Auto-paper

Paweł Mieczkowski, D.Sc., Eng.

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Part 1 – Reasons for this application

My scientific output in construction field relates to issues of heat flow in laminar systems, with particular stress on heat losses in asphalt mixtures during their compaction. The structure of the incorporated material is formed on this stage and process efficiency depends, inter alia, on temperature. Distribution of temperature in layer is various (transient flow) and depends on mixture properties and impact of external factors If these parameters are taken into account during incorporation of hot mixtures, it will allow for correct process and decide on their functional properties and life period.

The monograph, published after obtaining the Doctor of Engineering degree, titled **"Modeling of heat exchange process between the hot mix asphalt and the environment on compaction phase"** is a scientific work referred to in article 16 paragraph 2 point 1 of the Act dated 14. March 2003 on university degrees and university title and art degrees and titles (Journal of Laws No 65, item 595 with later amendments). The basic assumptions relating to the scientific target, realization method and possibility to use the obtained results in professional practice (obtained from theoretical calculations verified by laboratory and field research), are presented in the third part in this auto-paper (pages B9-B27). My most important, original scientific achievements, constituting significant input in development of road construction industry, include:

- employment of Fourier differential equation for description of temperature changes in layer of hot mix asphalt (HMA) (transient heat flow), presented in form of product of two functions: time and distance. It allowed to determine diversification of temperature in HMA layer cross-section in time, depending on distance from heat exchange surface. The former solutions appearing in literature used assumption that value of thermal conductivity coefficient $\lambda = \infty$ (or is very high), which result in omission of temperature drop in the cooled material and it means that temperature of layer in each location of cross-section is constant (averaged temperature for layer);
- determination of thermal conductivity coefficient λ for asphalt mixtures (AM) in temperatures 20 and 50°C. I determined values of this coefficient in laboratory tests (with plate apparatus) for the most commonly used asphalt mixtures, i.e. coated macadam for base course layer, binder course and surface course, SMA, porous asphalt and macadam mixture on two types of aggregate (diabase and granite). I conducted tests for each of mixtures for two ranges of void content (excluding porous asphalt and macadam mixture).
- development of nomographs, describing value of convective heat-transfer coefficient α depending on air parameters (temperature, humidity, pollution level, wind velocity), radiation energy (absorbed and radiated), layer properties (its dimensions, texture, etc.) for medial areas. This parameter describes quantitatively the environment ability to absorb the thermal energy;
- the detailed description of changes of temperature in hot asphalt mixture layer in layer edge area (considering its type) in result of intensification o external impact by side surface. The conducted calculations and tests indicate that these areas, in result of quick drops of temperature, require accelerated actions on incorporation stage and additional safeguards due to possibility of insufficient compaction;

- the detailed analysis of impact of water (base moisture, process water) on effectiveness of compaction of asphalt mixtures in result of intense heat consumption. Both bottom part of asphalt bedding (base course) and upper part of wearing course are areas subject to intense impact of external factors (motor traffic and weather factors). Therefore they shall have good compaction which is often in conflict with working practice because of water;
- development of nomographs, which allow for quick determination of temperature drop in HMA layer depending on type and magnitude of external impact, time, point location in cross-section (taking into account near-edge areas) and layer thickness;
- process recommendations, which allow to extend process period and to conduct surface works in unfavorable weather conditions, securing correct quality of works. It concerns both recommendations related to equipment operation and preceding operations, which minimize human errors.

Part 2 – The most important professional achievements

Diplomas and university degrees

1. **Master of Science, Engineer** – Szczecin Technical University (currently West Pomeranian University of Technical Szczecin), Faculty of Civil Engineering and Architecture, 1993. Master's thesis: "The examination of cold asphalt mixtures with cement". Thesis promoter: Prof. Z. Zieliński, D.Sc.
2. **Doctor of Engineering in road construction** – Szczecin Technical University (currently West Pomeranian University of Technology Szczecin), Faculty of Civil Engineering and Architecture, 1999. Doctor's thesis: *"The justification of strength requirements for coated macadam on municipal crossings"*. Thesis promoter: Prof. A. Wasiliew, D.Sc.

Information on former employment

1. 10/1993 – 02/2000: Assistant Lecturer on Department of Roads, Bridges and Construction Materials, Faculty of Civil Engineering and Architecture, Szczecin Technical University (currently West Pomeranian University of Technology Szczecin)
2. 02/2000 – till now Tutor on Department of Roads, Bridges and Construction Materials, Faculty of Civil Engineering and Architecture, Szczecin Technical University (currently West Pomeranian University of Technology Szczecin)
3. 1997 – 2007 Process Engineer in NCC Industri Polska
4. 2007 – till now Chief Process Engineer in Eurovia Polska S.A. in Poland

Specification of scientific and research works

My scientific and research output (with habilitation thesis) includes:

- **8 monographs** (7 as co-author), in that the first 3 [C1-1, C1-2, C1-3] constitute chapters in book "The construction errors and damages and their elimination" published by Wydawnictwo Informacji Zawodowej WEKA Sp. z o.o., the next two [C1-4, C1-5] are chapters in book "The General Construction. Construction materials and products" published by ARKADY, the next two are separate items in road construction and road materials field, published by WKiŁ. The last item is the habilitation monograph published by Wydawnictwo Uczelniane ZUT in Szczecin [C1-8];
- **3 publications in foreign magazines** (in that two on JCR list),
- **51 publications in Polish magazines** (on Ministry of Science and Higher Education list), in that 1 published before Doctor degree;
- **7 papers on foreign conferences** (co-author), in that 3 published after Doctor degree;
- **15 papers on Polish conferences** (4 as co-author), in that 10 published after Doctor degree;

- **432.7 points** for publications by Ministry of Science and Higher Education (in that 30 points for article accepted for publishing in The Baltic Journal of Road and Bridge Engineering), in that 37,5 points prior the Doctor degree;
- summary *impact factor* of scientific publications by JCR list **3,914** (taking into account *IF* from 2012 for article accepted for publication)
- number of quotations by WoS base **0** and Hirsh index **0** (only 1 article from 2010 in this base), number of quotations by SCOPUS base **1** and h-index **1** (2 articles are in this base), number of quotations by Google Scholar base **12** and h-index **2** (39 articles are in this base);
- **thesis promoter** for **49** master's thesis and **15** engineer's thesis;
- **reviewer** of articles in foreign and Polish magazines (The Baltic Journal of Road and Bridge Engineering, Archives of Civil and Mechanical Engineering, Drogownictwo);
- **45 expert opinions, 5 studies, 3 designs** ordered by territorial self-government authorities, enterprises and other business entities.

Part 3 – Scientific and research output

The scientific activities prior obtaining the Doctor of Engineering degree

I finished the Master of Science studies on Faculty of Civil Engineering and Architecture in Szczecin Technical University (current Western Pomerania Technical University in Szczecin), on *Civil Engineering* Chair, *Road Construction* specialization, in 1993. I prepared the master's thesis, titled "The examination of cold asphalt mixtures with cement" under supervision of Prof. Zygmunt Zieliński, D.Sc., Eng. This diploma work included development of recipes using quick break emulsions (K1), slow-breaking bitumen emulsions (K3), cement and uniform asphalt mixture, asphalt concrete type, production processes. The prepared in laboratory scale process was tested in production scale in Asphalt Plant in PEDiM company in Szczecin. The produced cold mixture with cement was incorporated into surface course of pavement in Św. Marcina street in Szczecin. This mixture had, after compaction, uniform structure, void content on 3-5% level and resistance to deformations from long-lasting loads by motor cars. The five years observation period of this experimental section did not disclose negative impact of weather factors and motor traffic on the pavement condition.

After obtaining the Master of Science, Engineer degree, from October 1993 I commenced work on assistant lecturer post on Faculty of Civil Engineering and Architecture in Szczecin Technical University, in the Department of Roads, Bridges and Construction Materials. I studied in my research (commenced in 1991) the reasons of viscoplastic deformations in form of lateral waves within crossing. Such form of pavement degradation occurred on crossings of many main communication routes in Szczecin and it caused danger that the wheel lost its adhesion with pavement and it was significant inconvenience for drivers. This research resulted in doctor's thesis titled *"The justification of strength requirements for asphalt concrete on municipal crossings"* which was aimed to present the specific conditions of pavement operation within municipal street crossings and development of requirements as regards physical and strength properties of the asphalt concrete, providing its faultless operation in these areas.

Such aim required many tests and observations, which were conducted in several parallel ways. They can be divided into three groups. The first group included determination of impact of influence of motor cars on the pavement, which required to determine the traffic volume (taking into account its fluctuations), type and direction structure, motor cars speed, decelerations and accelerations (initiating horizontal forces), number of stopping vehicles and related time periods (flowing deformation). The second group included measurements of changes in deformation on wearing course surface in time, determination of reasons of their occurrence and examination of composition and properties of asphalt mixtures in this course (in that also its components, i.e. bitumen and aggregate). This also required to verify if viscoplastic deformations are not propagated in binder course. The tests of properties of mixtures from this course, with determination of level of lateral deformation on its surface, were conducted for this purpose.

The mix asphalt belongs to viscoplastic materials due to binder in its composition. Their properties depend highly on temperature. Exactly this factor (temperature) constituted the third direction of research. It forced to determine the limit value of temperature in pavement (wearing course), outside which the permanent deformations will occur in result of influence from automotive

vehicles. The experiments conducted on domestic binders[1,2], available in the nineties in XX century in Poland, disclosed, that flowing zone of medium hardness asphalts (D50 and D70) starts just about 40°C. This was confirmed by conducted by me additional examinations of modulus of rigidity MMA with participation of these binders (creeping under static and dynamic load using ultrasound waves) in temperature range 20-60°C (each 5°C). The distinct drop of inclination angle of modulus of rigidity curve to temperature axis was observed n temperature range 40-45°C and its stabilization at higher temperatures (40-60°C). This allowed to adopt 40°C in further studies as the conventional limit of asphalt mix transition to condition of increased vulnerability for deformation, even under limited loads from automotive vehicles.

Brama Portowa crossing in Szczecin was the (main) measurement base. The traffic flow, its type and direction structure on this crossing were measured in 1991-1995. They allowed also for percentage number of stopped vehicles and related time period. The size of lateral deformations, caused by automotive vehicles, was measured also in this period. The similar research was conducted also on additional 3 crossings in 1995. On the base of depth of the measured deformations, each of sections (on individual traffic lanes on each inlet) was divided into three areas $L_1 - L_3$, with similar level of deformation. The decelerations and accelerations of vehicles (on the base of their passage times) were measured for these separated areas on each four crossings. This allowed to determine level of horizontal forces for each area and the related to them average stop times of vehicles (taking into account their type structure).

The detailed examinations of asphalt mix from the selected crossings (taken from individual inlets and traffic lanes) were conducted in 1997. Apart the standard determinations, made on asphalt-aggregate mixtures taken from the pavement (composition, density, volume density, content of free space, compaction degree, absorbability), additional determinations were made on samples formed in laboratory (stability and deformation by Marshall, density index, modulus of rigidity in creeping test and relative deformation in this test after 5s load). Furthermore, binder extracted from asphalt-aggregate mixture was tested (penetration in 5 and 25°C, softening point by RiB, ductility, viscosity in 60°C) and aggregate (grain size, grit over crushing level, shape index, sand type). The determination of deformation level on binder course was additional activity during the sample taking. The lateral deformations, caused by impact of horizontal forces from automotive vehicles, were not found on surface of this course. The samples of asphalt-aggregate mixture from binder course were taken also in the selected points and tests were conducted on them as for the wearing course.

The possibility to determine 40°C temperature in the wearing course allows to determine the actual, summary level of external influences from automotive vehicles on pavement, on which the incorporated asphalt-aggregate mixture has low deformation resistance (flow zone start). The climatic parameters for Szczecin area in 1991-95 were collected for description of the wearing course temperature in form of mathematic and physical model. They included: air temperature, wearing course temperature, wind speed, air humidity, precipitation, atmospheric pressure. The detailed data analysis allowed to separate three parameters, which were used in model, i.e. daily-average air temperature, amplitude of daily air temperature fluctuations and wind speed (measured values of wearing course temperatures constituted the base for model correctness verification). The

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[1] Stefańczyk B.: *Strukturalno mechaniczne właściwości asfaltów w szerokim zakresie temperatur.* Wydawnictwo Uczelniane Politechniki Szczecińskiej, Szczecin 1989

[2] Kalabińska M., Piłat J.: *Właściwości reologiczne asfaltów i kompozytów mineralno-asfaltowych.* Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 1993

assumption was adopted that temperature of the wearing course would be the component of air temperature and equivalent temperature, being effect of additional heating resulting from sun radiation, reduced by wind effect. The air temperature was modeled based on the average air temperature and amplitude of its daily fluctuations and it was found that there was additional impact of preceding day and next day in transition hours (for preceding day from 0 to 6 am, for the next day from 8 to 12 pm). The equivalent temperature was described based on two models. The first based on sun radiation density based on solar constant and equations from spherical trigonometry. It allowed for "blackness level" of MMA layer surface, atmosphere transparency and convective heat-transfer coefficient α (being the total of absorbed and radiated energy and energy exchanged with environment by convection). The second model (simplified) based on the daily-average air temperature, wind speed and hour (taking into account the "Sun height"). The verification of correctness of both theoretical models demonstrated their high convergence with actual temperature of wearing course. The simplified model was used for further studies. The nomographs prepared within this study were used to determine the total number of hours in which the wearing course would have 40°C temperature. The first of them allowed to determine, on the base of the daily-average air temperature, amplitude of its fluctuations and wind speed, the number of hours in which the wearing course would have temperature 40°C or higher. The second nomograph allowed to determine time intervals in which this effect took place. This allowed to determine the actual number of vehicles, and therefore level of impact on pavement in time period unfavorable for deformation reasons.

The next actions consisted in determination of horizontal forces for individual areas and resultants on vertical and horizontal loads. The summary values of impacts on pavement were determined depending on type of vehicle and braking and accelerating force levels (averaged for each area). It resulted from the conducted statistical calculations that the highest convergence between type of impact and level of deformation was achieved for the absolute sum of horizontal impacts caused by braking and accelerating of vehicles.

The next stage consisted in searching for relationship between physical and mechanical properties of asphalt concrete and their deformability. The best convergence was obtained based on mixture strength parameters, i.e. modulus of rigidity, stability and deformation by Marshall and relative deformation after 5s load (in creeping test). This allowed to develop equations describing growth of deformation in time on the base of influences from automotive vehicles. It was developed on the base of data obtained from *Brama Portowa* crossing and it was verified on the base of results from three remaining crossings.

The last stage of this work was formulation of requirements regarding asphalt-aggregate mixtures and their components (aggregate, asphalt) for the wearing course, resistant to deformations caused by horizontal influence from automotive vehicles. Four asphalt-aggregate mixtures were designed, with grain size up to 12,8 mm: two asphalt concrete (where in one case binder was modified by addition of 2% of LBSK polymer) and two SMA mixtures, where one also was modified by polymer. The result of studies disclosed that mixtures with developed mineral frame (SMA) had higher resistance to permanent lateral deformations. The impact of modifier (polymer) on reduction of this deformation is also apparent.

The scientific activities after obtaining the Doctor of Engineering degree

After obtaining the doctor's degree I conducted scientific and research works on the West Pomeranian University of Technology Szczecin (former Szczecin Technical University). The main area of my interests was heat flow in hot mix asphalt on stage of their incorporation. I expanded the scope of studies and observations on technical scale in cooperation with production companies NCC Industri Polska and Eurovia Polska S.A. this allowed me to verify results of laboratory research and theoretical calculations. The remaining fields of my interest include bridge pavements and possibility to use various types of additives to asphalts and mix asphalt, taking into account ecology issues.

Modeling of heat exchange process between the hot asphalt mixture and environment during compaction (monograph)

The presented monograph includes issues of heat flow in hot asphalt-aggregate mixtures resulting from its exchange with environment in compaction process. It is a very important process, in which mixture functional properties are decided [1, 2, 4, 8, 10, 12, 13, 16]. The susceptibility for compaction depends on compound temperature due to viscosity of included in it binder. Therefore, description of changes of temperature in time in cross-section of hot layer allows to plan operations which give possibility to obtain the correct structure of the mixture [3, 6, 7, 8, 10, 14, 17, 23, 24]. This concerns also preliminary operations, connected with condition of the base (its moisture level) or proper selection of equipment fir weather conditions. The conducted calculations and studies indicate also that it is necessary to undertake some steps already on stage of designing the pavement structure laminar systems, which shall allow to eliminate in high degree the human error (in particular at shorter contract completion periods and necessity to conduct works at unfavorable weather conditions) and prolong their operation life.

I determined changes of temperature in cross-section of hot asphalt-aggregate mixture layer on the base of Fourier differential equation, presented as product of two functions, i.e. time and space (1, 2) [5, 18, 19, 26]. They occur due to unsteady heat flow in the layer. The intensity of this effect depends on ability to conduct heat in MMA and possibility of its acceptance by external factors. They are expressed by, correspondingly: **thermal conductivity coefficient λ and substitute convective heat-transfer coefficient α**. The temperature drop ratio and its distribution on layer thickness depend on relationship between them.

$$T_w = T_{oś} + Y \times (T_p - T_{oś}) \tag{1}$$

$$Y = \sum_{n=1}^{\infty} e^{-\delta_n^2 \mathrm{Fo}} \frac{2\sin\delta_n}{\delta_n + \sin\delta_n \cos\delta_n} \cos\delta_n \frac{x}{s_m} \tag{2}$$

where: T_w – AM layer temperature in τ time and x distance from plane in layer axis [K], $T_{oś}$ – temperature of medium with the cooled HMA [K], T_p – initial temperature of HMA layer in time $\tau = 0$ [K], x – distance of the given point from plane placed in HMA layer axis [m], s_m – perpendicular distance between HMA layer surface and the plane placed in this axis [m], Fo – Fourier number, δ_n –

values corresponding intersection points of function $y_1 = ctg\,\delta$ and function $y_2 = \frac{\delta}{\mathrm{Bi}}$, Bi – Biot number.

The thermal conductivity coefficient λ, according to kinetic theory, expresses ability of particle with higher energy to transfer its part to particles with lower energy. The main factor influencing on level of this parameter in solid bodies is their volume density and correlated with it void content [5, 9, 11, 18, 19, 26]. The increased amounts of air voids in material cause drop of λ coefficient value, which is particularly significant for so called poured materials, where it reaches values of thermal conductivity for gas filling the void content [5, 18, 19, 26]. Any data concerning thermal conductivity for asphalt mix are scarce in literature. The value of thermal conductivity coefficient for bitumen is often wrongly provided as value for asphalt mix and vice versa. In individual cases AM bulk density is assigned to λ value without additional data, e.g. content of void content or type of the used stone material. With such various material as asphalt mix, thermal conductivity coefficient is necessary parameter in assessment of its cooling down. I measured, within these studies, the thermal conductivity coefficient λ on mixtures assigned for various structure layers. I prepared samples from each type of mixture, differing in content of void content and type of aggregate (diabase and granite). I tested 28 samples in total, of which 16 were asphalt concrete (BA), 8 – SMA mixture and 2 samples – porous asphalt concrete (PA) and macadam mixture (M). As the binder I used 50/70 asphalt for mixtures for wearing course, and 35/50 asphalt in case of binder and base course and macadam mixture. The void content in samples was important parameter for assessment of thermal conductivity coefficient λ. I determined it on the base of density and bulk density of the mixture.

I examined the thermal conductivity coefficient in the plate apparatus in 20°C temperature (averaged for both plate surfaces) and additionally, for selected AM, in 50°C temperature. I tested them on samples with dimensions 250x250 mm. The thickness of samples varied between 50 and 70 mm. The upper and lower surfaces of samples were polished to obtain parallel planes and their equality, which guarantees good adhesion to heating and cooling plate of the apparatus. Any roughness would have significant impact on values obtained for the examined parameter. This is connected with formed locally layer of air, between sample surface and heating (cooling) element of apparatus, which would result in diversified heat flow (air has low value of thermal conductivity coefficient). The results obtained from measurements of thermal conductivity coefficient λ fall in range between ca 0,5 and 1,3 W/(m×K) (fig. 1-2). It classifies the asphalt mix nearer the thermal insulation materials than materials which well heat conductivity.

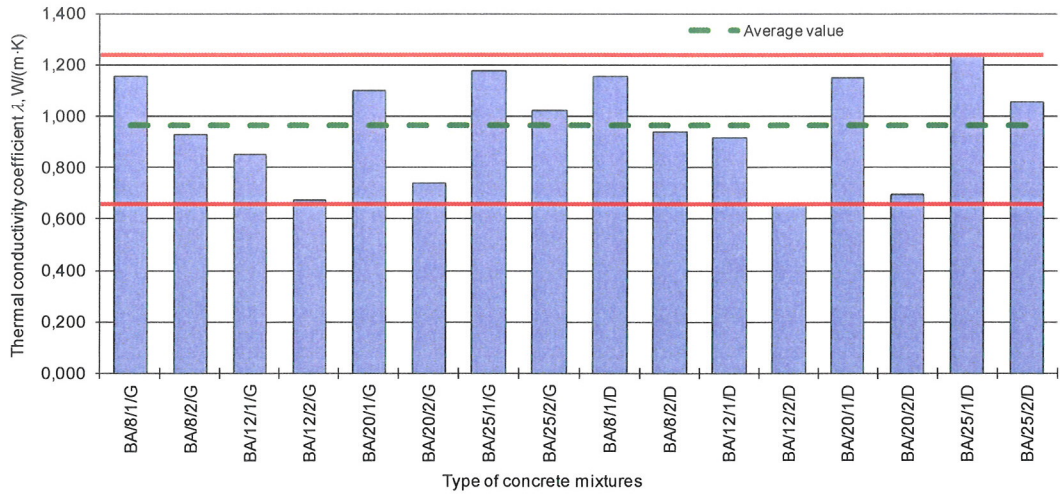

Fig. 1. The values of thermal conductivity coefficient λ for asphalt concrete (BA) type mixtures

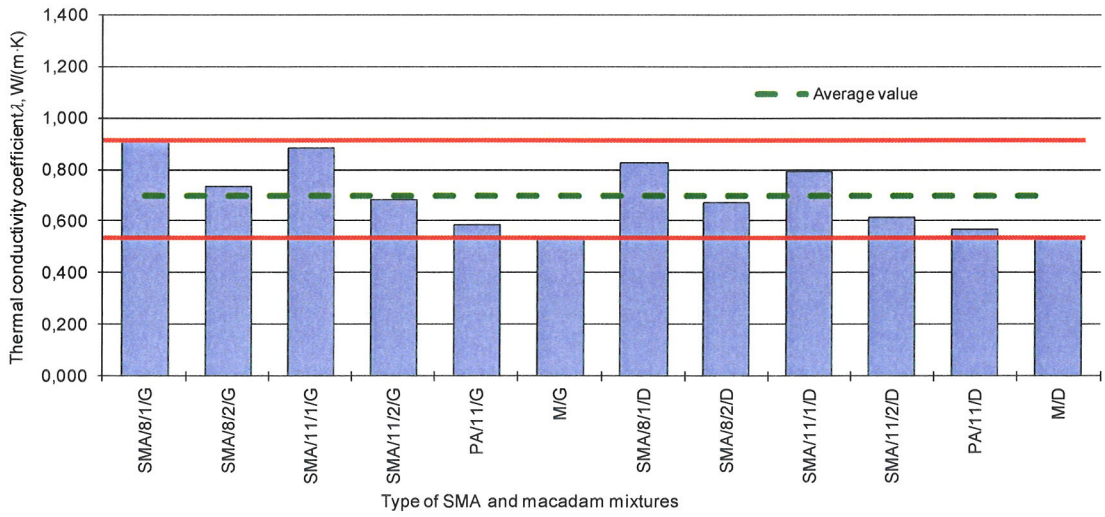

Fig. 2. The values of thermal conductivity coefficient λ for mixtures of intermediate (SMA) and contact type (PA, MD)

The value of λ parameter is variable and depends on many factors. They can be classified in two groups. The first group represents the material properties, i.e. type of the used aggregate, type of mixture and amount of individual components. The second group includes physical properties of mixture (asphalt mix and mineral) and testing temperature conditions. It may be found, analyzing individual elements of the first group, that type of stone has relatively low impact on value of λ parameter (AM). These are magmatic rock in both cases and diabase belongs to vein rocks (with composition similar to basalt), and granite belongs to intrusive rocks. The significant differences in properties of individual aggregates, i.e. thermal conductivity coefficient (for diabase 1,65–1,78AW/(m×K); for granite 2,9–4,1 W/(m×K)) and density (diabase – ca 3,1 g/cm^3; granite – ca 2,7 g/cm^3) do not influence on λ parameter for AM samples prepared with their participation. It was also hard to find impact of quantity of binder (both in weight and volume) and its type (35/50 and 50/70) on value of thermal conductivity coefficient. I observed such relationship examining types of

mixtures. And, for example, when comparing concrete type (BA) with intermediate type (SMA) mixtures, I found drop of thermal conductivity coefficient by 20% in average. I obtained even higher difference between asphalt concrete and contact (macadam) mixture - ca 40%. Such fundamental differences in λ coefficient values can result from the total contact surface between individual components of mineral mixture (surrounded by binder layer), which is the largest in concretes and the lowest in macadam (fig. 3). Therefore, one can assume that level of contact surface between MM grains shall decide in some degree on ratio of energy transfer (in form of heat) in this way in the whole mixture. The heat flow by conduction is decidedly higher than by natural convection in the closed pores of material.

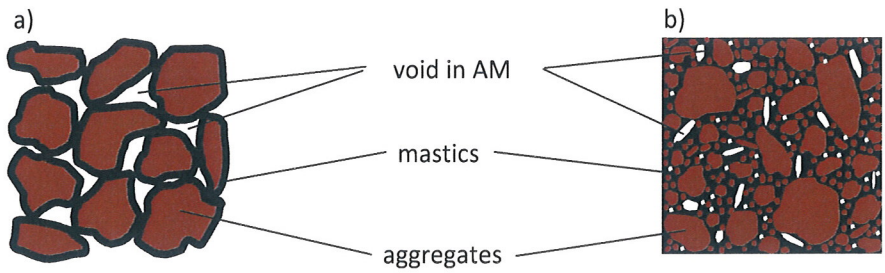

Fig. 3. The structure of contact type (a) and concrete type (b) mixtures

The highest impact on λ coefficient, as regards the second group of factors, has void content in mixture (mineral and asphalt) and – in little degree – mixture temperature. The low impact of the latter parameter (ca 0,3%) in mixtures with typical void content ($V < 8\%$) resulted mainly from small difference of temperature during tests (ca 30°C). The more distinct changes in λ coefficient can be observed with growth of HMA temperature (ca 170-200°C), which occurs during mixture incorporation. This change can reach even 20-30% [5, 15, 21]. In contact mixtures, with decidedly higher void content ($V > 15\%$), change in thermal conductivity coefficient reached already ca 3%. It may be caused by shapes of pores, and namely their size and system of connection between them. This can cause the additional form of heat exchange in pores of material (so called "floating"), i.e. (free) convection effect, of course in micro scale.

The highest changes in value of thermal conductivity coefficient result from modification of void content in mineral mixture (MM) and asphalt mix. Tests conducted by me disclosed that growth of void content by 1% in mineral mixture caused drop of λ coefficient value by 0,08 W/(m×K), in case of asphalt mix - by 0,07 W/(m×K). In my opinion, such behavior results from impact of two factors. The first is void content, filled with air. Air (with coefficient λ at 20°C equal to 0,0251 W/(m×K)) constitutes type of insulation barrier in AM mixture, slowing down the heat flow. The second factor is contact surface between mineral mixture grains, surrounded by mastic film (mixture of binder, filler and fine sand). The larger surface the higher ability to transfer the thermal energy. This results from significantly higher λ values for rock materials.

I found, analyzing results of λ coefficient tests, that contact mixtures (PA, M) reached the lowest values of conductivity. Despite the significant differences in void content between them (ca 15-16%), thermal conductivity is on the similar level (0,54-0,59 W/m×K)). This indicates that, from some specific void content in AM and MM, thermal conductivity changes in low degree. This is confirmed by λ values obtained for SMA mixture (intermediate type) with increased void content (ca 5%), on 0,61–0,68 W/(m×K)) level. The significantly higher values of this coefficient for concrete type

mixtures (at similar void content) indicate that the proposed thesis, that direct contact surface between individual aggregate grains decides in significant level on ability for heat flow, is correct.
The shapes of pores can have also impact on value of thermal conductivity coefficient of asphalt mix. In case of the closed pores, with relatively small sizes, heat flow will be provided by conduction. The accelerated heat flow by convection, even by radiation, is possible in case of air voids with significant sizes (at high temperatures of AM incorporation), mainly in the near surface layer (cooled down). These additional two types of heat movement are possible in pores of material but they require difference of temperature between opposite surfaces of air void (fig. 4) and properly large void content. This allows to generate convection flows (in case of free convection) and transfer of energy by the heated gas particles as well as heat flow by radiation.

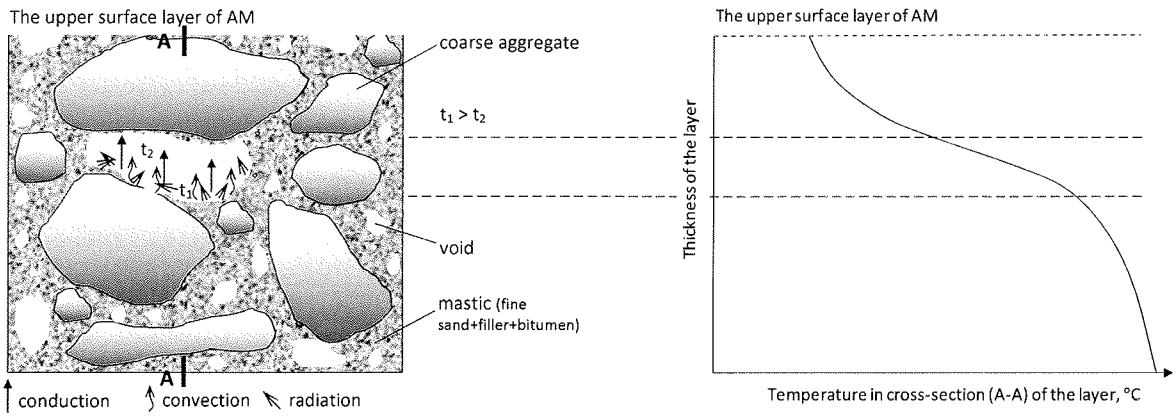

Fig. 4. The accelerated heat exchange in MMA pores with large volume in near surface layer with significantly differentiated temperature of both surfaces (upper and lower)

I tried also to determine impact of water content on this parameter in studies on thermal conductivity of asphalt mix. The multiple measurements conducted on various types of mixtures and at variable moisture values indicated distinct increase of thermal conductivity (even to 80–100%). The results obtained from studies were characterized anyway by high spread of values (reaching even 40%). The long measurement stabilization time, variability of obtained results and changes in moisture in time (despite various methods for sample protection) univocally level of water impact on λ parameter. This was caused by several factors. The very high value of water specific heat (4,182 kJ/(kg×K) at 20°C), even at its small amount, forces to deliver proper amount of heat necessary to increase temperature, which extend test conditions stabilization period. The possibility that water will change its state of matter (under the delivered heat) and its transformation into steam, is the next factor which cause that it is impossible to obtain the reproducible test conditions. The generated steam changes continuously level of humidity of air included in AM sample and, therefore, conductivity of this part of mixture. It was particularly observed for mixtures with high void content (PA, M), where composition of air in the entire sample volume was additionally changed (opened pores). The saturation with water forced to protect sample against its loss during test. I used for this purpose various insulation materials (PVC foil, aluminum foil, paraffin) with known λ coefficients (taken into account in calculations). No stable results of measurements, apart precise protection, using e.g. foil, was probably caused by accumulation of water vapor in area between sample surface and protecting layer. In case of paraffin the main problem was to obtain the fixed thickness of layer during application and local loss of tightness during tests. The lack of full control on

behavior of both factors at their low thermal conductivity (ca 0,025 W/(m×K) for moist saturated air and 0,268 W/(m×K) for paraffin) did not allow to obtain steady results, reflecting the actual thermal conductivity of AM sample saturated with water.

The next element of my research was determination of **substitute convective heat-transfer coefficient** α, which determines intensity of heat reception by environment from hot mix asphalt mixture in process of its incorporation. The heat can flow by:

- conduction (in result of direct contact with solid body, e.g. lower structure layer or roller drum), described by substitute convective heat-transfer coefficient α_z;
- penetration to fluid (air or water, not in boiling state) in result of free and forced convection (in case of wind), described by convective heat-transfer coefficient α_s and α_w;
- penetration to water in boiling state (α_{wr}),
- radiation (at difference in temperatures and transparency of medium), described by substitute convective heat-transfer coefficient α_r.

It is hard to say on heat reception by environment in result of exclusively one of these effects in actual conditions on the road. They occur mostly jointly or alternatively and they are described in form of summary convective heat-transfer coefficient α. The value of this coefficient depends on weather conditions (i.e. air temperature, wind speed above the cooled layer, cloud cover and air radiation density) and process conditions (quantity of water used for cooling the compacting equipment, steel or rubber contact time with hot AM, type and level of base surface moistness). The analysis of impact of individual factors allows to classify them as regards ability to receive heat, and therefore to indicate the highest dangers connected with quick cooling of the HMA in process of its incorporation, which may be important in later stage of its usage.

Air is one of such main factors. If there is no wind, its heat reception abilities are decided by free convection (with laminar or turbulent flow) and radiation, which depends on temperature, moisture, cloud cover, atmosphere pollution and sun radiation intensity. The conducted by me calculations indicated that value of substitute convective heat-transfer coefficient to air (in temperature range between –20 and 40°C) varies between 12 and 17 W/(m^2×K) and grows with growing air temperature (fig. 5). It results from growing share of radiated energy, constituting in average 53% of total value of this coefficient. The share of convection slowly increases with growing temperature and this is caused mainly by lowering level of air turbulence (characterized by Grasshof number or product of Grashoff number and Prandtl number). The calculations adopted value of sun radiation flux density I_S for Szczecin as 278,15 W/m^2, as average from period between March and November, between 6 am and 10 pm hours.

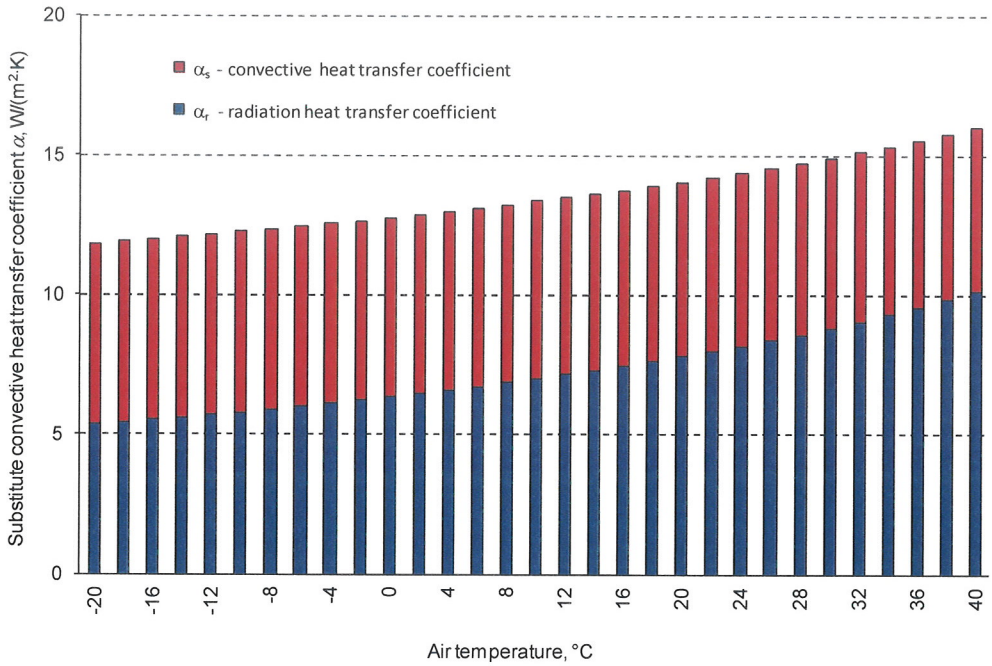

Fig. 5. The theoretical values of substitute convective heat-transfer coefficient in result of free convection and radiation (with share of sun energy) depending on environment temperature

Wind intensifies significantly the heat reception process. the wind causes that the entire layers of hot agent are taken away continuously from above the surface. The inflowing, colder air (at cooling) is characterized by higher abilities of heat intake from above the hot surface, which intensifies the entire process. At high wind speeds, amount of taken heat (from near surface layer) is much higher than that flowing from the middle layer by conduction (in case of bodies with low thermal conductivity coefficient). The wind velocity has deciding impact on value of summary convective heat-transfer coefficient α to air at the forced flow (taking into account radiation, free and forced convection). The temperature of air affects in low level, the width of layer which give away heat in a little higher level (in particular due to quicker change of nature of air flow from laminar into turbulent). The calculated be me, averaged (due to air temperature) values of convective heat-transfer coefficient vary between ca 20 W/(m^2×K) at wind velocity 1 m/s and almost 60 W/(m^2×K) at wind velocity 16 m/s (i.e. velocity permitted at MMA incorporation) (fig. 6). The share of forced convection constitutes ca 15% of total value of convective heat-transfer coefficient at velocity 1 m/s and increases to ca 67% at 16 m/s. This significant increase results from increasing air flow velocity and level of its turbulence above heat giving away layer (described by Reynolds number or product of Reynolds number and Prandtl number).

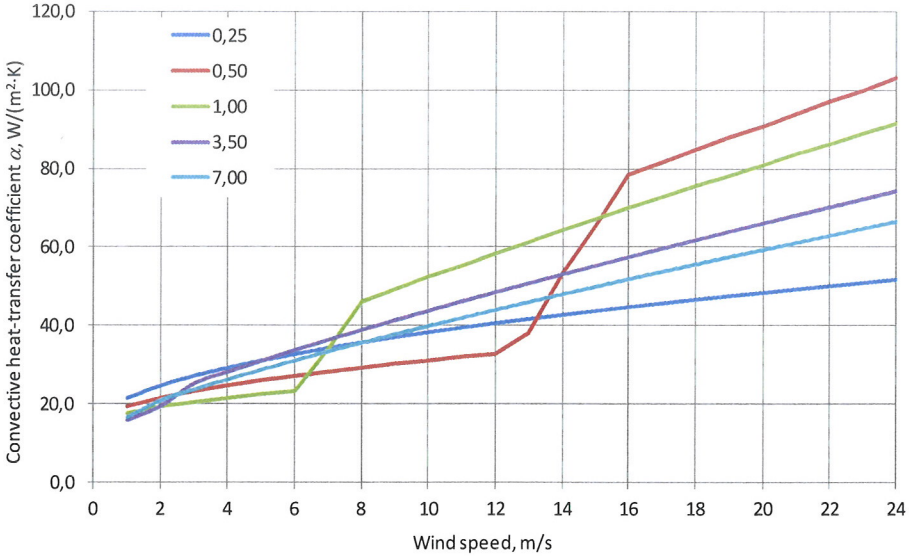

Fig. 6. The theoretical values of substitute convective heat-transfer coefficient depending on width of HMA layer (averaged for air temperature)

Water is this factor which has the highest abilities to receive heat on stage of incorporation of asphalt mix. Its presence results from compaction process (and precisely, participation of steel rollers) and moisture of base on which the hot mixture is placed. As incorporation process is conducted at high temperatures (initial temperature of incorporation and compaction – above 100^{0}C), water reception (penetration) at boiling water can occur (in particular water spraying the roller drum). Boiling belongs to phase transition of the first type and, to occur, water absorb heat necessary for phase transition (at constant pressure), called heat of evaporation. This heat is delivered to water through the upper and lower surface (if base is moist) of the incorporated AM. More than 85 % of this heat is used in phase transition process (result of very high value of heat of evaporation – 2256,685 kJ/kg), ca 15 % is required to bring water to boiling starting temperature. Only small amount of this energy is absorbed to increase water vapor temperature (ca 0,1 %). The main factor, deciding on process energy-consuming, is water volume.

The heat absorption at boiling is associated by very high density of heat flux and corresponding high values of convective heat-transfer coefficient. Depending on overheating level (difference between layer surface temperature and saturation temperature), value of this parameter varies in range between 1000 and even 20000 W/(m^2×K). Such intensive heat absorption leads to immediate cooling of surface of HMA layer, and therefore it is further given away by free convection. It is hard to say on water boiling process in real conditions. It is possible only at the first water contact with HMA and this phenomenon is very short. Almost immediate of layer surface cooling (temperature drop below 100^{0}C) shuts possibility to continue this process. Heat is further received at the same time by convection and water phase transition into steam. The whole cycle, its intensity, evolve in time and depend on temperature of layer surface and amount of water. Such high variability of effects reduced possibility to use data from literature and forced determination α coefficient in laboratory tests. I determined within these research works the value of parameter, depending on reaction time and amount of medium. At low intensity of precipitation (ca 3l/m^2/h), for the first 5 minutes, parameter falls in range between 100 and 150 W/(m^2×K). After this period (between 5 and 60 minutes) the value of this coefficient decreases which results from deceleration of thermal processes

on surface, and reaches 50-80 W/(m^2×K). The higher intensity of precipitation (5-6 l/m^2/h) accelerates cooling processes, mainly in the first stage (up to 5 minutes). The value of this coefficient for this time period is 140-240 W/(m^2×K). The heat transfer process slows down with time (5-60 minutes), which is reflected by determined values of α parameter, which falls in range between 65 and 115 W/(m^2×K).

The last factors taking part in heat exchange with hot asphalt-aggregate mixture may include solid bodies, i.e. bottom layer of pavement structure, steel roller drum or rubber roller wheel. I assumed in calculations that heat will flow for these cases in result of conduction. I determined the substitute convective heat-transfer coefficients on the following levels:

- 1,5-5 W/(m^2×K) for piled aggregate (diversification results from type of rock and content of content),
- 7-8 W/(m^2×K) for asphalt concrete layer with thickness 10-15 cm,
- ca 2350 W/(m^2×K) for steel drum with shell thickness 17 mm,
- 6,5 W/(m^2×K) for tire wheels (tire thickness 25 mm) in case of pneumatic roller.

The distinct departure in value of convective coefficient concerns the steel roller drum. But in this case, this factor effect time on the pavement is very short (similar as in case of tire wheel). It results from calculations that drum contact with hot mixture is ca 1–2 seconds (assuming 5 roller passages). Such short time, even in case of high values of α coefficient, may result in cooling of only near surface layer, with thickness ca 3-5 mm.

I used the determined specific parameters, i.e. thermal conductivity coefficient λ (describing heat flow in layer) and substitute heat-transfer coefficient α (specifying ability of external factors to absorb heat from layer surface) to determine **heat losses during HMA compaction**. The consideration was based on Fourier differential equation, describing the heat exchange process. Its solution in form of product of two functions, i.e. time and space, allowed me to determine the theoretical drops of temperature in hot mix asphalt, taking into account time, position of point in layer cross-section for real values $\lambda \ll \infty$. The former descriptions of heat losses in HMA were based on assumption that $\lambda = \infty$, which gave in results the averaged values of temperature, not considering its distribution on layer thickness [2, 3, 20, 22, 25, 27].

In conducted by me calculations of heat losses during HMA compaction I took into account the impact of various climatic and weather conditions, thickness and width of layer, type of base and its moistness, and type of compacting equipment. The additional aspect taken into account in calculations, was location of area depending on distance from the layer edge. The conducted calculations required from me to adopt some simplifications, resulting from changing conditions with progress of compaction process. This had no significant impact on values obtained from model and facilitates only to conduct the complex calculations. They related both to the mixture itself and environmental factors. The main simplifications include adoption of:

- constant bulk density of asphalt mix, corresponding to compaction level 100%;
- AM layer thermal conductivity coefficient, specified for temperature 20°C;
- temperature of boundary layer (heat conducting) as average from initial and final compaction temperature on HMA surface and air temperature;
- constant level of radiated energy, corresponding to the averaged temperature of sample surface (average from compaction initial and final temperature);

- averaged level of sun radiation flux density I_S, absorbed by HMA in the adopted period of time (equal to 278,15 W/m^2);
- averaged convective heat-transfer coefficient α to environment agents for the entire cooling period (both in case of air and water).

The adopted simplifications resulted in differences between real temperature in layer cross-section and values and values obtained from calculations. Some of them accelerate the cooling process (e.g. constant value of bulk density), some of them decelerate it (e.g. MMA thermal conductivity) and some change with heat exchange process (e.g. heat penetration to environment).

In order to take into account so many external factors and layer parameters on heat losses in HMA incorporation processes, I had to conduct the considerable number of calculations. But this allowed me to develop nomographs to determine drops of temperature in HMA layer depending on type and size of external impact, time, point location in cross-section (taking into account the near edge area) and layer thickness (fig. 7-8). It is possible to determine with them, simply and quickly, time in which the HMA will reach the limit temperature, i.e. temperature corresponding to the final viscosity of binder (or mastix) compaction in AM (20 Pa×s).

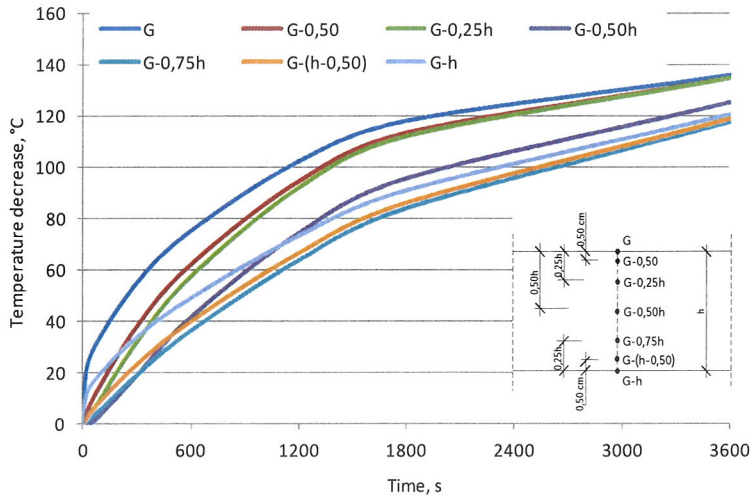

Fig. 7. Nomograph for determination of temperature drop in cross-section of HMA layer (150°C) with thickness 3 cm in result of mixed convection (α = 40 W/(m^2·K), $T_{oś}$ = 10°C) depending on time

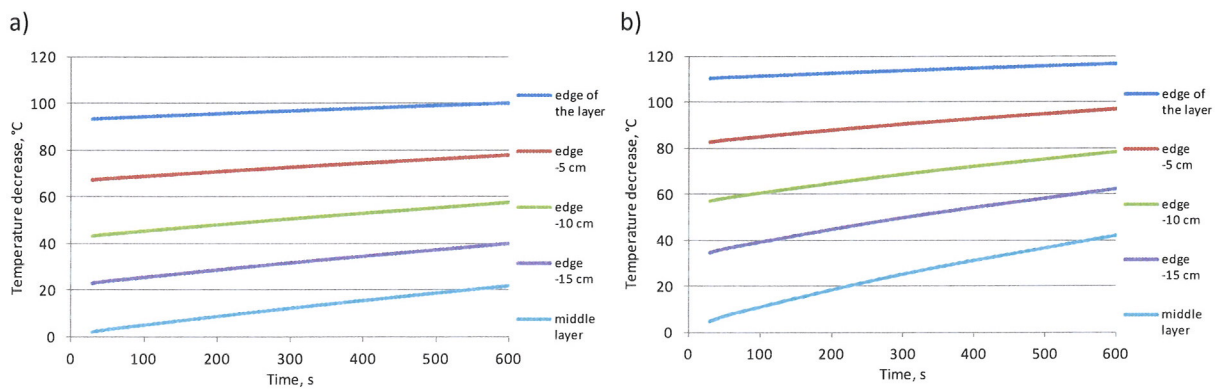

Fig. 8. Nomograph for determination of temperature drop in HMA layer with thickness 3 cm depending on time, distance from side edge and external factors: a) α coefficient for side edge and upper and lower surface equal to 10 W/(m^2×K); b) α coefficient for side edge and upper horizontal surface equal to 40 W/(m^2×K), for lower surface 10 W/(m^2×K)

I conducted laboratory tests to confirm theoretical assumptions and the adopted model. I conducted them on samples on which values of λ thermal conductivity coefficient were determined. I measured drops of temperature for the middle of layer and its edge. I conducted tests for three cases of external impact, i.e.:

- free convection, in range of temperatures between –10 and 25°C;
- mixed convection (forced and free convection), at wind speed between 2 and 16 m/s and in range of temperatures between –10 and 25°C;
- free convection connected with water cooling, 3 and 6 l/m^2/h, in range of temperatures between 0 and 25°C.

For the first two cases (free and mixed convection and radiation without water), heat was given away through the upper surface (I cycle of tests) and through both horizontal surfaces, i.e. upper and lower (II cycle of tests). This allowed me to verify correctness of the adopted model as regards the layer thickness. I did not take into account share of sun radiation which was caused by conditions in which i conducted tests (closed rooms, without windows). The third group of tests (free convection, radiation and water) included sample cooling only through the upper horizontal surface. I conducted part of tests, confirming correctness of theoretical assumptions, in technical scale.

The general conclusions from calculations and tests, with scientific and application significance, include:

- **air temperature** shall not be the determinant of production possibilities, in particular due to necessary extension of construction season. The cooling effect, resulting from the increased difference between HMA temperature and air (taken into account in theoretical model as $T_{oś}$ i $T_p - T_{oś}$) is not disputable. However, it has no deciding impact on cooling speed, expressed by parameter Y (in model), depending on coefficients α and λ. The air ability to absorb thermal energy is in low temperatures lower than in high temperatures, among others due to lower water content (absolute humidity). Therefore, heat receiving ratio will be lower at lower air temperatures, and the initial effect resulting from difference between HMA and air temperatures can be minimized raising mixture temperature on stage of its fabrication. The impact of transport and heat losses on this stage can not be, of course, omitted in studies. In low air temperatures it is absolutely necessary to use means of transport provided with systems reducing the heat flow (steel semi-trailers with double-wall sides, filled with thermal insulation material or hot flue gas from engine, and tight covers, protecting against air penetration from outside). Other, additional disadvantages are connected with possible freezing of process water (for steel roller drum spraying) can be minimized by application of defrosting additives (e.g. methanol);
- **wind** is one of external factors which determine HMA cooling. The intensity of heat absorption and difference between temperature of middle of the layer and its surface area increase with increasing wind velocity. The convective heat-transfer coefficient value α increases at 6 m/s wind twice in relation to free convection, and for times at 16 m/s wind. This causes the accelerated mixture cooling, in the first period in surface area. In case of large void content in mixture (with not compacted AM), this area becomes the insulator and still more slows down the heat flow from the middle to edge of the layer, leading to further surface cooling (fig. 9) and creation of the stiff crust. In result, compaction effectiveness can be minimal in case of delayed passage of compacting equipment, there may occur problems with evenness, surface texture, cracking, etc.

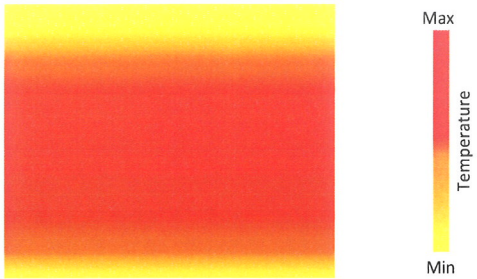

Fig. 9. The distribution of temperature in cross-section of hot MMA at high wind (surface cooling), in particular at thicker layers (above 6-8 cm).

- **water** belongs to these external factors which determine not only heat flow but which can also reduce quality and effectiveness of compaction works. Due to its thermal properties, water can be deciding in distribution of temperature in the incorporated HMA, in particular in thin layers. The water heat capacity (and therefore ability to receive heat), physical transformations with its participation (change of state, evaporation) are factors determining almost immediate cooling of the layer surface. The convective heat-transfer coefficient for water may vary between 50–60 W/(m^2×K) and even 10000–20000 W/(m^2×K) (at boiling). This means that water (its content) can not be accidental on MMA incorporation stage. Water used to moisten drums in rollers causes cooling of the upper surface of the layer already in the first passage (steel also absorb heat quickly) and additionally, penetrating into not jest compacted HMA, reduces its temperature, and therefore its binding and plastic abilities. Furthermore, when water is deposited in the base, it evaporates when heated and, as the unsaturated vapor (at high content of water) penetrates upwards the layer, cooling higher and higher areas, it may be hard to obtain correct compaction, even at high temperatures in summer. Furthermore, it can occur problem of adhesion between layers, which compromise operation of structure and its load capacity.
- **steel and rubber** are materials with which some compacting components of rollers are made (steel and tire rollers). The contact time of these materials with the layer surface is very short (between 1 and 5 s), and therefore they have no deciding effect on drop of temperature in layer. This is valid mainly for rollers on pneumatic wheels where rubber belongs to thermal insulators rather than conductors. In case of steel, despite relatively high convective heat-transfer coefficient, reaction time is decisive. Water may be a problem when the steel rollers are used. It is used to spray the drums, preventing adhesion of HMA to drums. It constitutes some type of anti-adhesion insert, which operation is based, among others, on quick surface cooling. Its output shall be reasonable and it shall not compromise the mixture structure.
- **lower structure layers** (asphalt, aggregate with continuous graining, ground stabilized by hydraulic binder), due to their low susceptibility to absorb heat, do not cause sudden drop of temperature in the incorporated HMA. Heat flows by conduction and depends on layer thickness and its λ coefficient. This situation may be changed when the base is moist and the base shall be protected against such situation;
- environmental factors shall be analyzed in connection with **geometry of the layer**, i.e. its thickness, width and location (in plane and cross-section). The thickness of the layer will decide on distribution of temperature in its cross-section (at known, low values of asphalt thermal conductivity). In case of low thickness (up to 3-5 cm), temperature will be similar in the entire cross-section. The difference between surface areas and the middle will increase with its growth. It will be particularly clear at high heat absorption by environment. The temperature decreases

significantly faster on layer surface, process is slower in the middle of the layer (and particular at thickness ca. 12–15 cm), It is connected with relatively large distance from surface to centre of the layer. The width of the incorporated layer is significant at forced heat exchange and it is connected with occurrence of transition area from laminar to turbulent movement. The heat flow intensity increases at turbulent exchange, which causes faster mixture cooling. At small width (up to 0,5 m) turbulent flow starts at wind velocity above 13–16 m/s, with width 1–2 m, the similar effect is obtained just at 4–8 m/s. In case of large width (3,5–7 m), turbulence occurs even at low wind, ca. 1-2 m/s. Therefore, it can be assumed in incorporation of asphalt-aggregate mixture in technical scale that the forced air flow above the layer will be turbulent which will intensify the heat exchange.

- area covering ca. 10 cm from **outside edge** of the layer is particular sensitive for accelerated cooling. Size of this area depends in small degree on the layer thickness. The decisive factors are thermal processes, i.e. development of thermal and hydraulic stabilization zone and heat output by side edge. This is illustrated by α coefficient, which value changes with distance from the side of the layer (fig. 10).

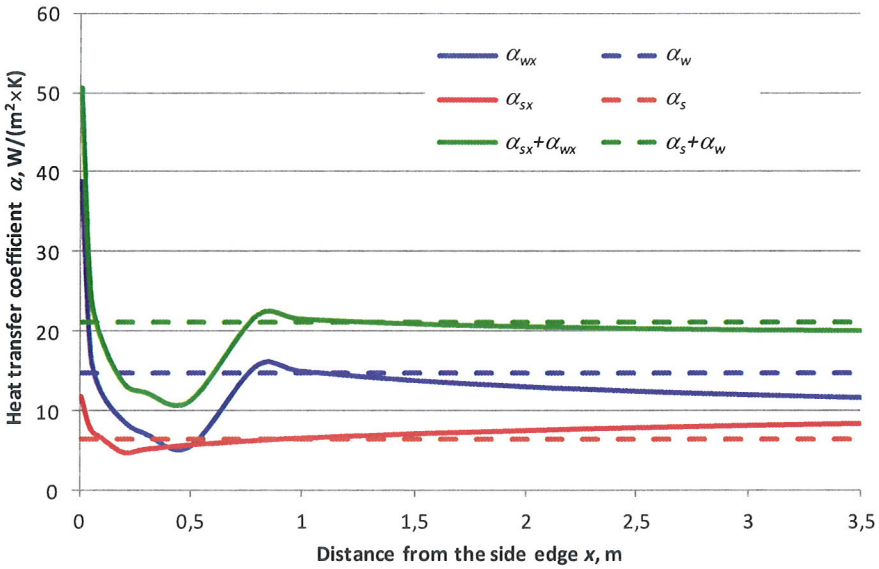

Fig. 10. The local values of convective heat-transfer coefficient at forced convection (α_{wx}) and free convection (α_{sx}) and average (α_w – forced convection, α_s – free convection)

The almost immediate passage of compacting equipment is necessary to obtain proper volume density for this area. The drop of temperature can reach even 100^{0}C just after ca. 2–3 minutes (which was confirmed in laboratory test results) and compaction attempt after this period makes practically impossible to obtain proper volume density of mixture. The additional studies in technical scale, by infrared camera, confirmed correctness of adopted by me assumptions. These studies determined distribution of temperature on surface of the incorporated SMA 11 wearing course , incorporated on the half of roadway width. These measurements were conducted in October. The air temperature varied in range 3–7°C, wind velocity ca. 2–3 m/s at relative humidity ca. 65%. It is clear from these measurements that even after the first minute after mixture spreading, higher temperature drop is visible on edges (fig. 11). They reach in area of *external edge* ca. 70–80°C, at *internal edge* (on joint with previously incorporated mixture) cooling process is slower, and difference reaches 30–40°C. After ca. 6 minutes and four passages of steel roller in external edge area it is possible to observe significantly quicker heat output

(fig. 12) which is cause also by wind direction. It is zone of thermal and hydrodynamic stabilization. The wall layer (heat conducting), decelerating the exchange process, is only creating in this area. Furthermore, the cold air inflow in result of the forced convection from the external edge (left side of diagram). Even small increase of temperature of this air (resulting from heating), further from the edge, moderates additionally process of heat exchange with environment.

- indication of reasons which determine **heat losses on stage of transport** of hot MMA and determination of recommendations, reducing results of quick cooling of mixtures.

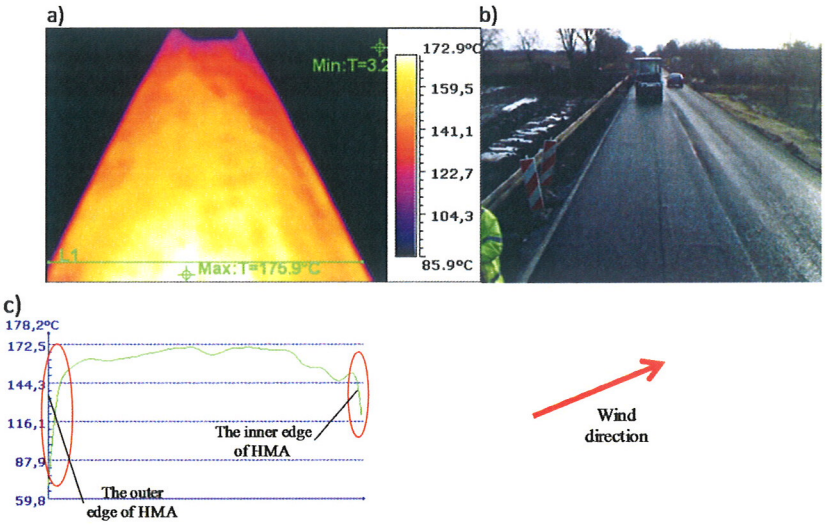

Fig. 11. The thermal picture of SMA 11 after 1 minute from laying, with exemplary distribution of temperature

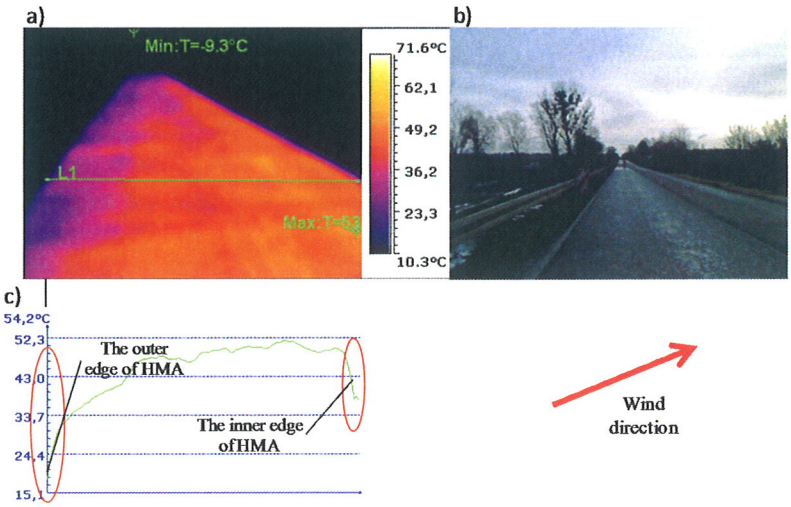

Fig. 12. The thermal picture of SMA 11 after 6 minutes from laying and four passages of steel roller, with exemplary distribution of temperature

The important element of my study is possibility of transfer of theoretical knowledge supported by laboratory experiments to technical scale. I used the obtained results to develop process recommendations, aimed to improve effectiveness of works and to obtain product (asphalt concrete, stone mastic asphalt, etc.) with the best possible properties. The main recommendations include:

1. asphalt mix shall be transported, irrespective of weather conditions, in semi-trailers with double-wall sides (steel are the best) filled with thermal insulation material or air, with possibility to introduce there the hot exhaust gases, and very tight cover from the top (heat output to air can be intensive due to turbulent flow even at favorable weather conditions – these precautions shall reduce heat flow, also by modification of nature of exchange: a) convection or flow through air or thermal insulator layer will decide within side areas, b) top area will give away heat by free convection);
2. moist base, on which HMA is to be incorporated, shall be dried (on ca. 2–3 cm depth at not set base and set layers). The infrared radiators or dry air compressors (also hot air) may be used for this purpose. Water left in the base can cause immediate cooling of HMA layer, reducing possibility of its compaction and adhesion with lower layer. It will result in reduced fatigue life of this layer and the entire pavement structure;
3. application of asphalt emulsion to prepare the bonding layer on the base or edge connections shall be made in advance, allowing for water evaporation. In case of bad weather conditions (high humidity, possibility of small precipitation), emulsions shall be replaced by hot bitumen. It is particularly important for this asphalt layers, connections and edge protections;
4. negative impact of base moisture on the incorporated HMA can be reduced by making the thin layer (max. 1–2 cm) with asphalt mix based on the soft binder (bitumen 100/150 or 160/220). This will provide additional extension of construction season and allow to conduct works even at small precipitation. Decision to use such layer shall be undertaken by the Investor on designing stage which secure additionally extended fatigue life for the structure;
5. irrespective of air temperature, wind velocity and layer thickness, the first passages of rollers shall be made directly after spreading, just after mixture pavers. In case of thin layers, it is forced by reduced compaction process time possibilities, in case of thicker layers, it allows to accelerate heat flow process, minimizes results of creation of rigid (due to cooling) layer on the surface (and therefore possible cracking during equipment operation) and accelerates works connected with proper layer compaction;
6. compaction time of asphalt mix in thin layers (up to 3–4 cm) shall not exceed 4–5 min., and the possible vibration shall concern the first half of this time (max. 2–3 min.), in particular in case of wind, even from 4-6 m/s. In unfavorable conditions, mixtures shall be spread at minimum speed of paver (i.e. 1–2 m/min.) with switched on table heating. This allow to heat up the layer surface and enables the quick passage of compacting equipment;
7. thick layers are compacted in stages. After the preliminary stabilization (point 5), next passages of rollers shall be conducted gradually, taking into account drop of temperature inside the mixture. The roller shall move with minimum speed (1–3 km/h), which shall provide the required evenness on the layer surface;
8. compaction shall start, irrespective of weather conditions and layer parameters, from the layer edge ("external" in the first place). It is forced by accelerated drop of temperature in area ca 10 cm from the layer edge.
9. near edge areas require protection of surface by their greasing with hot bitumen due to possibility of increased void content (quick temperature drop and no resistance makes impossible to obtain proper level of compaction).

The presented above recommendations are justified by the nature of changes occurring in HMA during its incorporation. This stage is decisive for mixture structure, and therefore its functional

properties, and it shall be subject to strict control on works stage. The justification and correctness of these above recommendations were confirmed during incorporation of wearing courses (asphalt concrete, SMA), 4–5 cm thick, on Szczecin streets (Eskadrowa and Hangarowa streets – 2005, Miodowa street – 2007, Struga street – 2012). The pavement works were conducted at very unfavorable weather conditions, in December – January. The air temperature varied between –3°C and 4°C, wind reached 4–8 m/s. In case of Eskadrowa and Hangarowa streets, the additional problem consisted in works conducted during weather conditions (rain and snow) which forced to use infrared radiators. Their main task was to evaporate deposited water and snow and to dry the base. The level of delivered energy and distance from radiators to surface did not cause significant increase of temperature of the existing layer (surface temperature did not exceed 15–25°C). In case of Miodowa street, pavement works were started after intensive rain. The compressed air was used to remove water from the layer surface. The incorporation of mixture was started in both cases directly after drying the base. The main problem on Struga street was negative air temperature and wind ca 8 m/s. This required to reduce in maximum degree the mixture storage time in means of transport and its incorporation (mainly compaction). The sun radiation brought the surface layer temperature to ca. 3–5°C (at air temperature between –3 and –1°C), which reduced possibility that the frozen water was deposited (layer surface was additionally protected on the previous day by the binder layer). The incorporation process (mixture laying and compacting) was reduced to ca. 5 minutes. The results of examinations of compaction and inter-layer adhesion obtained on the mentioned above construction sites indicated that it was possible to conduct the pavement works at unfavorable weather conditions, even with thin wearing courses.

The proposed model for description of temperature changes in the layer may be also used also in other fields of construction industry, among other in bitumen felt application. The standard process used to connect bitumen felt with the base is heating its bottom part by gas-fired burners, which flame temperature varies in range 700–1200°C. The high temperatures, even at short reaction time, may lead to significant ageing of the bottom layer of binder, and in consequence, to its improper work. This imposes necessary modification of thinking on method of felt binding to the base and to use process of its heating, based on the forced flow of hot air, with controlled temperature (e.g. 250–300°C).

The theoretical model used by me can be used, apart determination of drop of temperature in HMA, to forecast increase of temperature of the base on which it is incorporated. The effect of increased temperature can result in changes in humidity in the base and it can cause bulges due to growing partial pressure of water vapor. This effect is observed often on bridge plates, on which asphalt layers are incorporated on the tight bitumen felt insulation. The physical transformations (water – water vapor) and increasing temperature result in the significant growth of pressure on bitumen felt – base border, which result in separation of felt (in particular in places with weak or no adhesion). It is possible to forecast heat flow level toward lower layers and level of growth of their temperature in time, and therefore possibility of such effect, depending on type of mixture and intensity of external factors.

Recapitulating, it is possible to forecast, on the base of the proposed in this study theoretical model, temperature changes in the cooled (heated) layer, and therefore to undertake proper actions, allowing for correct work process, guaranteeing their correct quality.

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Other research works

My scientific and research works **after obtaining doctor's degree**, apart the discussed one in the previous part and constituting the monograph, concerned issues connected with construction materials, road pavement technology, additives to bitumen and asphalts, thermal conductivity of laminar systems as regards civil engineering. The short specification of issues for individual fields is presented below:

The cycle of publications, including problems of **additives to bitumens and asphalts** [C1-3, **C1-5**, **C1-7**, C3-14, C3-35, C3-36, C4-5, C4-7, C5-10, C5-11], was aimed to introduce field of knowledge which was and is the carrier of modernity and technical progress in bitumen works technology. These publications (as author and co-author) analyze products of chemical industry and related industries (petrochemical, chemistry of coke and fat industry) and waste materials (sulfur, PVC, rubber from tires) and their impact on properties of binders and materials with binders. The chemical processes occurring in these environments were explained due to the increased temperatures of applications of these additives to bitumen or asphalts. These discussions included also impact of mineral surface of aggregate, mainly due to their surface activity, which depends on amount of oxides of heavy metals and alkaline earths elements. Each type of additives, i.e. metallic-organic catalysts (Chemcrete, Ferronaft, Pakwat Fe), surface-active substances, plasticizers and emulsifiers, were characterized as regards chemical composition, predicted reactions occurring in modification process, faults and advantages of their use. The importance of mineral surface was in particular stressed in case of surface-active substances, responsible, among others, for improvement of binder adhesion to the aggregate. They were classified as regards very good, medium and insufficient adhesion to bitumen. It was recognized on the base of the conducted tests that the rock materials including more than 50% of heavy metal oxides and alkaline earths elements, demonstrated permanent adhesion to bitumen. This results from the fact that these materials enter into chemical reactions with surface-active bitumen compounds of anion nature (generation of soap – salt calcium, ferric and aluminum compounds, insoluble in water). Temperature has additionally positive effect on these processes. The rock materials, which include 30–50% of heavy metal oxides and alkaline earths elements, have satisfying adhesion to bitumen. Only the acid rocks (including up to 30% of such compounds) insufficiently bond with the binder and they obligatory require to apply bitumens artificially activated by adhesion additives. However, this need not disqualify aggregate with high content of silica (SoO_2) as component of MMA (granite, syenite, quartzite, sandstone, greywacke with silica binder, etc.). SiO_2 silica is present in rock materials mainly in such minerals, as: quartz, orthoclase, ($K_2O{\cdot}Al_2O_3{\cdot}6SiO_2$), acid plagioclase ($Na_2O{\cdot}Al_2O_3{\cdot}6SiO_2$). As is apparent from the provided chemical formulas, these minerals include in majority, apart silica, also alkaline oxides (Na_2O, K_2O) and amphoteric aluminum trioxide (Al_2O_3). These are important components of mineral mixture, in particular as regards its forming for bitumen adhesion. They provide mosaic structure to grain surface, characterized be alternate position of positive charges (Na^+, K^+) and negative charges ($SiO_2^=$). Despite quantity disproportion between positive and negative ions, large volume of positive ions of sodium or potassium secures balance of positive and negative fields in the grain surface mosaic system. The such configured electrostatic condition favors good bitumen adhesion to the mineral aggregate surface. With high natural surface activity or strengthened by introduction of adhesion agents, such materials will demonstrate the required level of adhesion to the binder.
The issues of bio-bitumens were also undertaken in studies, supported by significant progress as

regards improvement of technology of oil painting materials by metal-organic connections (manganese, cobalt, lead and other salts). It was inspired by searching for more quality preferable organic binders by application of vegetable oils as substitute for mineral oil in bitumen. Such substitution will also have its economic justification, consisting in reduction of AM (warm) production temperatures by binder fluidization in surrounding moment (savings in energetic material consumption) and reduction of ageing process intensity. The lower viscosity of binder will have also effect (through reduction of AM production temperature) on reduction of emission of toxic and greenhouse gases to atmosphere. The preliminary reduction of viscosity does not collide with the need to obtain the required consistence in final product. It is obtained by application of metal-organic catalyst, supporting oxidizing polymerization processes.

The mentioned above thematic cycle included also utilization of selected waste materials (sulfur cake, worn tires and PVC). These problems were discussed taking into account ecological consequences and their application on road construction processes. The attention was called on the need to keep caution and objectivism in utilization of any waste materials, in particular as regards:

- high fragmentation of processes in HMA production plant conditions and relatively high process temperatures and complex chemical composition are almost always the sources of vapors and gases very toxic for people and environment;
- awareness of harmfulness of technologies developed in laboratory is relatively low or even none, as amount of toxic gases and vapors is small and almost unnoticeable. The scale of problems increases with increased weight of the processes materials.

The utilization of organic and inorganic substances as post-user wastes from various industries shall be organized, with participation of competent research teams and technology developed in details (big plants with system of filters and absorbents in chimney systems, filters and sedimentation tanks for process water treatment).

Publications (as author and co-author) in the field of **road pavement technology** [**C1-5**, **C1-6**, C3-2, C3-3, C3-5, C3-11, C3-15, C3-24, C3-31, C3-32, C3-34, C3-38, C3-43, C3-46, C3-48, C30-49, C3-50, C4-6, C5-6] include problems of construction of asphalt layers, taking into account material engineering, structural parameters formed on AM production and incorporation stages and mechanical and energy effects occurring during pavement operation. They include also the asphalt-mix designing. It is based on one side on introduced European standards regarding research and requirements, taking into account type of mixtures and their functional properties. On the other side, mixtures are dealt as dispersion systems, which properties depend on bulk density, internal angle of incidence and cohesion. The dispersed phase in dispersion system is aggregate with graining above 0,5 mm, and continuous phase – mixture of bitumen, filler and fine sand. The continuous phase may be treated as micro-structure which, in result of consolidation with mineral frame in compaction process, creates micro-texture, understood as the formed construction product. The proposed structural approach in asphalt mix designing allows to explain impact of individual components on properties of conglomerate and mechanisms occurring on production and incorporation stages. The important group includes issues connected with production of pavement layers on bridges. They include insulation of deck plate as well as wearing and protecting layer problems. The many years of research experiments on behavior of pavement layers on bridges with different materials of deck plates (steel, concrete) found their application in constructions (designs, supervision) conducted in West Pomerania Voivodship. They concerned mainly the innovative construction solutions and process recommendations (in that joint design supervisions) on the repaired structures with steel

and reinforced concrete plates or prestressed (Cłowy Bridge, Długi Bridge, Akadmicki Flyover, Estakada Pomorska, Bridges, including J. Poniatowskiego and K. Świerczewskiego within Poznańska Highway in Szczecin, bridge in Dziwnów).

As regards problems regarding **construction materials**, publications (as author and co-author) discussed issues connected with utilization of industrial wastes [C3-7, C3-21, C3-25, C3-33], which in many cases constitute danger for human life and health. One of such group are asbestos-cement products. The method of protection against their harmful effect may include their painting with dispersion paints with acrylic binders. In this case it is possible that hydrogen (proton) bonds will occur between the active oxygen of organic resin and hydroxyl group hydrogen (-OH) included in structure of chrysolite asbestos. This inclines to presumption that relatively strong intermolecular bonds will be generated and cohesion of all components of asbestos-cement product will occur. Apart physical and chemical reactions in form of hydrogen bond, paint with synthetic resin can be joined with mineral base by dispersion forces (van der Waals forces), increasing reaction on boundary of phases, specified as adhesion. The last ones, although weaker as hydrogen bond forces, are sufficient to generate the compact mineral-organic monolith. The stability of asbestos-cement material can be more increased by giving the paint the distinct water-repellant nature, joining the acrylic resin with silicone resin. This bond may have chemical nature (copolymerization) or physical nature, consisting in mixing of both materials in specific weight relation. The accurate covering of mineral surface with paint of adhesive and flexible consistence (demonstrating water-repellent properties), excludes possibility of further erosion of cement mortar by rain water and therefore eliminates asbestos dust emission to atmosphere. The second group of the discussed waste materials include commodity synthetic resins, which include polyvinyl chloride (PVC). It is one of the most popular plastics in the world, with current consumption ca. 24 million tons annually. PVC is a polymer with low thermal resistance, glass transition temperature 80°C and flow temperature 145–170°C. Its decomposition starts just in temperature 120°C, with emission of toxic chloro-organic and inorganic compounds, e.g. HCl (hydrogen chloride), furanes (PCDD and PCDF) – one of the most harmful substances for people and environment. The sun radiation, in particular UV radiation, has similar effect. The incineration is one of PCV (and other plastics, not suitable for recycling) utilization methods. The thermal conversion results in uncontrolled reactions, which initiate generation of toxic organic compounds, including chlorine derivatives from aromatic compound group, specified as polychlorinated dibenzodioxins (PCDD) and biphenylene oxides (PDF). This the most often used utilization method forces to suffer immense expenditures for special filter, which absorb dioxins and other pollutants. The possible attempts to use such waste materials in road engineering (in particular in production of hot asphalt-aggregate mixtures) shall be limited or even prohibited, due to their harmfulness for people and environment.

The last group of topics includes publications (as author and co-author) on **heat flow in laminar systems**, operated in housebuilding industry [C3-8, C3-9, C3-10, C3-16, C3-17, C3-18, C3-19, C3-20, C3-22, C3-26, C3-27, C3-28, C3-30]. They discuss issues concerning possibility to use laws of thermodynamics and chemical engineering to assess building element heat losses. It was presented on example of selected space dividers, i.e. walls and windows. The results of calculations demonstrated that the simplified approach, presented in European standards, provides approximated values of thermal conductivity in relation to these which are obtained on the base of analysis of physical laws. The material conditions as regards glass used in construction industry were

discussed additionally. The assessment was conducted on the base of properties of this material as well as for the entire partition, taking into account gas in the inter-panel space. Apart the thermal properties, window panels shall be characterized by their acoustic insulating power, which have significant impact on comfort of people occupying the rooms. The noble gases are responsible in high degree for thermal and acoustic insulating power. They constitute barrier for heat flow (lower thermal conductivity) and acoustic barrier, contributing in attenuation of mechanical vibrations. It is directly connected with atomic structure, and exactly, with quantity and arrangement of protons and neutrons. The growth of atomic number of noble gases improves thermal and acoustic insulating power properties. Such behavior of noble gases is described by large atomic volume and their relatively high density. These interpretations often touched the role of interatomic viscosity, which counteracts the vibrating atom movements during relocation of thermal energy by conduction and convection, and by mechanical way (conduction of mechanical energy). In interpretation of effect of attenuation of mechanical vibrations (noise) by noble gases, one more effect was discussed, which is often omitted. The high volume and weight of noble gas atoms, friction forces between atoms (viscosity), fulfill, apart transport of energy, role of absorber and they disperse (relax) energy, which undoubtedly reduces the energy output value and improves therefore effectiveness of its attenuation. Recapitulating, usage of noble gases as insulation medium in composite windows, contributes to improvement parameters of thermal and acoustic insulating power parameters (in relation to air). The thermal insulating power of noble gas results mainly from inhibition of convection processes, and acoustic insulating power – from inhibition of mechanical energy by its dispersion. The size (volume) of atoms, gas pressure and its temperature have decisive significance in both cases.