environment is not compensated by its flow from the centre of the layer.

Accelerated cooling of mix close to the edge is related to thermal and hydrodynamic stabilisation. Over HMA surface, layers are generated close by the wall, and in consequence, there occurs a large differentiation of the values of heat exchange. In the zone directly by the edge, a much more intense collection of heat takes place than at the stabilised flow, and it is a consequence, first of all, of the activity of forced flow. This illustrates the changeability of values of the local coefficients of heat penetration determined by the author (Fig. 3).

The values of local coefficients of heat penetration at forced convection for layered and turbulent flow were determined for Eqs (4) and (5), and free convection is described by Eq (6) (laminar movement) and Eq (7) (turbulent flow) (Wiśniewski 1988).

$$\alpha_{wx} = 0.332 \frac{\lambda_p}{x} Re_x^{\frac{1}{2}} Pr^{\frac{1}{3}}, \quad (4)$$

$$\alpha_{wx} = 0.0292 \frac{\lambda_p}{x} Re_x^{\frac{4}{5}} Pr^{\frac{1}{3}}, \quad (5)$$

$$\alpha_{sx} = 0.508 \frac{\lambda_p}{x} Pr^{\frac{1}{2}} (0.952 + Pr)^{\frac{1}{4}} (Gr_x)^{\frac{1}{4}}, \quad (6)$$

$$\alpha_{sx} = 0.0295 \frac{\lambda_p}{x} Gr_x^{\frac{2}{5}} Pr^{\frac{7}{5}} \left( 1 + 0.494 Pr^{\frac{2}{3}} \right)^{\frac{2}{5}}, \quad (7)$$

where  $\alpha_{wx}$ ,  $\alpha_{sx}$  – local ratios of heat penetration at forced and free convection, W/(m<sup>2</sup>K);  $\lambda_p$  – coefficient of heat conduction in the air, W/(mK);  $Re_x$  – local value of Reynold number;  $Pr$  – Prandtl number;  $Gr_x$  – local value of Grasshof number,  $x$  – distance from the layer edge, m.

The local ratio of heat penetration  $\alpha_{wx}$  at the section up to 5 cm from the edge was raised on average by over 92% in relation to  $\alpha_w$ , and at the section up to 10 cm by over 56%. This process is deepened by free convection whose capability to collect heat (expressed by the averaged  $\alpha_{sx}$  coefficient) for the area of 5 cm from the edge is larger in relation to  $\alpha_s$  by over 51%, and at 10 cm by over 35%.

The increased capability to collect heat in the area directly close to the layer edge is linked to the occurrence of the layer close to the wall. Following the distance, a significant drop in the value of the coefficient of heat penetration takes place which is a result of the increase in the thickness of the small layer which conducts the heat and the nature of the flow (laminar flow). The further growth in the distance from the edge (for the case in Fig. 3 – on the section of about 0.2 m at free convection and about 0.5 m at forced convection) contributes to breaking the dropping trend and the penetration coefficients start to grow. This change is dictated by the occurrence of turbulence (swirling), and by the same, accelerated collection of heat from over the hot surface. This section corresponds to the transitory area. At a distance of about 0.4 m at free convection and 0.8 m at forced convection the situation is stabilised, which corresponds to the layer formed by the wall (together with a small heat conducting layer) of a turbulent flow.

The size of the area on which intensive changes occur in the value of the coefficient of heat penetration  $\alpha$ , depends, among others, on the temperature of the surface, its texture (coarseness), inequality, wind velocity, obstacles directly before the surface which gives up the heat and free convection which contributes also to changes in the air swirls.

### 3. Theoretical temperature within the edge of HMA being cooled

The places of cumulative heat collection are areas close to the edges of HMA layers. Generation of parietal layers (hydraulic and thermal) on the surface and additional heat collection by the vertical edge hinder significantly from carrying out the precise calculations on the beginning section of the layer. Introduction of the averaged values of  $\alpha$  for this area allows setting out approximate values of temperature in the profile of HMA being cooled in time.

The speed of HMA cooling was additionally made dependent upon the type of edge. The outer edge is understood as the lateral edge of the mix laid out exposed to direct impact of atmospheric conditions (Fig. 4). The inner edge is treated as the place of contact with AM, laid out earlier (spreading out in one half of roadway width). For these two cases, the distribution of the theoretical temperature was set out in the layer 3.5 m wide and 5 cm thick and 10 cm away. The results were obtained for two air temperatures 0 °C and +20 °C, with wind of 0 m/s and 10 m/s velocity, stable humidity against the air  $\phi = 80\%$  and the input temperature of HMA equal to 135 °C. The temperature drops on the outer edge of the layer, in the distance of 5 cm, 10 cm, 15 cm from it, and in the „centre” of the layer are presented in Figs 5–8, and for the inner edge in Figs 9–10.

It results from the calculations carried out, that independently upon atmospheric conditions and thickness of the layer, the areas close to the outer edges shall be compacted directly after spreading out the HMA. The lateral/side (outer) surfaces themselves get cooler nearly immediately, practically in all atmospheric conditions. A similar sensitivity to cooling is shown by places at a distance ranging from 5–7 cm from these edges. There, even at favourable atmospheric conditions (20 °C, no wind) and a thick layer (10 cm), the temperature is reduced to the boundary temperature already after 30 s, in which it is still possible to carry out correctly the process of compaction (Fig. 8). Less favourable atmospheric conditions (first of all, wind and water) shift the dangerous area up to 10 cm from the outer edge, even in the case of thick layers (Fig. 6). In extreme cases, i.e. with bad atmospheric conditions and insignificant thicknesses, the area of quick cooling reaches as much as 15 cm (Fig. 7). A larger distance limits the impact of the lateral/side edge to heat loss in the layer being cooled down.

In the theoretical description of heat losses, in the area of inner edge, no significant differences are noted in

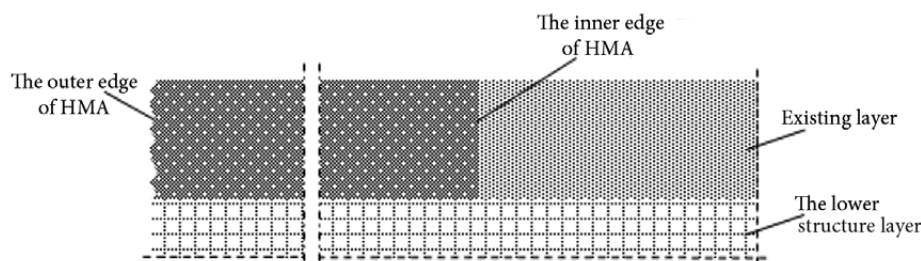


Fig. 4. Outer and inner edge of the HMA layer laid out (scheme adopted for calculations)



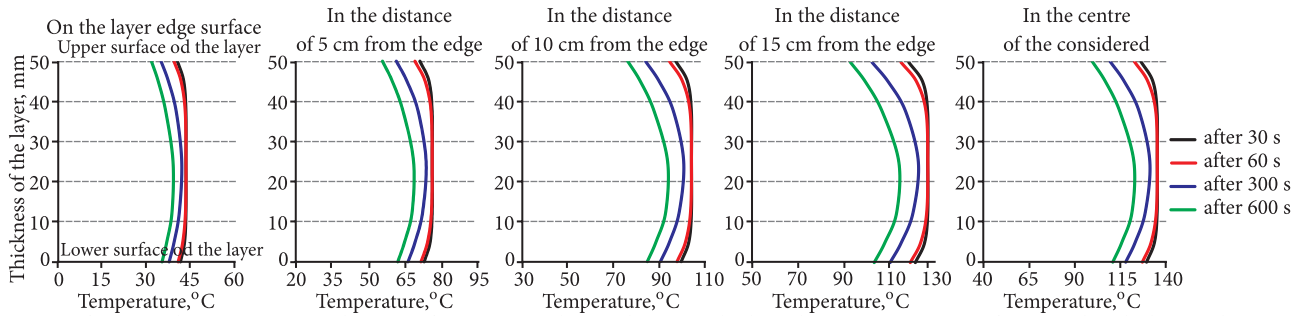


Fig. 5. Theoretical temperature in the area of outer HMA layer edge 5 cm thick in the air temperature of 0 °C and with the wind velocity of 0 m/s, depending upon the time

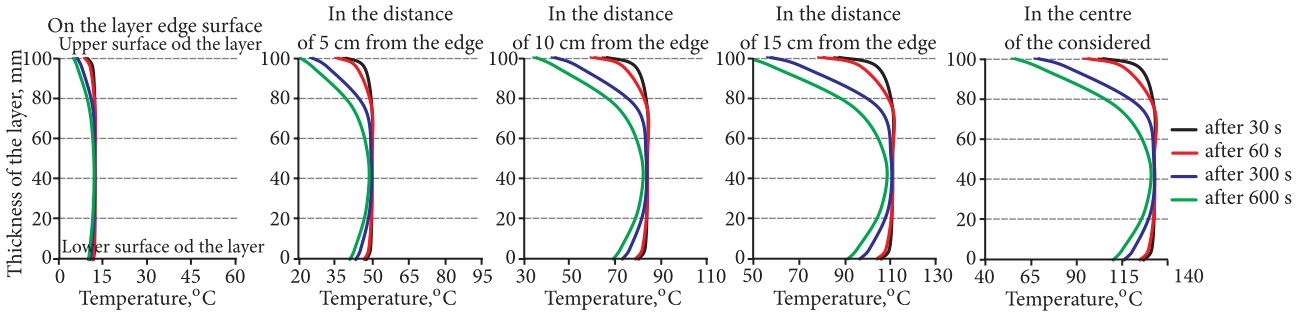


Fig. 6. Theoretical temperature in the area of outer edge of the HMA layer, 10 cm thick in the air temperature of 0 °C and with the wind velocity of 10 m/s, depending upon the time

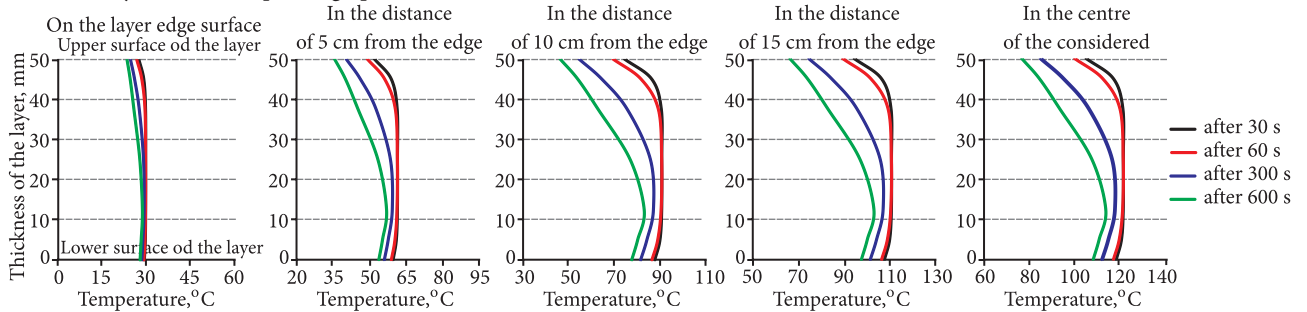


Fig. 7. Theoretical temperature in the area of outer edge of the HMA layer, 5 cm thick in the air temperature of 20 °C and with the wind velocity of 10 m/s, depending upon the time

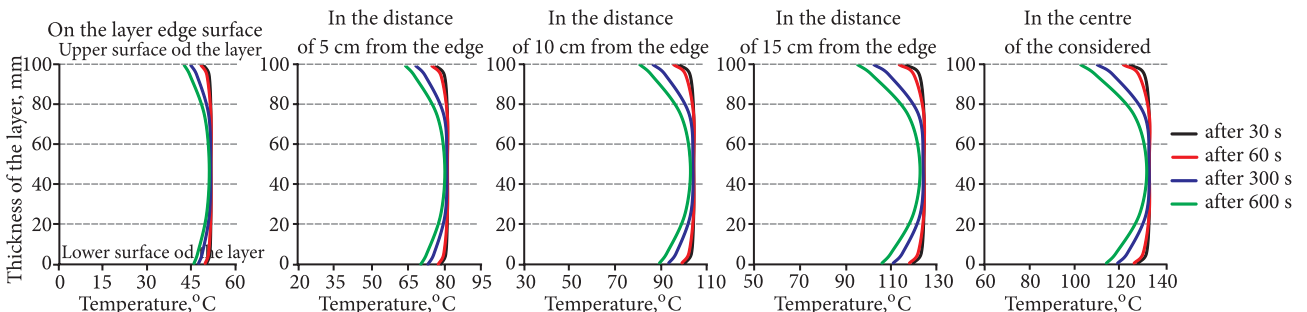


Fig. 8. Theoretical temperature in the area of outer edge of the HMA layer, 10 cm thick in the air temperature of 20 °C and with the wind velocity of 0 m/s, depending upon the time

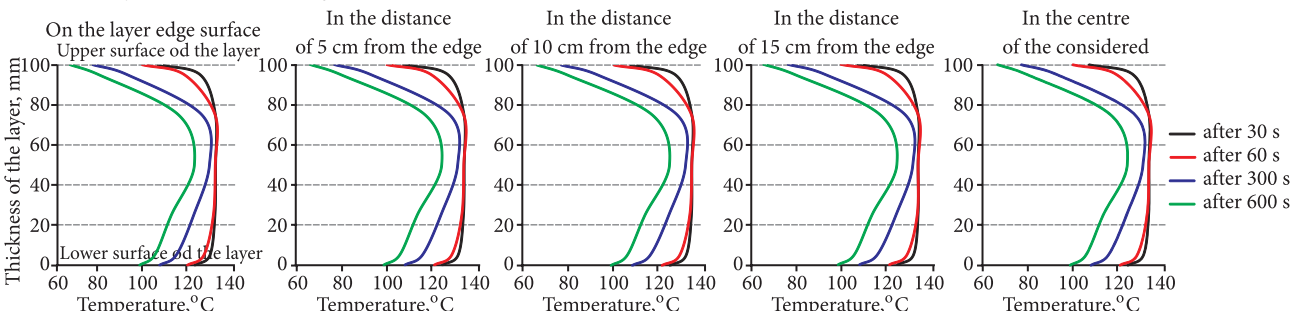


Fig. 9. Theoretical temperature in the area of inner edge of the HMA layer, 10 cm thick in the air temperature of 20 °C and the wind velocity of 10 m/s, depending upon the time

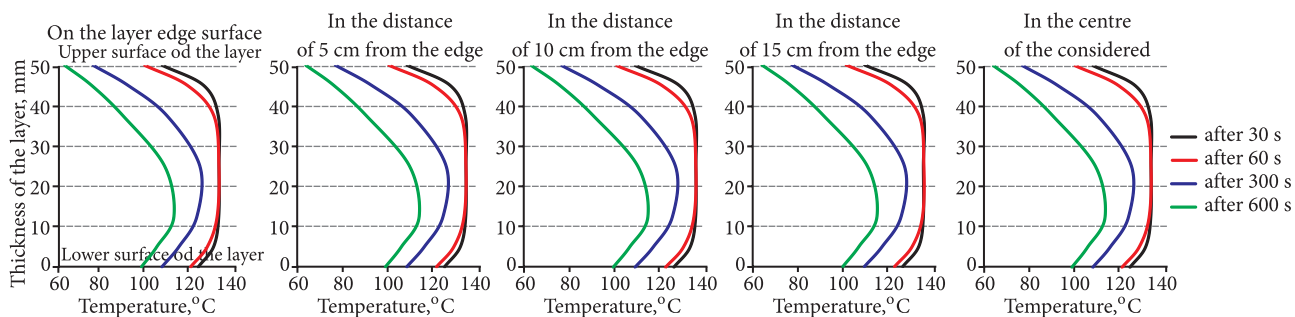


Fig. 10. Theoretical temperature in the area of inner edge of the HMA layer, 5 cm thick in the air temperature 20 °C and the wind velocity of 10 m/s, depending upon the time: a) – e) as in Fig. 5

relation to the centre of the layer. Both the nature of temperature changes and the speed of the course of this phenomenon are maintained. The boundary conditions adopted for calculations, among others, the equal height of both layers and the heat flow exclusively to the earlier laid-out AM decide upon this. Physical and heat parameters of the mix predestine it more to the group of insulators than heat receivers (first of all, because of relatively small value of thermal conductivity coefficient), which slows down the heat collection of HMA being laid-out. The situation changes in the case of lateral/side edge of the existent layer being humid. Then, an immediate cooling down of the mix being spread out at the width of about 1–2 cm shall take place. This area shall be characterised by an increased void content and, by the same, no resistance to atmospheric factors impact.

**4. Verification of a model in laboratory and field research**

Theoretical drops in the temperature in the area of HMA layer edges obtained from calculations required a review. For this purpose, research was conducted on the laboratory and technical scale in the road. In the laboratory, tests were performed on AM samples of 250×250 mm and about 50 mm thick. They consisted of setting out the temperature drops in samples heated up to 150 °C and exposed to air impact of a flow velocity of 0 m/s and 8 m/s in the temperature of 0 °C and 20 °C. The values of temperature were measured at the distances of 5 cm and 10 cm from the uninsulated lateral/side edge of the sample (Fig. 11).

The readings of temperatures were carried out on the sample surface with the use of a pyrometer, and in the remaining places with thermoelectric thermometers (fused thermoelements). To minimize heat losses, through the remaining three lateral/side edges and the bottom plane, the samples were protected by aluminium foil, insulated with a layer of hard mineral wool (5 cm thick – lateral edges, 10 cm – bottom plane) with the heat conductivity coefficient  $\lambda = 0.037 \text{ W/(mK)}$  and by hydroinsulating (heat-resistant) foil, which fulfils the function of protection against the possible heat penetration. For the assumptions adopted in this way, a laboratory sample 5 cm thick corresponds to the layer 10 cm thick in the real conditions.

The results of heat losses measurement in the profile of a HMA layer for the determined wind velocity and air

temperatures are presented on Figs 12–14 (Note: T1pom. – T10pom. – temperature measured in the profile of the layer, in accordance with Fig. 11, T1teor.–T10teor. – theoretical temperature in the layer profile, according to Fig. 11). According to them the suggested theoretical model reflects the nature of temperature changes in the sample being cooled. A particularly good representation was achieved with measurements 10 cm distant from an uninsulated edge. At this distance (for the adopted conditions of outer impact) the influence of edge ceases and heat penetration to the surroundings through the upper horizontal surface starts to play a decisive role. At 5 cm distance from the edge, there are more distinct divergences between the measured and theoretical temperatures, and the average value of differences between the results obtained amounts to about 7.5 °C. At 10 cm distance, this difference is only 4 °C.

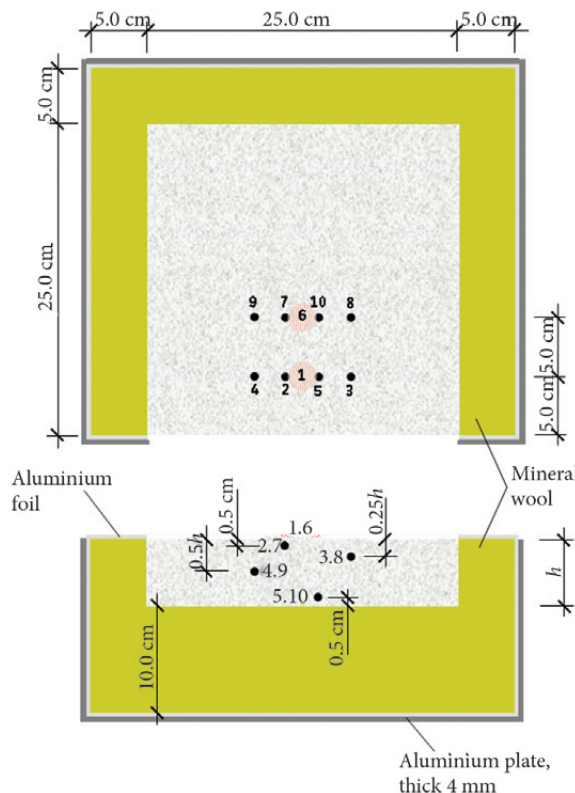


Fig. 11. Scheme of AM sample to test temperature drops with the „edge effect” taken into account, together with the distribution of measuring points

The larger mismatch of the results obtained from the measurements and the model (5 cm distance) is the consequence of the introduced simplifications related to a differentiation of  $\alpha$  value on both the surfaces and the degree of turbulence.

Quicker drops in temperature of the HMA layer edge area were confirmed on the technical scale. Tests of temperature distribution on the abrasive layer surface made of SMA 11 were performed by means of a thermographic camera, as distributed in one half of the roadway width. Measurements were carried out in October, 2011. The air temperature ranged from 3–7 °C, wind velocity was about 2–3 m/s with a relative humidity of about 65%.

According to the measurements taken already after the 1<sup>st</sup> min following spreading out the mix; larger drops in temperature appear on the edges (Fig. 15). In the area of the outer edge, they amount to about 70–80 °C, at the inner edge the process of cooling takes places slower and the differences reach 30–40 °C. After approximately 6 min and 4 passes of a steel roller on the outer edge area, a quicker flow of heat is observed (Fig. 16), which is also affected by wind direction. This is the zone of thermal and hydrodynamic stabilisation. In its area, the parietal layer is generated only now (conducting heat), which slows down the exchange process. Furthermore, as a result of forced convection, cold masses of air flow to the outer edge (left side

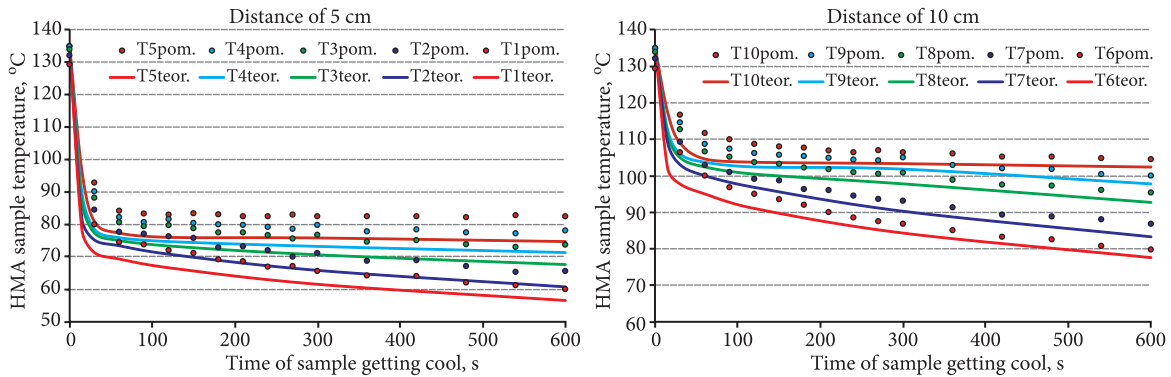


Fig. 12. Temperature in the HMA layer 5 cm thick, at different distance from the uninsulated edge, with the air temperature of 0 °C and wind velocity of 0 m/s

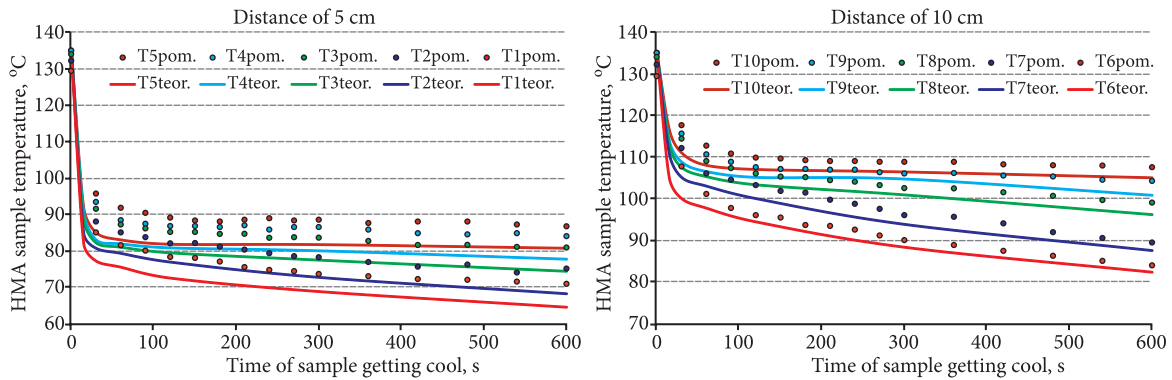


Fig. 13. Temperature in the HMA layer 5 cm thick, at different distance from the uninsulated edge, with the air temperature of 20 °C and wind velocity of 0 m/s

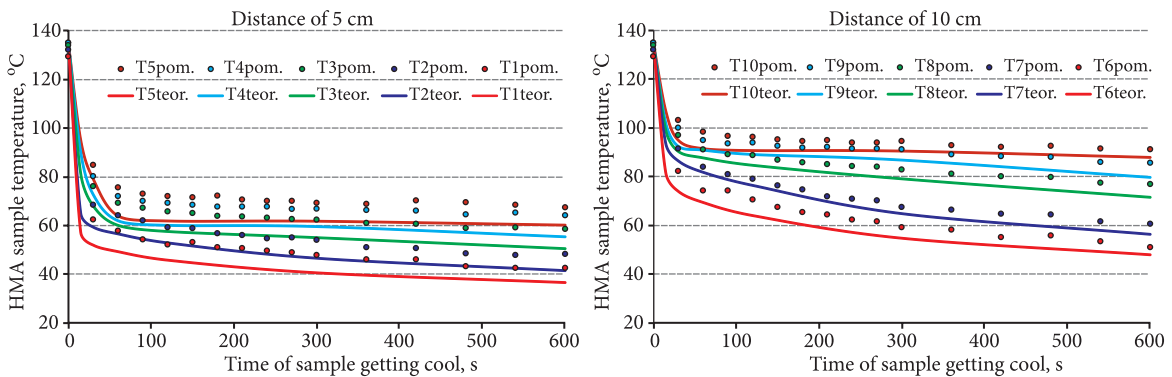


Fig. 14. Temperature in the HMA layer 5 cm thick, at different distance from the uninsulated edge, with the air temperature of 20 °C and wind velocity of 10 m/s

of the chart Fig. 16). Even an insignificant increase in the temperature at a further distance slows down additionally the process of heat exchange in the surroundings.

**5. Conclusions**

1. Compaction of mineral asphalt mix shall be conducted at the optimum temperature. Too quick emission of heat hinders compaction and by the same lead to an increase of void content. This, in turn, leads to a reduced resistance of the mix to the influence of climate and weather conditions and the drop of tensile strength.

2. The theoretical analysis conducted, supported by laboratory and field tests, indicates that in the area of edges of the laid-out hot mix asphalt there is accelerated emission of heat. The suggested Fourier’s model allows to set out the speed of temperature drops in the layer and after Newton’s principle being taken into account also in the area of its edges. This allows to set out the time necessary to compact asphalt mix.

3. A place particularly sensitive to cooling down is the area of about 10 cm from the outer edge of the layer. Its size depends, to a small extent, on the layer thickness. Decisive

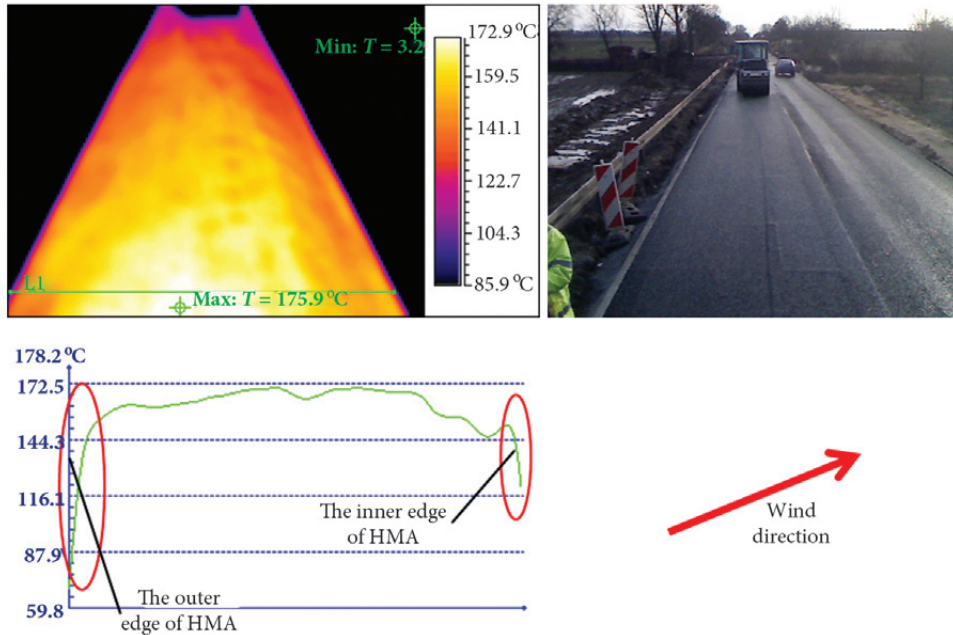


Fig. 15. Thermal image of SMA 11 layer surface after 1 min from spreading out with an example of temperature differentiation

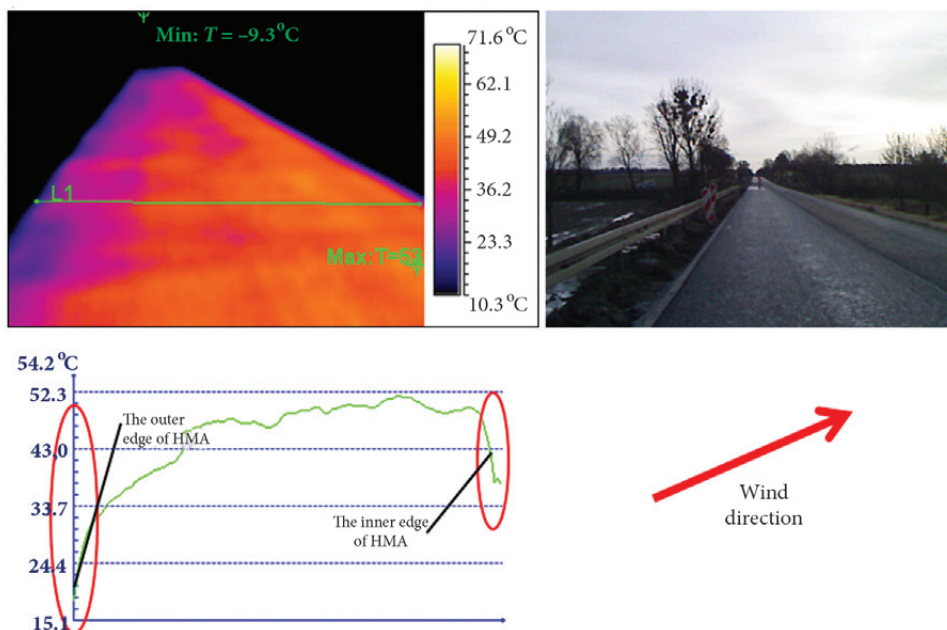


Fig. 16. Thermal image of SMA 11 layer surface after 6 min from spreading out and four passes of steel roller with an example of temperature differentiation



factors here are thermal processes i.e. the creation of the zone of thermal and hydraulic stabilisation and heat emission through the lateral edge. Obtaining of an appropriate volumetric density for this area of the layer requires a nearly immediate pass of compacting machines. Already after 2–3 min, the drops in temperature reach even 100 °C, and this makes the correct hot mix asphalt compaction practically impossible. The resulting increased void content in the layer requires protection at least against climatic and weather factors, first of all against water and ultraviolet radiation.

4. To protect the edges of the individual layers, the edges are packed on the surface by means of lubricating with asphalt emulsion or pure asphalt which shall limit the penetration of water, ultraviolet radiation and small particles into the structure of the hot mix asphalt. In the case of an abrasive layer, this area requires being additionally coarsened.

5. In accordance with the calculations made, the drops in temperature on inner edges shall be similar to those in the centre of the layer. The executory practice shows that also in these places, there are problems with getting an appropriate compaction. The reasons for this state of matters are multiple:

- the top layer of hot mix asphalt getting cold;
- water occurring on the edge of the existing layer (for instance, as a result of its lubricating with asphalt emulsion, directly before laying out a new layer);
- errors in spreading out the hot mix asphalt (insufficient quantity of the hot mix asphalt in the area of connection with the existent layer).

6. In the calculations of heat losses for the inner edge, an assumption was made that the layers have an identical thickness. This means that the heat flow in this area was practically from one mix to another. Because of the coefficient of heat conduction, this phenomenon was not too intense. The situation is different in real conditions. The layer thickness of the hot mix asphalt being laid out is higher compared to that existent by about 20–25%. This means that for the layer 4–5 cm thick about 1.0–1.2 cm of the part close to the surface is exposed to a much more intense heat collection (the heat penetration coefficient is similar as in the case of outer edges of a thinner layer). In consequence, a small layer, about 1.0 cm thick, cools down in a very short time and then the void content is overstated. Relatively quickly occurring surface damage of about 1 cm thickness and 2–5 cm width (depending upon the atmospheric conditions) occurs as a result.

7. Humidifying of the lateral edge of the layer leads to an immediate cooling of hot mix asphalt, and by the same, makes it impossible to connect the layers. This is eliminated by the application of infra-red searchlights (attached to the spreader) which allow evaporating water from the layer close to the surface of the existent asphalt mix. It is crucial to eliminate the improper conduct of contractors related, among others; to lubricating with asphalt emulsion the edges of the existent layer directly before laying out another layer (water is introduced into the area of layer edge).

8. The new hot mix asphalt shall be spread out with an overlay of about 1–2 cm on the existent layer. This allows forming a small shaft in the area of layer connection, which after compaction gives a uniform and tight surface.

9. The analyses and tests conducted testify to the accelerated cooling of hot mix asphalt in the edge area. This confirms the justification of the hot mix asphalt compaction technology, in which the operation of rollers shall start from the layer edge towards its centre. These operations shall be immediate, which shall allow obtaining the required level of hot mix asphalt compaction and, by the same, shall ensure its durability.

## References

- Bell, C. A.; Hiks, R. G.; Wilson, J. E. 1984. Effect of Percent Compaction on Asphalt Mixture Life, *Placement and Compaction of Asphalt Mixtures*, ASTM Special Technical Publication 829: 48–66. <http://dx.doi.org/10.1520/STP32504S>
- Bražiūnas, J.; Sivilevičius, H. 2010. The Bitumen Batching System's Modernization and Its Effective Analysis at the Asphalt Mixing Plant, *Transport* 25(3): 325–335. <http://dx.doi.org/10.3846/transport.2010.40>
- Choubane, B.; Page, G. C.; Musselman, J. A. 1998. Investigation of Water Permeability of Coarse Graded Superpave Pavements, *Journal of the Association of Asphalt Paving Technologists* 67: 254–276.
- Dubois, V.; De La Roche, Ch.; Burban, O. 2010. Influence of the Compaction Process on the Air Void Homogeneity of Asphalt Mixtures Samples, *Construction and Building Materials* 24(6): 885–897. <http://dx.doi.org/10.1016/j.conbuildmat.2009.12.004>
- Harvey, J. T.; Tsai, B. W. 1996. Effects of Asphalt Content and Air Void Content on Mix Fatigue and Stiffness, *Journal of the Transportation Research Board* 1543: 38–45. <http://dx.doi.org/10.3141/1543-05>
- Hobler, T. 1986. *Ruch ciepła i wymienniki* [Movement of Heat and Heat Exchangers]. Warszawa: WNT. 772 p. (in Polish).
- Houman, S. 2012. Assessment of Compaction Temperatures on Hot Mix Asphalt (HMA) Properties, *World Academy of Science, Engineering and Technology* 62: 197–201.
- Hughes, C. S. 1989. *Compaction of Asphalt Pavement*. National Cooperative Highway Research Program Synthesis of Highway Practice 152, Transportation Research Board, National Research Council, Washington, D.C. 48 p.
- Kassem, E.; Scullion, T.; Masad, E.; Chowdhury, A. 2012. Comprehensive Evaluation of Compaction of Asphalt Pavements and a Practical Approach for Density Predictions, *Journal of the Transportation Research Board* 2268: 98–107. <http://dx.doi.org/10.3141/2268-12>
- Kennedy, T. W.; Roberts, F. L.; McGennis, R. B. 1984. Effects of Compaction Temperature and Effort on the Engineering Properties of Asphalt Concrete Mixture, *ASTM Special Technical Publication* 829: 48–66. <http://dx.doi.org/10.1520/STP32500S>
- Linden, R. N.; Mahoney, J. P.; Jackson, N. C. 1989. Effect of Compaction on Asphalt Concrete Performance, *Journal of the Transportation Research Record* 1217: 20–28.



- Mahoney, J. P.; Muench, S. T.; Pierce, L. M.; Read, S. A.; Jakob, H.; Moore, R. 2000. Construction-Related Temperature Differentials in Asphalt Concrete Pavement, *Transportation Research Record* 1712: 93–100. <http://dx.doi.org/10.3141/1712-12>
- Mieczkowski, P. 2006. The Heat Balance in the Process of Compacting of Hot Asphalt Mineral Mixture Using Steel Rollers, *Archives of Civil Engineering* LII(1): 151–175.
- Mrawira, D. M.; Luca, J. 2006. Effect of Aggregate Type, Gradation, and Compaction Level on Thermal Properties of Hot-Mix Asphalts, *Canadian Journal of Civil Engineering* 33(11): 1410–1417. <http://dx.doi.org/10.1139/106-076>
- Rafei, K.; Kavussi, A.; Yasrobi, S. 2012. Construction Quality Control of Unbound Layers Based on Stiffness Modulus Criteria, *Journal of Civil Engineering and Management* 18(1): 5–13. <http://dx.doi.org/10.3846/13923730.2011.619328>
- Scherocman, J. A. 1984. Guidelines for Compacting Asphalt Concrete Pavement, *Better Roads* 54(3): 12–17.
- Tarefder, R.; Yousefi, S. 2012. Laboratory Evaluation of Moisture Damage in Asphalt, *Canadian Journal of Civil Engineering* 39(1): 104–115. <http://dx.doi.org/10.1139/l11-114>
- Timm, H. D.; Voller, R. V.; Lee, E.; Harvey, J. 2001. Calcool: a Multi-Layer Asphalt Pavement Cooling Tool for Temperature Prediction during Construction, *The International Journal of Pavement Engineering* 2(3): 169–185. <http://dx.doi.org/10.1080/10298430108901725>
- Williams, S. G.; Pervis, A.; Bhupathiraju, L. S.; Porter, A. 2009. Methods for Evaluating Longitudinal Joint Quality in Asphalt Pavements, *Journal of the Transportation Research Board* 2098: 113–123. <http://dx.doi.org/10.3141/2098-12>
- Willoughby, K. A.; Mahoney, J. P.; Pierce, L. M.; Uhlmeier, J. S.; Anderson, K. W.; Read, S. A.; Muench, S. T.; Thompson, T. R.; Moore, R. 2001. *Construction-Related Asphalt Concrete Pavement Temperature Differentials and the Corresponding Density Differentials*. Research Report. Research Project Agreement T9903, Task A3, Washington State Transportation Center, Washington DC. 153 p.
- Wiśniewski, S. 1988. *Wymiana ciepła*. [Heat Exchange]. Warszawa: PWN. 363 p. (in Polish).

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