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INFLUENCE OF HYDRATED LIME ON DURABILITY OF SMA ASPHALT PAVEMENT WITH QUARTZITE AGGREGATE

Abstract

The durability of pavement layer desponds on the type of mineral aggregate. In 1999, while rebuilding road infrastructure in Kielce (Poland), a SMA wearing coarse layer with hydrated lime was placed on the town's main streets. SMA mixture contained 63% of quartzite aggregate. The hydrated lime was dosed into the SMA mixture to replace 30% of the filler mass. The pavement surface condition after 12 years life was very good. The hydrated lime additive was found to have a positive effect on water resistance of SMA pavement.

Keywords: hydrated lime, SMA, durability, quartzite aggregate, water resistance

1. Introduction

In Poland the quartzite sandstone could be considered as the most resistant aggregate to abrasion and polishing process. One of the largest deposits of this material are located in the vicinity of Kielce, near the Świętokrzyskie mountains [4]. An important advantage of the quartzite aggregates is its bright color in comparison with the color of the basalt aggregate, which is used as the standard aggregate in asphalt mixes. The use of the quartzite aggregates in asphalts causes significant brightening of the wearing course surface, which is important from the point of view of ensuring road safety at night. It also contributs to reduce the amount of electricity needed to provide the required stationary lighting on sections of pavement. Despite the advantages of the quartzite aggregates there are some disadvantages. Due to the high silica content up to 95% of its composition, it shows week affinity with the bitumen, which in some way, makes it difficult to use this aggregates in asphalt mixtures. This property for some technological reasons from the beginning of 90's last century, limited the applicability of this aggregate. The studies that started at this period reveled that there are no barriers to the use of this type of the mineral aggregate in asphalt mixtures [2]. It was posed that it is necessary to apply the adhesives agent to improve the covering effect of this type of aggregate by bituminous binder. The most common adhesion agents are fatty amines. Unfortunately, they may cause an adverse effect on the bitumen parameters such the softening point that it may be reduced. A consequence of this influence of the adhesive agent is a decrease of the resistance to forming ruts. It is necessary to use other adhesive agents that don't play such an important role regarding bitumen properties. Another type of adhesive agent is hydrated lime, which has been used in the Central and the Eastern Europe in the 60's of the twentieth century [8]. However, due to technological difficulties in dispensing during production process into the bitumen, application of this adhesion agent was abandoned. The development the road technique on XX and XXI century contributed that the earlier problems had stopped to exist [3, 7, 9].

In 1999, due to the renovation of Zelazna street in Kielce (Poland) which is the main communication street, the wearing coarse layer was built with application into SMA the composition of the quartzite aggregate. The second purpose of application of this type of aggregate was ensuring a high anti-skid resistance. In order to ensure proper affiliation between the bitumen and aggregate the hydrated lime was used. The fatty amine was used as a reference adhesive agent.

2. SMA performing

Modernization of pavement construction located at Żelazna street in 1999 was carried out with deep cold recycling technology. On the basis of measurements of traffic it was specified as KR4 category [6].

The design of road construction met the requirements which were set out in guidelines developed by IBDiM [13]. The design consisted of a recycled sub-base layer in the cold recycling technology with a thickness of 20 cm with using bitumen emulsion, cement and recycled materials derived from existing asphalt layers and stone foundations. The next layer was the binder coarse of 8 cm and the last was the wearing course made of SMA which thickness was 4.0 cm [14]. Under the new layers there was still a layer of aggregates with a variable thickness from 15 to 24 cm, which remained from the previous pavement construction. Road construction has been designed for 20 years of operation.

2.1. Study design

Tests program for determining the impact of the type of adhesion agent on the properties of SMA mixture and its preservation in terms of using quartzite aggregate was divided into two stages - laboratory and operational. In the first stage (laboratory), special attention was paid to the mineral mix design and carrying out the necessary studies for assessing the impact of hydrated lime and fatty acid amines on the properties of SMA. After modernization of Zelazna street measurements were continuously conducted of layer condition parameters during operation. A current program of research of the first stage of SMA consisted of :

– standard properties,
– rut resistance,
– water and frost resistance (PANK 4302 of Finnish standards and AASHTO T283 standards, specifying the coefficient of resistance to water WR_w, and the coefficient of resistance to water and frost WR_{wm}).

An important element of the study was to evaluate the homogeneity of the work. The measurements were taken only for samples whose void fraction content ranged between V - 2s ; V + 2s), where: V – is a mean void fraction content value in asphalt concrete, s – standard deviation. On this basis the identity of mean void fraction content values of the samples was assessed.

It should be noted that majority of studies in 1999 were performed in accordance with the methodology, at that time, obligatory in Poland.

2.2. Mineral mix design

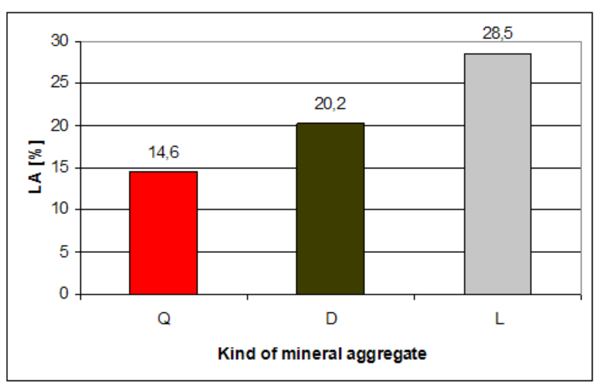
During designing of mineral mix of SMA, the main assumption was that, except for quartzite aggregate (whose content was in scope of 50% and 70%) which was resistant to the abrasion and polishing process, the mineral mix should have aggregate of smaller resistance to previously mentioned factors i.e. the aggregate dolomite or limestone. This action was validated due to different grade of polishing for different aggregates. Therefore, during the operation, the texture of layer will have expanded. The consequence of this will be an increase in value of the friction coefficient. It should be noted that the percentage of second aggregate in the mineral mix was selected on the basis of laboratory tests so as not to cause a reduction in the physical and mechanical properties.

It should be noted that the dolomite and limestone aggregates also play an important role in improving the adhesion of the bitumen in the asphalt, reducing its negative potential due to the use of quartzite aggregate. Significant aspect in that way was contribution of the fine dolomite aggregate of 0/4 granulation. The expanded specific surface area contributes to the intensification of the chemical processes at the contact zone between aggregate – bitumen.

The framework composition of SMA 0/12.8 was performed using aggregate coming from the Świętokrzyskie Mountain. The mentioned mineral mix consisted of the following composites:

– the quartzite sandstone (Q): granulation 2/6.3 mm and 6.3/12.8 mm,
– dolomite (D): granulation 2/6 mm,
– the Devonian limestone (L): granulation 0/4 mm.

The primary aggregate properties such as: resistance to abrasion in the Los Angeles drum according to EN 1097-2, the resistance to the effect of the frost (PN-S-11112), water absorption and PSV coefficient according to EN 1097-8 and the content of the silica SiO_2 were presented in Figure 1.

a)


b) c) d) e)

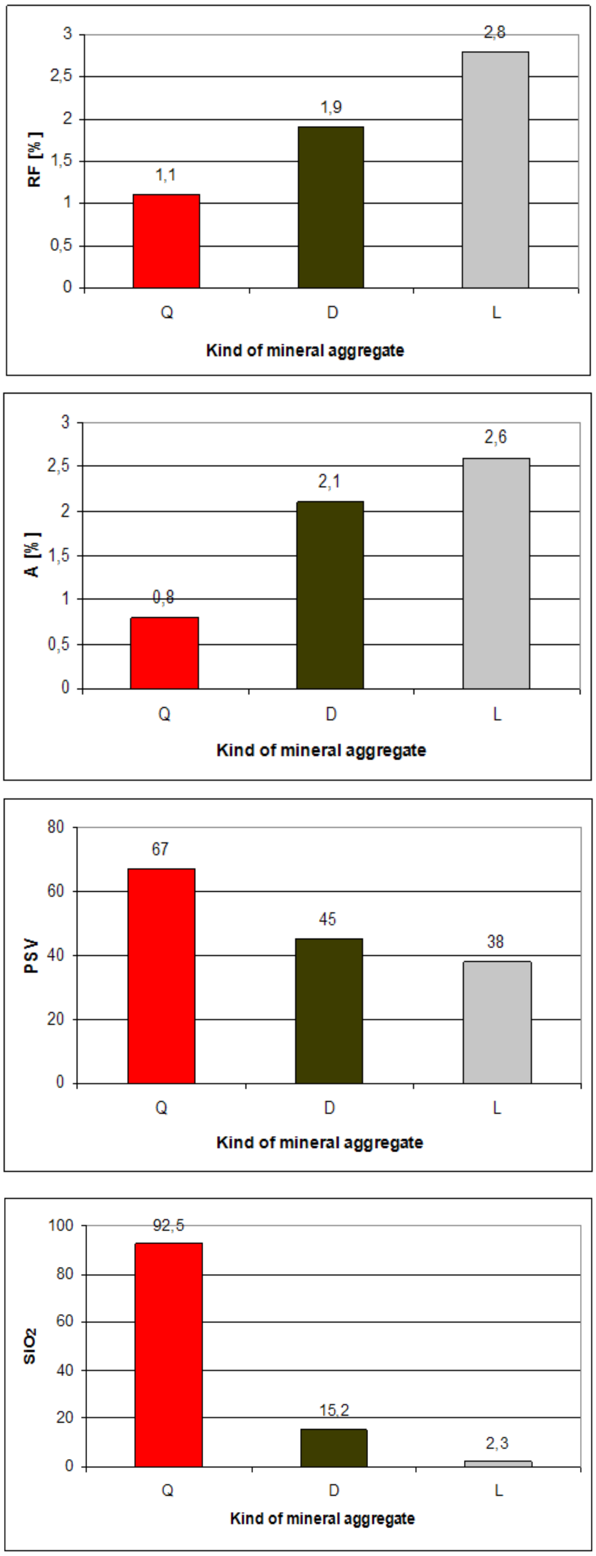


Fig. 1. Properties of SMA mineral mix; a) resistance to abrasion in the Los Angeles drum LA, b) resistance to the effect of the water and frost RF, c) water absorption A, d) polished stone value PSV, e) silica content SiO_2 [6]

The aggregate from the quartzite sandstone is characterized by a lower level of the indicator LA that testifies about its high resistance to the crushing process. It is classified to the aggregate group of the greatest resistance to crushing according to methodologies LA. The application of the quartzite sandstone wearing coarse layer, like SMA, ensures its high resistance to the effect of the stress coming from axle. Moreover, it delivers a high level of roughness of the layer [4, 10]. The dolomite aggregate is less resistant to crushing process in comparison with a quartzite sandstone. The indicator LA characterizing this aggregate has the value of 20.2%, hence it was within the limit of hard aggregates applied to wearing coarse layers for category traffic from KR4 to KR6 (the type the motorway) and a soft aggregate applied to regional road of the category of KR3 and lower rank. Devonian limestone turned out to be very poor and at least it was able to apply for local traffic category of KR1 and KR2.

Values of the PSV indicator correlate with the resistance to crushing of the aggregate according to LA methodologies. The most resistant on polishing process is the quartzite sandstone aggregate whose indicator of PSV amounts to 67. It is most resistant to polishing aggregates among natural aggregates in Polish conditions. This type of aggregate guarantees retaining optimal level of the roughness in the long service life. The dolomite aggregate, applied as an independent component in SMA, was characterized by the value of PVS amounted to 45 and it does not guarantee ensuring the roughness of the surface during operational period. The aggregate with Devonian limestone is characterized by much smaller value of the indicator PSV (PSV = 38) than the dolomite aggregate.

The aggregate from the quartzite sandstone thanks to its smaller water absorption and higher water and frost resistance will be resistant to the destructive climatic factors. The dolomite aggregate is less resistant to these destructive climatic factors. However, the aggregate with Devonian limestone is characterized by highest water absorption and low frost resistance. To sum up, it is less resistant to the effect of the water and frost.

Properties of the examined aggregates are connected with a mineralogical composition of the rock from which they were derived. Very essential is the content of the silica SiO_2 which decides about a mechanical parameters of the aggregate. The aggregate from the quartzite sandstone contains 92.5% silica in the mineralogical composition. That is why it is characterized by such large resistance to the crushing process and has a high level of PSV value. The dolomite limestone contains far less silica than the quartzite sandstone, that is why its resistance to crushing and polishing process is proportionately smaller than the quartzite sandstone. However, the Devonian limestone contains only minute quantities of the silica, therefore from those examinated aggregates it has the least resistance level to the crushing and polishing process.

The silica SiO_2 has a very favorable influence on mechanical parameters of aggregates, but unfortunately in a very negative way influences the affinity of bitumen and the aggregated. Thereby, SMA performed with a quartzite sandstone can not be resistant to the effect of the water and frost [4]. However, the mix of dolomite and limestone aggregate is distinguishes by a very good affinity with the bitumen.

The use in the SMA mineral mix aggregates with different resistance to crushing and polishing could provide a good roughness during long service life. However, the addition of the dolomite and Devonian limestone aggregate have a good influence on the adhesion of entire SMA components included affinity with a quartzite sandstone.

It should be noted that the dolomite and limestone aggregates also play an important role in improving the adhesion of the bitumen in the asphalt, reducing its negative potential due to the use of quartzite aggregate. Significant aspect in that way was the contribution of the fine dolomite aggregate of 0/4 granulation. The expanded specific surface area contributes to the intensification of the chemical processes at the contact zone between aggregate – bitumen.

The framework composition of SMA 0/12.8 which was performed in accordance with the guidelines of IBDiM [14] is summarized in Table 1.

Table 1. The percentage of mineral materials in SMA 0/12.8

Quartzite mix	
Component	Percentage share [%]
Limestone filler	10
Fine limestone aggregate 0/4	12
Dolomite aggregate 2/6	15
Quartzite aggregate – fraction 2/6.3 – fraction 6.3/12.8	 10 53
Total	100

Hydrated lime (HL) was added to the mineral mix by entering it as a substitute in mineral filler in an amount of 10, 20, 30, 40 and 50%. After mixing hydrated lime with the limestone filler the “blended filler” was received, which was incorporated into the mineral mix.

2.3. SMA properties

Table 2 summarizes the characteristics of the recommended SMA mixtures included hydrated lime and fatty acid amine.

Table 2. Selected SMA properties

No	SMA parameters	Kind of adhesive agent	
		HL	A
1	Void fraction content [%]	3.5	3.7
2	Voids filled asphalt [%]	79.2	78.5
3	Water absorption [%]	0.28	0.35
4	Static creep modulus [MPa]	24.8	22.5
5	Indirect tensile strength ITS [MPa]	1.46	1.52
6	Maximum rut depth [mm]	5.1	5.6
7	Low temperature cracking PANK 4302 [MPa]	2.2	3.1
8	Resistances according to AASHTO T283 standard: – water resistance WR_w [%] – water and frost resistance WR_{wm} [%]	 89.2 79.4	 86.1 77.8
9	Binder content [%]	6.1	6.1
10	SBS polymer content in bitumen [%]	4.0	4.0
11	Adhesive agent: [%] – hydrated lime (variable in filler) – acid fatty amine	30	0.2

Analyzing of the impact of the type of adhesive agent on properties of SMA it can be concluded that during research process comparable level of parameters for two kind of adhesive agent were obtained by recommended contents of adhesive additive. However, using hydrated lime in comparison to the fatty amine higher properties of SMA are achieved.

3. SMA pavement

In 1999 SMA was made which was intended for wearing course layer of the experimental section of dual carriageway localized in Żelazna street in Kielce. On the I section of SMA it was built with the addition of the hydrated lime and the II section was built with liquid adhesive agent. During the production, transport and performing there were no adverse effects caused by the adhesive agent. During the macroscopic evaluation it can be concluded that the kind of adhesive additive caused no impact. The surface texture made from SMA does not depend on its composition. Only the color difference occurred. The use of hydrated lime in the composition of SMA made a surface dull in color of the control surface (fatty amine) which was glossy. SMA was subjected to continuous monitoring in accordance with the methodology in Poland (SOSN - Pavement Condition Assessment System [12]). The examination concerned the following basic operating parameters such as surface condition, evenness, roughness and

Table 3. SMA surface damage during operations

No.	Damage type	Service time											
		2		4		6		8		10		12	
		Kind of adhesive agent											
		HL	A	HL	A	HL	A	HL	A	HL	A	HL	A
1	Raveling	–	–	–	–	–	–	–	N	N	N	N	N
2	Stripping	–		–		–	–	–	–	–	–	–	N
3	Low temperature cracks	–	–	–	–	–	–	–	–	–	–	–	–
4	Fatigue cracks	–	–	–	–	–	–	–	–	–	–		–
5	Mesh cracks	–	–	–	–	–	–	–	–	–	–	–	–
6	Longitudinal cracks	–	–		–	–	–	–	–	–	–	–	–
7	Transverse cracks	–	–	–	–	–	–	–	–	–	–	–	

symbol:
" –" – lack of damage
"N" – rare symbolical damages

rut resistance. The depth of macro texture was also investigated using the volumetric method ([11] and PN-EN 13036-1). In order to obtain comparable results of the parameters the measurement on each year in April was performed.

Particular attention during the test surface of SMA was paid to the impact of climatic factors and particularly the impact of water and frost on durability in aspect of the type of adhesion agent. Six types of defects of surface were selected, which may be caused by climatic factors (Table 3).

Examination of the results of the surface condition, in aspect of water and frost impact, shows that the applied adhesive agents (hydrated lime, fatty amine) effectively realized their task. During a seven years operation on the surface of SMA there were no damages caused by effect of water and frost. In case of SMA with fatty amine additive in eight year operation there were rare symbolical damages caused by water and frost effect, especially raveling of great particles of aggregate. Similar defects appeared on SMA pavement made of the hydrated lime in the blended filler but only after 10 years of operation. It should be noted that in 12 year of use of SMA layer with the liquid adhesion had a defect connected with stripping.

After 12 years of operation of SMA pavement it can be concluded that the surface condition, regardless of the type of the adhesive additives, has still very good quality.

4. SMA properties after 12 years operation period

According to schedule contracts 2.33/1.28 the evaluation of SMA mixture was made with the following parameters:

- void fraction contents Vm according to PN-EN 12697-8,
- water resistance ITSR according to PN-EN 12697-12 and WT2-2010 standards,
- water resistance TSR [1].

Average values of void fraction content Vm [%] in SMA pavement in section I (hydrated lime HL) and II (fatty amine A) in rut (RD) and out of rut (N) were presented in Figure 2.

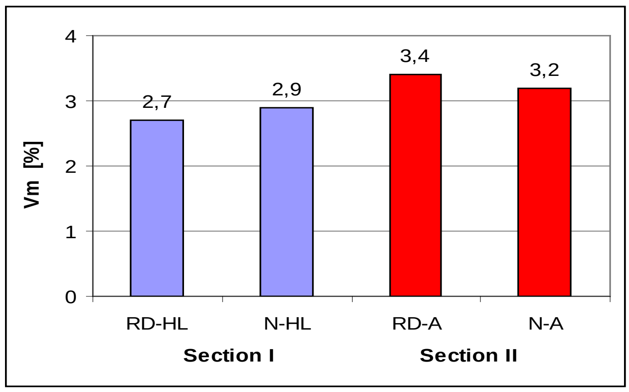


Fig. 2. Void fraction content Vm in SMA pavement [6]

Test results revealed that the void fraction contents in the pavement were lower then their amount determined during laboratory design. It means that the compaction during rolling process is more efficient than Marshall method in the laboratory.

The void content in SMA pavement in section I is greater than in section II. The use of the hydrated lime beneficial influenced the compaction process than application of the fatty amine. The level of the void fraction content in section I in rut is lower then the rest area of the pavement. It testifies that the pavement is permanently compressed because of stress from traffic load. However, in section II a beginning of destructive process as a result of the loss of adhesion between bitumen and aggregate caused by the interaction of climatic factors and traffic can be observed.

The evaluation of the void fraction content of SMA pavement indicated that the hydrated lime has a favorable influence on ensuring a proper durability and resistance to the climatic factors in comparison to application of fatty amine during 12 year service life.

The resistance on the influence of water (ITSR parameter) of the surface SMA in section I and II determined in accordance with PN-EN 12697-12 was reported in Figure 3. It should be noted that the assessment was carried out on specimens taken from the pavement with the same compaction level in compliance with the requirements in standards.

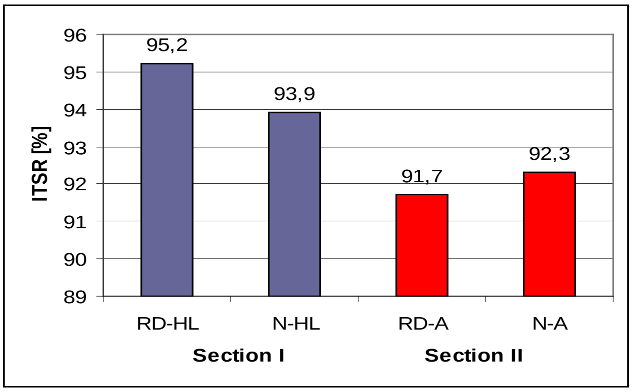


Fig. 3. Water resistance of SMA pavement – ITSR parameter [6]

The test result revealed that the void content Vm and the type of the additive have a great influence on the water resistance according to PN-EN 12697-12 in section I and II.

SMA pavement in section I located in rut has a high value of ITSR parameter amounted to 95.2%. The permanent compaction process caused by the traffic is responsible for this. It should be noted that the minimal value of ITSR is 90% according to PN-EN 12697-12. The water resistance out of the rut has a similar value of ITSR which amounts to 93.9%. SMA pavement out of the root was not subjected to regeneration process, hence it did not neutralize a adverse moisture effect out of the rut. The opposite effect appeared in section II. Much more resistant to the effect of the water is pavement out of the rut where ITSR parameter amounts to 92.3% and it is greater than ITSR for specimens received from the rut (ITSR = 91.7%). It proves that in section II there is a beginning of destructive process of the pavement. According to the macroscopic investigation a raveling effect was found.

The resistance to the water effect of TSR (after 6 conditioning cycles) of SMA pavement in section I and II was determined by application of specific procedure relying on cyclic freezing through 15 h at temperature of -18ºC and the next thawing through 24 h in 60ºC according to standards mentioned in [1].

Average values of moistures effect TSR in SMA pavement in section I and II in rut (RD) and out of rut (N) were presented in Figure 4.

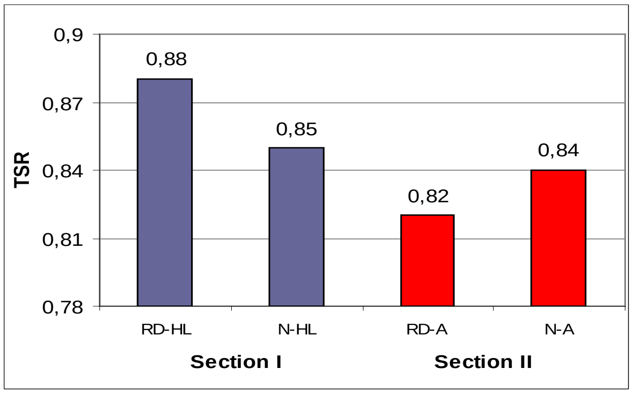


Fig. 4. Water resistance TSR of SMA pavement in section I and II [6]

Based on the analysis of TSR ratio results it can be concluded that the SMA surface on sections I and II is resistant to water and frost. The determined factors TSR of SMA pavements in both Sections I and II are greater than the required value of 0.80. The TSR parameter for specimens performed in laboratory should be characterized by value = 0.80. Therefore, it can be concluded that the SMA pavement in sections I and II is characterized by continuous high water and frost resistance. Analyzing the indicator TSR of SMA pavements expressed in terms of the type of adhesion agent (HL, A) it can be concluded that there is a similar relationship in relation to the ITSR methodology in accordance with PN EN 12697-12.

The highest resistance to water and frost (TSR) is characterized by SMA in section I (TSR = 0.88). A lower value gained a TSR parameter in section I (TSR = 0.85). The traffic permanently increased density index, hence the resistance to the effect of water and frost is higher in the rut then out of the rut. In section II the level of the TSR is lower in the rut than in adjacent area, which suggest the loss of adhesion in the rut. The use of fatty amines as an adhesion agent in a mixture of SMA is less effective than the use of hydrated lime for ensuring adhesion and durability during long operating period of SMA pavement.

5. Conclusion

On the basis of the test results taken from twelve period of operation the following conclusions can be drawn:

- water and frost resistance of SMA was improved as a result of the use of hydrated lime in comparison with the use of fatty amines;
- hydrated lime plays an important role in ensuring the resistance of SMA mixture to the effect of climatic factors especially with using the quartzite aggregate (aggregate with a high silica content), for example the sandstone;
- hydrated lime can be used in SMA mixture simultaneously replacing the liquid adhesive additives (fatty amines) influencing the improvement the water and frost resistance,
- SMA pavement surface condition with the addition of hydrated lime (30% filler) in the 12 years of operation is comparable (even better) to SMA pavement with the fatty acid amine;
- the use of hydrated lime in an amount of 30% of limestone filler in the composition delivers the durability of the pavement by application of 4% SBS modified polymer (which was noticed during the 12 years service life).

References

[1] Huang et al.: *Impact of lime modification of asphalt and freeze-thaw cycling on the asphalt-aggregate interaction and moisture resistance to moisture damage*, J. Materials in Civil Engineering 17(6), 2005, pp. 711–718.

[2] Iwański M.: *The influence of technological process on properties of asphalt concrete*. Proceedings 3rd International Conference "Civil Engineering and Environmental". Lithuania, 1998, pp. 9–14.

[3] Iwański M.: *Water- and freeze resistance of asphalt concrete with quartzite aggregate*. Proceedings V International Conference „Durable and Safe Road Pavements". Poland, Kielce, 11–12 May 1999, p. 77–84.

[4] Iwański M.: *Kruszywo kwarcytowe do mieszanek mineralno-asfaltowych* [Asphalt mix with quartzite aggregate]. Materiały Budowlane. Nr 11, 2000, pp. 55-59.

[5] Iwański M.: *Influence of hydrated lime on physico-mechanical properties of asphalt concrete*. Proceedings IX International Conference "Durable and Safe Roads Pavements". Kielce, Poland, 6-7 May, 2003, p. 77-84.

[6] Iwański M., Chomicz-Kowalska A., Major H., Mazurek G., Buczyński P.: *Effect of hydrated lime on properties of SMA pavement (mixture) located in Żelazna Street*, Kielce. Kielce University of Technology. Poland. Report for Research Project No. 2.33/1.28/2011/2012.

[7] Judycki J., Jaskuła P.: *Investigations on resistance to action of water and frost of asphalt concrete containing hydrated lime*. Proceedings V International Conference „Durable and Save Road Pavements". Poland, Kielce, 11-12 May 1999, pp. 111–118.

[8] Koroliow I.W.: *Puti ekonomii bituma w dorożnom stroitielstwie* [Methods of economics bitumen in road construction]. Transport, Moskwa, 1986, p. 148.

[9] Piłat J., Kalabińska M., Radziszewski P.: *Mieszanki mineralno-asfaltowe z dodatkiem miału gumowego i wapna hydratyzowanego* [Asphalt mix with the fine rubber and hydrated lime]. Materiały Budowlane. Nr 11. 2000, pp. 60–62.

[10] Sybilski D., Mechowski T.: *Właściwości przeciwpoślizgowe nawierzchni a technologia wykonania warstwy ścieralnej* [Influence of technological proces on the asphalt surface roughness]. Prace IBDiM Nr 3-4, 1998, pp. 109–143.

[11] Instrukcja pomiaru tekstury nawierzchni za pomocą piasku kalibrowanego [Manual measurement of surface texture using a calibrated sand]. Prace IBDiM, Nr 4. Warszawa, 1977, s. 85–91.

[12] System oceny stanu nawierzchni [Pavement Condition Assessment System]. Warszawa, GDDP. 2001, s. 8.

[13] Warunki techniczne wykonania warstwy podbudowy z mieszanki mineralno-cementowo-emulsyjnej (M-C-E) [Technical guideline of performance of the base mineral-cement-emulsion (MCE) mix]. Zeszyt Nr 61, IBDiM, 1999, s. 44.

[14] Zasady wykonania nawierzchni z mieszanki SMA (ZW-SMA 95) [Technical guideline of performance of the SMA asphalt pavements]. Zeszyt Nr 49. IBDiM. Warszawa, 1995, s. 20.

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Wpływ wapna hydratyzowanego na trwałość nawierzchni SMA z kruszywem z piaskowca kwarcytowego

1. Wstęp

Istotną zaletą kruszywa kwarcytowego jest jego jasna barwa. W porównaniu z barwą kruszywa bazaltowego, które jest uznawane jako kruszywo standardowe do mieszanek mineralno-asfaltowych, można przyjąć, że jest ono białe. Zastosowanie kruszywa kwarcytowego w nawierzchni asfaltowej powoduje znaczne jej rozjaśnienie, co ma istotne znaczenie dla zapewnienia bezpieczeństwa ruchu drogowego w warunkach nocnych. Wpływa również na zmniejszenie ilości energii elektrycznej potrzebnej do zapewnienia wymaganego oświetlenia nawierzchni na odcinkach, na których ze względów na natężenie ruchu samochodowego oraz bezpieczeństwo stosuje się oświetlenie stacjonarne.

Pomimo zalet, jakimi charakteryzuje się kruszywo kwarcytowe, posiada ono jednak pewien niedostatek. Ze względu na dużą zawartość krzemionki, dochodzącą nawet do 95% jego składu, wykazuje brak powinowactwa z asfaltem, co w pewien sposób utrudnia wykorzystanie tego kruszywa w mieszankach mineralno-asfaltowych. Niezbędne jest stosowanie środków adhezyjnych. Mineralnym środkiem adhezyjnym jest wapno hydratyzowane, które w krajach Europy Centralnej i Wschodniej było stosowane jako środek adhezyjny w latach 60. XX wieku [8]. Ze względu jednak na trudności technologiczne dozowania go w procesie wytwarzania mieszanki mineralno-asfaltowej w tym czasie stosowanie jego zostało zaniechane. Rozwój techniki drogowej pod koniec lat 90. XX wieku spowodował, że przesłanki tego rodzaju przestały istnieć [3, 5, 7, 9].

W 1999 roku w związku z remontem ul. Żelaznej w Kielcach (Polska) stanowiącej główny ciąg komunikacyjny zostawano, w celu zapewniania w długim okresie eksploatacji wymaganej szorstkości nawierzchni, wykonanie warstwy ścieralnej z mieszanki SMA z kruszywem z piaskowca kwarcytowego. W celu zapewnienia prawidłowej adhezji asfaltu do kruszywa zastosowano wapno hydratyzowane i jako środek kontrolny aminę kwasu tłuszczowego

2. Właściwości mieszanki SMA

Modernizowaną konstrukcję nawierzchni ul. Żelaznej w 1999 roku zaprojektowano z wykorzystaniem technologii recyklingu głębokiego na zimno. Na podstawie wykonanych pomiarów ruchu pojazdów określono kategorie ruchu na KR4.

Konstrukcja nawierzchni odpowiadała wymaganiom przedstawionym w wytycznych opracowanych przez IBDiM [13]. Składała się ona z warstwy recyklowanej podbudowy w technologii na zimno o grubości 20 cm z zastosowaniem emulsji asfaltowej i cementu oraz materiału istniejących warstw asfaltowych i podbudowy kamiennej. Następną warstwą jest warstwa wiążąca o grubości 8 cm wykonana z betonu asfaltowego i warstwa ścieralna z mieszanki SMA o grubości 4,0 cm [14]. Pod nową konstrukcją nawierzchni znajdowała się jeszcze warstwa kruszywa o zmiennej grubości od 15 do 24 cm, które pozostało z poprzedniej konstrukcji nawierzchni. Konstrukcja nawierzchni została zaprojektowana na 20 lat eksploatacji

2.1. Program badań

Program badań dotyczący określenia wpływu rodzaju środka adhezyjnego (wapna hydratyzowanego i aminy kwasu tłuszczowego) na właściwości mieszanki SMA i jej trwałość w aspekcie zastosowanego kruszywa kwarcytowego podzielono na dwa etapy – laboratoryjny i eksploatacyjny. W ramach pierwszego etapu (laboratoryjnego) szczególną uwagę zwrócono na zaprojektowanie mieszanki mineralnej oraz wykonanie niezbędnych badań pozwalających dokonać oceny wpływu wapna hydratyzowanego i aminy kwasu tłuszczowego na właściwości SMA.

Szczegółowy program badań pierwszego etapu polegał na określeniu:

- właściwości normowych mieszanki SMA,
- odporności na powstawanie kolein mieszanki SMA,

– odporności na oddziaływanie wody oraz wody i mrozu mieszanki SMA (PANK 4302 i SHTO T283, określając wskaźnik odporności na oddziaływanie wody WR_w oraz wskaźnik odporności na oddziaływanie wody i mrozu WR_{wm}).

Istotnym elementem badań była ocena jednorodności wykonywanych prac. Do badań przyjmowano tylko próbki, w których zawartość wolnych przestrzeni zawierała się w przedziale (V - 2s ; V + 2s), gdzie: V – średnia wartości wolnych przestrzeni w mieszance SMA, s – odchylenie standardowe zawartości wolnych przestrzeni w badanych mieszankach SMA.

Należy podkreślić, że większość badań w 1999 roku wykonano zgodnie z wówczas stosowaną w Polsce metodyką badawczą.

2.2. Projekt mieszanki mineralnej

Opracowując mieszankę mineralną SMA kierowano się założeniem, że w mieszance mineralnej oprócz odpornego na proces ścierania i polerowania kruszywa kwarcytowego, którego zawartość może wahać się w przedziale od 50% do 70%, powinno znajdować się również kruszywo o mniejszej odporności na te procesy tj. kruszywo dolomitowe lub wapienne.

Zaprojektowano mieszankę mineralną SMA wykorzystując następujące rodzaje kruszywa: piaskowiec kwarcytowy (Q), dolomit (D) oraz wapień dewoński (L). Zastosowano również w jej składzie wypełniacz podstawowy zawierający 95% węglanu wapnia $CaCO_3$.

Podstawowe parametry kruszywa takie jak odporność na rozdrobnienie wg metodyki Los Angeles (EN 1097-2), odporność na oddziaływanie wody i mrozu (PN-S-11112), nasiąkliwość wagową oraz wskaźnik PSV (EN 1097-8) przedstawiono na rysunku 1.

Na podstawie wykonanych badań dokonano oceny przydatności badanych kruszyw do mieszanki SMA.

Projekt mieszanki mineralnej SMA 0/12,8 opracowanej zgodnie z wytycznymi IBDiM [14] zestawiono w tabeli 1.

Wapno hydratyzowane (HL) dodawano do mieszanki mineralnej wprowadzając go zamiennie do wypełniacza mineralnego w ilości 10, 20, 30, 40 i 50%. Po dokładnym wymieszaniu wapna hydratyzowanego z wypełniaczem wapiennym uzyskiwano wypełniacz mieszany.

2.3. Właściwości mieszanki SMA

Właściwości rekomendowanej mieszanki SMA z wapnem hydratyzowanym oraz aminą kwasu tłuszczowego zestawiono w tabeli 2.

Dokonując analizy wpływu rodzaju zastosowanego środka adhezyjnego na właściwości mieszanki SMA można stwierdzić, że przy rekomendowanej ich zawartości praktycznie uzyskano bardzo porównywalne wartości badanych parametrów. Niewiele korzystniejsze jest zastosowanie wapna hydratyzowanego w porównaniu z aminą kwasu tłuszczowego w składzie mieszanki SMA.

3. Program badawczy eksploatowanej nawierzchni SMA

W 1999 roku wykonana została z mieszanki SMA warstwa ścieralna odcinka doświadczalnego dwujezdniowej nawierzchni ul. Żelaznej w Kielcach. Na jezdni północnej (sekcja I) wbudowano mieszankę SMA z dodatkiem wapna hydratyzowanego, a na jezdni południowej (sekcja II) wybudowano SMA z płynnym środkiem adhezyjnym.

Szczególną uwagę w czasie badania powierzchni nawierzchni SMA zwracano na wpływ czynników klimatycznych, a zwłaszcza oddziaływanie wody i mrozu na jej trwałość w aspekcie zastosowanego rodzaju środka adhezyjnego. Wyróżniono sześć typów zniszczeń nawierzchni, które mogą być spowodowane oddziaływaniem czynników klimatycznych oraz składem mieszanki mineralno-asfaltowej z określonym rodzajem środka adhezyjnego (tab. 3).

Analiza przedstawionych wyników pomiarów stanu powierzchniowego w aspekcie odporności na oddziaływanie wody i mrozu nawierzchni SMA pokazuje, że zastosowane środki adhezyjne (wapno hydratyzowane, amina kwasów tłuszczowych) skutecznie spełniają swoje zadanie. Po okresie 12 lat eksploatacji nawierzchni SMA można stwierdzić, że jej stan powierzchniowy niezależnie od rodzaju zastosowanego środka adhezyjnego jest bardzo dobry.

Dokonując oceny makroskopowe stanu nawierzchni SMA sekcji I i II można stwierdzić, że praktycznie nie widać występowania na niej uszkodzeń powierzchniowych oraz kolein.

4. Właściwości nawierzchni SMA po 12 latach eksploatacji

Zgodnie z planem badań dokonano oceny następujących właściwości warstwy nawierzchni wykonanej z mieszanki SMA:

– zawartość wolnych przestrzeni Vm, zgodnie z PN-EN 12697-8,
– odporność na oddziaływanie wody ITSR, zgodnie z PN-EN 12697-12 i WT2 z 2010 roku,
– odporność na oddziaływanie wody [1].

Zawartość wolnych przestrzeni w nawierzchni SMA oraz jej odporność na oddziaływanie wody ITSR, zgodnie z PN-EN 12697-12 i WT2 z 2010 roku oraz odporność na oddziaływanie wody wg [1], charakterystyczną dla sekcji I i II określone w koleinie

(RD) i poza koleiną (N) przedstawiono graficznie na rysunkach 2, 3 i 4.

Analiza wyników badań pozwoliła stwierdzić, korzystny wpływ wapna hydratyzowanego na analizowane parametry nawierzchni SMA. Okazał się on jeszcze bardziej korzystny w przypadku nawierzchni w koleinie, niż w nawierzchni bez deformacji trwałych.

5. Wnioski

Na podstawie wykonanych badań laboratoryjnych oraz terenowych w czasie 12 lat eksploatacji nawierzchni SMA można sformułować następujące wnioski:

– wodo- i mrozoodporność mieszanki SMA ulega poprawie w wyniku zastosowania wapna hydratyzowanego w porównaniu z wykorzystaniem amin kwasów tłuszczowych;
– wapno hydratyzowane odgrywa istotną rolę z zapewnieniu trwałości mieszanki SMA w zakresie oddziaływania czynników klimatycznych, szczególnie w przypadku zastosowania w niej kruszywa o dużej zawartości krzemionki np. piaskowca kwarcytowego;
– wapno hydratyzowane może być stosowane w mieszance SMA zastępując ciekłe środki adhezyjne (aminy kwasów tłuszczowych) wpływając na poprawę odporności nawierzchni na oddziaływanie wody i mrozu;
– stan powierzchniowy nawierzchni SMA z dodatkiem wapna hydratyzowanego (30% w wypełniaczu) w okresie 12 lat eksploatacji jest porównywalny z nawierzchnią SMA w której zamiennie stosowano jako środek adhezyjny aminę kwasu tłuszczowego, a nawet nieznacznie lepszy;
– zastosowanie wapna hydratyzowanego w ilości 30% w składzie wypełniacza wapiennego zapewniło trwałość nawierzchni wykonanej z mieszanki SMA, modyfikowanej 4% polimeru SBS w okresie 12 lat jej eksploatacji.

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MODAL ANALYSIS OF SELECTED BAR DOMES

Abstract
The research paper presents the results of a modal analysis of selected bar domes. The description of geometry and physical features is based on specialist literature. A module added to the computer programme permitted the performance of dynamic calculations. The numerical models were developed using Autodesk Robot, implemented into the MES3D. The static and dynamic tests confirmed the correctness of the performed calculations. The paper presents some results of a modal analysis. Computational models presented here will be used in the analysis of the dome reliability in the case of dynamic loads.

Keywords: bar domes, normal mode vibrations, resonance

1. Introduction. Historical background

Domes, which as architectural structures are among the most outstanding achievements of human civilization, had their beginning in the fourth millennium BC when reed huts with a circular or oval base were covered with domed roofs. Over the centuries domes have acquired different shapes: cupola, semi-circular, semi-elliptical, pointed-arch or bulbous. Continuous cupolas built over circular, elliptical, or polygonal compartments were placed on a wall or drum. The construction of domes involved the application of stone blocks or bricks in the shape of a wedge (arch stones/blocks) [2].

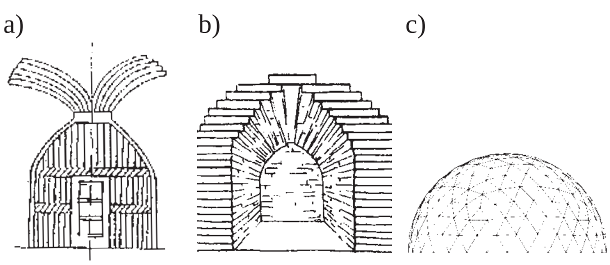


Fig. 1. Development of domes over the centuries: a) reed hut – app. IV century BC [1], b) false underground vault [2], c) geodesic dome [3]

Domes can be classified according to several criteria. With respect to the structure, domes can be defined as continuous or bar ones. The continuous dome underwent a gradual transformation from a covering of an opening in the wall, through a covering of a quadrilateral area, to the dome proper with a hemispherical vertical cross section. The shape of such a dome is generally connected with a classical double curved surface of revolution which is formed by the rotation of a curved or straight line around a vertical axis going through the highest central point [2].

Bar domes began to be constructed in the 19th century, when the steel and cast iron production technology was developed. The idea was to produce a lightweight structure, easy to assemble and disassemble, which covers very large spans. The methods applied in their calculation are relatively simple, especially when using a computer.

With respect to the arrangement of the bars, domes can be divided into: longitudinal-latitudinal, lamella, latitudinal-spiral and geodesic [7].

2. The phenomenon of resonance

To talk about the phenomenon of resonance, one must first define the concept of normal mode (natural) vibrations. Each elastic body is characterized by normal mode vibrations of constant periods. Floorboards, building walls, window panes etc. are all subject to vibration. The light impulses (shocks) which a vibrating body receives from the outside, may affect the vibration amplitude in different ways. The impulses directed opposite to the velocity cause

Fig. 2. General view of the CUS building in Psary

the vibration damping, whereas those directed in line with the velocity – increase the vibration amplitude.

The vibration amplitude increases to infinity when the impact frequency of the exciting force coincides with the normal modes frequency of the structure. Then the system is said to have got into resonance.

In present days with numerous hurricanes and natural disasters, the phenomenon of resonance has become very common. The failures of structures are caused by the increased vibration amplitude resulting from vehicle or human movement, wind pressure or flow, earthquakes and machines operation. In the case of oscillating vibrations, material fatigue is to be observed [4]. As a consequence, structures may collapse and window panes in vehicles or factory halls may crack. In engineering the resonance is a very dangerous phenomenon. A bridge may become damaged due to the vibrations caused by vehicles or a military column marching in unison.

Preventing the resonance is the responsibility of designers and it generally involves incorporating elasticity in the design to reduce the transmission of vibrations and to damp the already existing ones [5].

3. Examples of calculations

The further discussion will focus on the analysis of the reliability of the domes when subjected to dynamic loads. While numerous computer programmes can be applied to solve the eigenproblem, the difficulties of connecting them to the STAND – a destination system for performing the tests – led to the decision of using the individually developed MES3D programme. A calculation module was included in the programme, permitting the solution of the full eigenproblem for any matrix. It made use of the Lapack library procedures developed in the universities of Tennessee, Berkley and Denver [6] in the years 2006-2012.

This paper presents the results obtained for a number of selected steel domes. The first of them is located on top of the former Satellite Services Centre in Psary (Fig. 2). The structure, which rests on a reinforced concrete roof plate, spans 12 metres and has the height of 6 metres. The loadbearing structure is composed of 24 longitudinal supporting members made from RP120x60x4 profiles connected to 2L60x60x6 latitudinal members by means of rigid joints. The calculation model, which provided the basis for the preparation of the data for the MES3D, was developed in the Autodesk Robot. The programme used the elements of a spatial frame with six degrees of freedom in the node. The structure was made up of 144 nodes and 280 members. The dynamic analysis did not take into account the weight of the covering or additional elements. The correctness of the model was verified by static tests, which confirmed that the solutions were fully consistent with the Robot programme.

Figures 3 and 4 show the vibration forms determined in both programmes. They differ slightly, due to the fact that the calculations were performed with the application of different inertia matrices and with a different level of the accuracy.

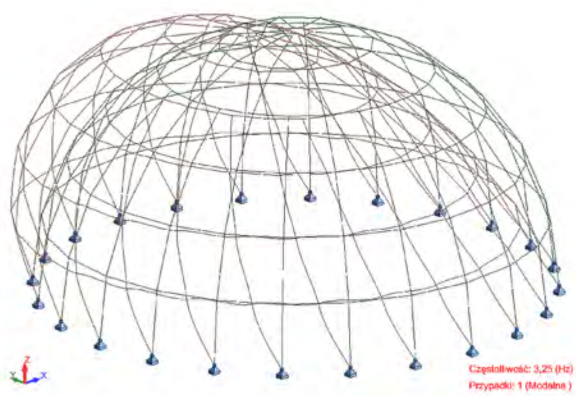


Fig. 3. The first form of normal modes – Robot

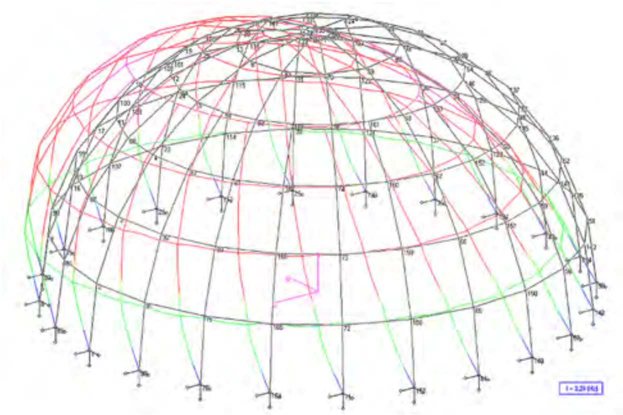


Fig. 4. The first form of normal modes – the MES3D

a)

b)

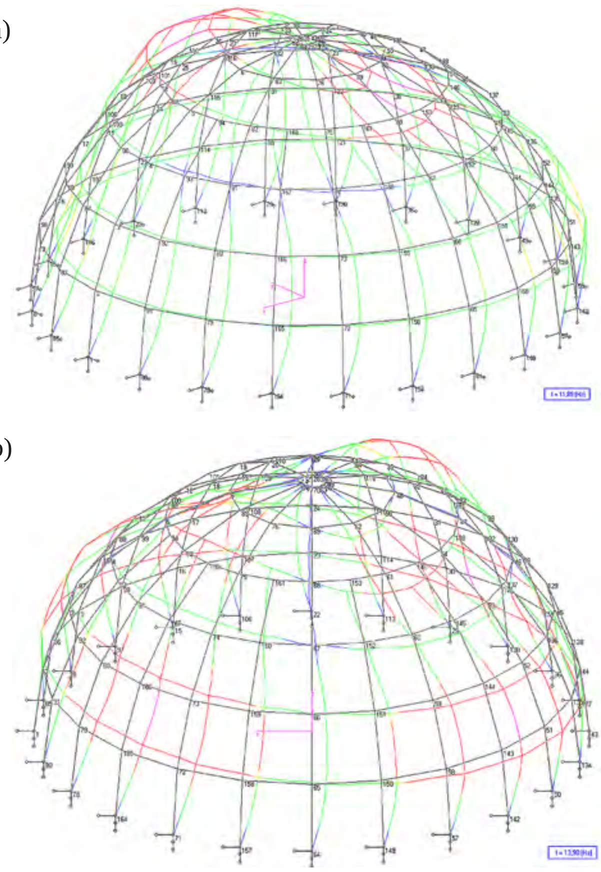


Fig. 5. Further forms of vibrations – the MES3D: a) the fourth, b) the sixth

A further figure show the results obtained for a dome with a bar structure arranged on a hexagonal base. Due to a lack of reference to an actual object, the characteristics were provided by the authors [8]. The calculation model was made with the application of frame elements; the structure consists of 20 nodes and 25 members. The obtained vibration forms are presented in Figure 6.

a)

b)

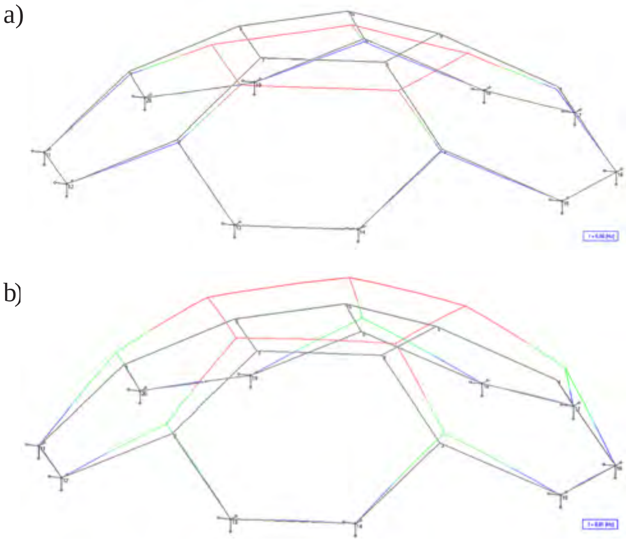


Fig. 6. Dome 2 vibration forms: a) the first, b) the fourth

a)

b)

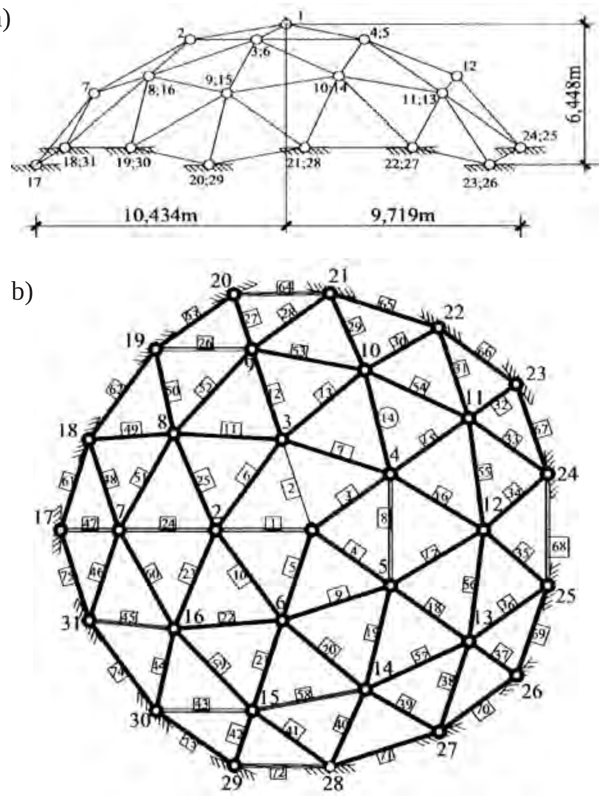
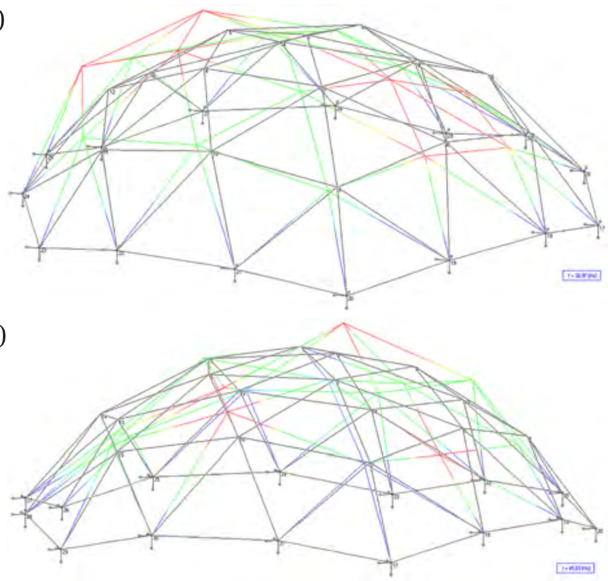


Fig. 7. Geodesic dome diagram: a) bar dome geometry, b) lattice [9]

The next diagrams show the solutions for a geodesic dome in Figure 7. The geometry is based on the research paper [9]. The RO108x10 profiles were adopted. A spatial truss element was applied in the description of the structure; the numerical model was characterized by 31 nodes and 93 degrees of freedom. The selected forms of normal mode vibrations are presented in Figure 8.



a)

b)

Fig. 8. Forms of geodesic dome vibrations: a) the first, b) the fourth

4. Conclusions

The paper presents the results of a modal analysis of three bar domes. A module was developed to perform this type of calculations. The numerical tests confirmed the correctness of the programme and of the provided calculation models. The further analyses will focus on continuous domes with triangular disc-plate elements used for their modelling. The structures will be subject to the dome reliability analysis in the context of dynamic problems.

References

[1] Muszyński W.: *Wpływ materiału na rozwój konstrukcji. Architektura i Budownictwo.* Zeszyt Specjalny nr 1. Politechnika Krakowska. Kraków (1966), pp. 351–410.

[2] Mirski J.: *Geneza i morfologia kopuł pełnościennych.* Kwartalnik Architektury i Urbanistyki. Tom XLVII. Zeszyt 2/2002. Warszawa (2003), pp.126–146.

[3] *http://www.geometer.org/mathcircles/geodesic.pdf*

[4] Lewandowski R.: *Dynamika konstrukcji budowlanych*, Politechnika Poznańska, Poznań 2006.

[5] Lewandowski R., *Redukcja drgań konstrukcji budowlanych*, Wykład obieralny 2002, 03.

[6] *http://www.netlib.org/lapack/*

[7] Kowal Z. i inni: Rozdz. 2. *Hale o dużych rozpiętościach*. Poradnik projektanta konstrukcji metalowych. T. 2. Praca zbiorowa pod kierunkiem W. Boguckiego, Arkady, Warszawa 1982.

[8] Pilarska D.: *Geometria i stateczność dwóch rodzin struktur prętowych jedno i dwuwarstwowych kopuł sferycznych*. Praca doktorska wykonana w Katedrze Architektury i Urbanistyki, Kielce 2012.

[9] Radoń U.: *Zastosowanie metody FORM w analizie niezawodności konstrukcji kratowych podatnych na przeskok*. Monografie, studia, rozprawy nr M27. Kielce 2012.

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Analiza modalna wybranych kopuł prętowych

1. Wprowadzenie. Rys historyczny

Kopuły jako obiekty architektoniczne należą do najbardziej wybitnych osiągnięć cywilizacyjnych ludzkości i swój początek miały już w IV tysiącleciu p.n.e. jako trzcinowe chaty o podstawie kołowej lub owalnej, sklepione kopulastym dachem. W ciągu wieków kopuły zaczęto budować jako sklepienia o kształcie czaszy, półkoliste, półeliptyczne, ostrołukowe lub cebulaste. Pełnościenne czasze były oparte na murze lub bębnie, budowane nad pomieszczeniami o planie kolistym, eliptycznym albo wielobocznym. Do budowy kopuł używano ciosów kamiennych lub cegieł w kształcie klina (klińców) [2].

Kopuły można klasyfikować według wielu kryteriów. Ze względu na ich konstrukcję możemy je podzielić na pełnościenne i prętowe. Kopuły pełnościenne stopniowo przechodziły od przekryć otworów w murach, poprzez nakrycia powierzchni czworobocznych, aż do właściwej kopuły o kształcie półkolistym w przekroju pionowym. Kształt takiej kopuły najczęściej wiąże się z klasyczną powierzchnią obrotową dwukrzywiznową, która powstaje poprzez obrót linii krzywej lub prostej wokół pionowej osi przechodzącej przez najwyżej położony punkt centralny [2].

Kopuły prętowe zaczęto konstruować w XIX w., kiedy nastąpił rozwój technologii produkcji stali i żeliwa. Kierowano się przy tym stworzeniem lekkiej konstrukcji łatwej w montażu i demontażu, która przekrywa bardzo duże rozpiętości. Do ich obliczeń można zastosować stosunkowo proste metody obliczeniowe, zwłaszcza przy zastosowaniu komputerów.

Ze względu na układ prętów kopuły możemy podzielić na: południkowo-równoleżnikowe, lamella, równoleżnikowo- spiralne, geodezyjne [7].

2. Zjawisko rezonansu

Aby mówić o zjawisku rezonansu musimy najpierw zdefiniować pojęcie drgań własnych.

Każde ciało sprężyste charakteryzuje się drganiami własnymi o stałym okresie. Drgają deski podłogi, ściany budynków, szyby w oknach itd. Gdy ciało drgające otrzymuje z zewnątrz lekkie impulsy (uderzenia) mogą one wpływać na amplitudę drgań w różny sposób. Impulsy skierowane przeciwnie do prędkości drgań powodują ich tłumienie, zgodne – powodują zwiększenie amplitudy drgań.

Amplituda drgań rośnie do nieskończoności, gdy częstość oddziaływania siły wymuszającej pokrywa się z częstością drgań własnych konstrukcji. Mówimy wtedy, że układ wpadł w rezonans.

Zjawisko rezonansu w obecnych czasach licznych huraganów i kataklizmów stało się bardzo powszechne. Za awarie obiektów odpowiedzialny jest wzrost amplitudy drgań wywołany ruchem pojazdów lub ludzi, parciem lub opływem wiatru, trzęsieniem ziemi lub maszynami. Jeżeli drgania przyjmują charakter oscylacyjny dochodzi do zjawiska zmęczenia materiałowego [4]. W konsekwencji może dojść do zawalenia się obiektu, pękania szyb w pojazdach lub halach fabrycznych. Zjawisko rezonansu jest bardzo niebezpieczne w technice. Most może ulec zniszczeniu na skutek drgań wywołanych przez przejeżdżające pojazdy, lub przez kolumnę wojskową maszerującą równym krokiem.

Przeciwdziałanie występowaniu rezonansu leży w gestii projektantów i najczęściej obejmuje elastyczne projektowanie obiektów redukujące przenoszenie się drgań oraz tłumienie drgań już istniejących [5].

3. Przykłady obliczeniowe

Tematem dalszych rozważań autorów będzie analiza niezawodności kopuł w przypadku obciążeń dynamicznych. Rozwiązywanie problemu własnego opisującego zagadnienie jest możliwe w wielu programach komputerowych. Ze względu na trudności w podpięciu ich do systemu STAND, w którym docelowo będą wykonywane badania, zdecydowano się na wykorzystanie autorskiego programu MES3D. Dołączono do niego moduł obliczeniowy, umożliwiający rozwiązywanie pełnego zagadnienia własnego dla dowolnych macierzy. Wykorzystano w nim procedury biblioteczne Lapack opracowane w latach 2006–2012 na uniwersytetach Tenessee, Berkley i Denver [6].

W niniejszej pracy przedstawiono wyniki uzyskane dla wybranych kopuł stalowych. Pierwsza z nich znajduje się na budynku byłego Centrum Usług Satelitarnych w Psarach (rys. 2). Konstrukcja ma 12 m rozpiętości, 6 m wysokości i opiera się na żelbetowej płycie stropu. Układ nośny zbudowany jest z 24 południkowych elementów wsporczych wykonanych z profili RP120x60x4 sztywno połączonych z elementami równoleżnikowymi 2L60x60x6. Model obliczeniowy został zbudowany w programie Autodesk Robot, na jego podstawie przygotowano dane do programu MES3D. Wykorzystano w nim elementy ramy przestrzennej o 6 stopniach swobody w węźle. Układ liczył 144 węzły i 280 elementów. W analizie dynamicznej pominięto masę przekrycia i elementów dodatkowych. Poprawność modelu zweryfikowano wykonując testy statyczne. Uzyskano w nich pełną zgodność rozwiązań z programem Robot.

Na rysunkach 3 i 4 pokazano formy drgań wyznaczone w obydwu programach. Różnią się one nieznacznie między sobą, co związane jest z wykorzystaniem w obliczeniach różnych macierzy bezwładności i poziomem dokładności wykonywanych obliczeń.

Na rysunku 5 przedstawiono wyniki uzyskane dla kopuły z układem prętów zbudowanym na bazie sześciokąta. Ze względu na brak odniesienia do obiektu rzeczywistego wykorzystano w nim charakterystyki przedstawione przez autorów [8]. W modelu obliczeniowym wykorzystano elementy ramowe, układ zawiera 20 węzłów i 25 elementów. Uzyskane formy drgań przedstawiono na rysunku 6.

Kolejne plansze pokazują rozwiązania dla kopuły geodezyjnej przedstawionej na rysunku 7. Geometrię zaczerpnięto z pracy [9]. Przyjęto profile RO108x10. Do opisu konstrukcji wykorzystano element kratownicy przestrzennej, model numeryczny zawierał 31 węzłów i 93 stopnie swobody. Wybrane formy drgań własnych przedstawiono na rysunku 8.

4. Wnioski

W pracy przedstawiono wyniki analizy modalnej trzech kopuł prętowych. Zbudowano moduł umożliwiający wykonywanie tego typu obliczeń. Wykonano testy numeryczne potwierdzające poprawność programu oraz zbudowanych modeli obliczeniowych. Kolejne analizy dotyczyć będą kopuł pełnościennych, do ich zamodelowania zostaną wykorzystane trójkątne elementy płytowo-tarczowe. Układy te zostaną wykorzystane w analizie niezawodności kopuł w przypadku zagadnień dynamicznych.

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INFLUENCE OF SYNTHETIC WAX F-T ON AGING OF ROAD BITUMEN 35/50

Abstract
The research and analysis presented in this papers is to assess the influence of Fischer-Tropsch synthetic wax on road bitumen 35/50 aging. The scope of the research include: penetration at 25°C, the softening temperature according to the method of "Ring and Ball", Fraass breaking point and dynamic viscosity at 60°C and 135°C. The research show that bitumen modified by synthetic wax are characterized by a significant increase in the softening point and a smaller change in penetration. Moreover, research show an increase in brittleness temperature, increase in viscosity at 60°C in each case the amount of added synthetic wax and the viscosity value at 135°C notes a smaller increase.

Keywords: Synthetic Wax F-T, viscosity, bitumen 35/50, aging

1. Introduction

In recent years there has been rapid development of modern technologies of production and paving asphalt mixes in order to reduce interference with the surrounding environment. Primarily technologies are currently being developed to produce asphalt mixes with such technology as WMA (Warm Mix Asphalt). This technology is characterized by lower production temperature of asphalt mixes than produced traditionally, with identical physical and mechanical parameters.

One way to reduce the temperature of the production of asphalt mixes is the use of so-called low-temperature binder. These are road bitumen containing additional ingredients to lower the viscosity of asphalt at high temperatures. One of these ingredients is a synthetic wax produced by the Fischer-Tropsch synthesis [4]. Addition of a small amount of synthetic wax lowers the viscosity of the asphalt mixture all at temperatures above 130°C, thereby allows proper mixture surrounding of mineral aggregate grains at a lower temperature [1]. Through the use of binders at low temperature can lower the temperature of the production and incorporation of mineral mixture – asphalt about 30°C, it leads to the energy saving during production of the mixture and lowering the emission of volatile compounds of asphalt [3].

The use of this type of modified binders also has a direct impact on improving the properties of asphalt mixtures, resulting in increased resistance to permanent deformation, and fatigue life. It should be noted that the durability of asphalt pavements is largely dependent on the course of aging processes, which result in reducing the value of the physical and chemical parameters and rheological properties of asphalt [7]. Degradation of asphalt parameters, causing deterioration in quality of the performed asphalt layer, as well the pavement structure.

The aging of asphalt binders can be divided into two main stages: technological aging (short-term) involving the process of storage, production and incorporation of asphalt mixture and exploitation aging (long-term) covering the service life of the pavement, during which it is influenced by the climatic conditions and the impact factors of environment [3]. The most intensive processes occur during the aging of asphalt mixing with hot aggregate in the paving mixer. The temperature is then highest (approximately 160–180°C), and the aggregate asphalt layer is thinnest. Evaporation occurs in oil fractions and rapid oxidation of asphalt [4]. Currently, the issue of aging low-viscosity asphalt is not quite well understood due to the complexity of the processes during aging [2, 4, 5].

This paper presents the results of the laboratory tests of the impact of synthetic wax modified with Fischer-Tropsch on the properties of asphalt bitumen 35/50 subject to technological aging using the method RTFOT.

2. Methodology and test results

In the research to determine the effect of aging of the synthetic wax, as an input material bitumen 35/50 were used. As the modifier Fischer-Tropsch synthetic wax (present in granular form) was used. The wax was added in the amounts of 1.5, 2.0, 2.5 and 3.0%.

The samples were subjected to laboratory testing, indicating basic standardized properties:

– penetration at 25°C, according to PN-EN 1426,
– softening point „Ring and Ball", according to PN-EN 1427,
– Fraass breaking point, according to PN-EN 12593,
– dynamic viscosity at temperature 60°C and 135°C.

Next all the binders were subject to simulated aging in the laboratory using the Rolling Thin Film Over Test (RTFOT) method by PN-EN12607-1. Assessment of the resilience of the synthetic wax-modified asphalt aging was based on the analysis of changes in their properties as a result of aging simulated in the laboratory.

2.1. The effect of the additive on the basic parameters of bitumen after aging

Changes the basic properties of the bitumen 35/50 before and after aging such as penetration and softening point, as a function of the amount of added modifier are shown in Figures 1-2.

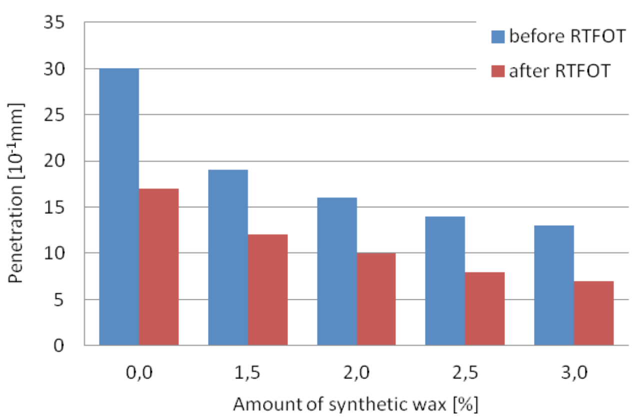

Fig. 1. Penetration at 25°C of bitumen 35/50 before and after aging RTFOT

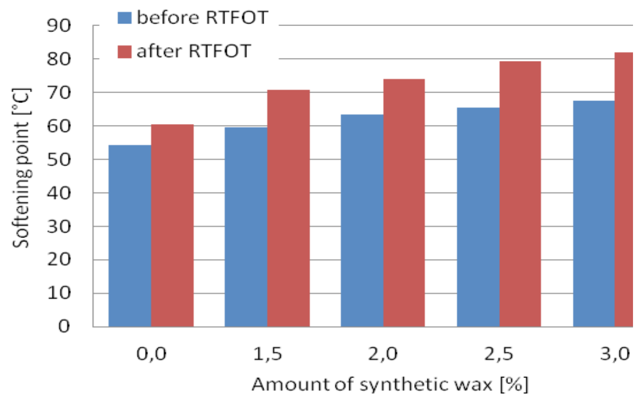

Fig. 2. Softening point "Ring and Ball" of bitumen 35/50 before and after aging RTFOT

Based on the analysis of the obtained results it can be concluded that the increase of synthetic wax additive cause a change of bitumen rheological characteristics. The aging process causes a stiffening of the bitumen, observed by decrease in the penetration and proportional increase in softening point. In the graph, we can see that the decrease of penetration with increasing quantities of added synthetic wax is much smaller than in the case of asphalt reference. For bitumen 35/50 containing 2.0% synthetic the smallest decrease of the penetration after aging wax observed. The highest increase of softening point was obtained for the wax content of 2-3%.

The results of Fraass breaking point before and after aging of modified bitumen are shown in Figure 3.

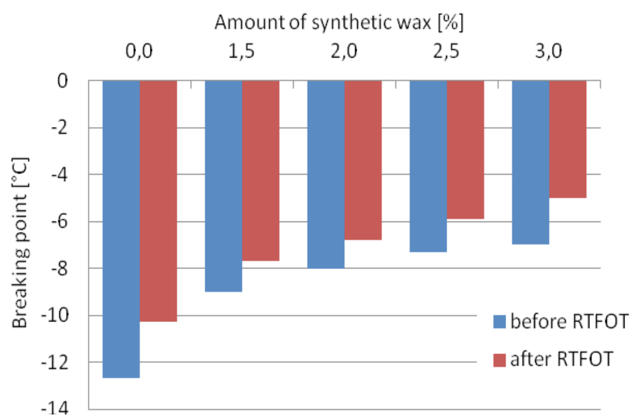

Fig. 3 Fraass breaking point of bitumen 35/50 before and after aging RTFOT

Based on the analysis of the test results it can be concluded that the temperature of brittleness increases with the amount of wax addition. Reference bitumen after aging with RTFOT method is characterized by increased Fraass breaking point about 2.5°C. The addition of synthetic wax F-T in the amount of 2.0% after aging is characterized by the smallest change in Fraass breaking point of approximately 1°C.

structure

2.2. Penetration index

On the basis of the test results of penetration at 25°C, softening point and breaking point specified penetration index (PI), which is the measure of thermal sensitivity of the bitumen. The change of penetration index (Fig. 4) was calculated according to DIN EN 12591 using the formula:

$$IP = \frac{20T_{PiK} + 500\log P - 1952}{T_{PiK} - \log P + 120} \tag{1}$$

where: T_{PiK} – softening point, °C, P – penetration at 25°C.

Subsequently, the temperature range of plasticity (TZP) defines the range of temperatures at which bitumen has viscoelastic properties. TZP was calculated using the formula:

$$TZP = T_{PiK} - T_{lam} \; [°C] \tag{2}$$

where: T_{PiK} – softening point, °C, T_{lam} – breaking point, °C.

Changes in the value of penetration index and plasticity temperature range of bitumen 35/50 modified synthetic wax F-T are shown in Figures 4 and 5.

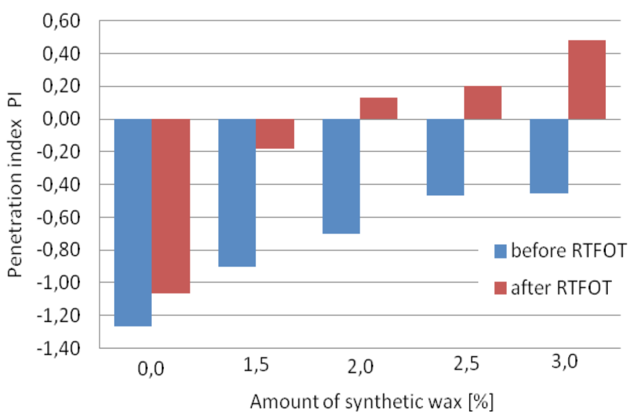

Fig. 4 Penetration index bitumen 35/50 before and after aging RTFOT

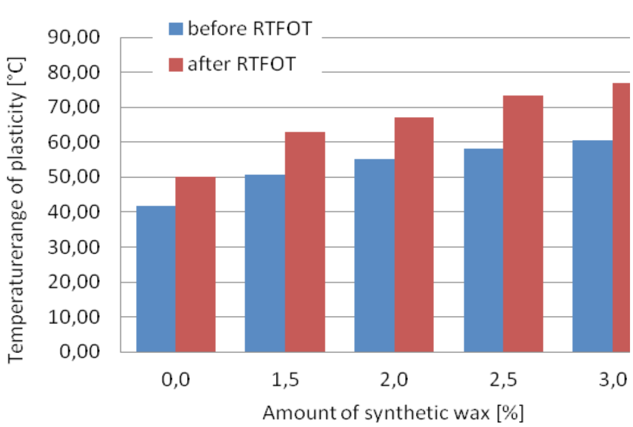

Fig. 5. Temperature range of plasticity bitumen 35/50 before and after aging RTFOT

Results shown prove that with increasing amount of addition of wax penetration index increased. In the case of the reference bitumen after aging RTFOT an increase is negligible. The largest increase of penetration index was obtained after aging of bitumen 35/50 with the content of synthetic wax 1.5-2.0%, thereby resulting in a greater resistance to temperature changes. Temperature range of plasticity after aging in all cases increased, which means that it can increase the temperatures at which the bitumen retains its viscoelastic properties. Synthetic wax in the amount of over 1.5% caused that the temperature range of plasticity is maintains above 60°C.

2.3. Dynamic viscosity

An important element of the study was to evaluate the effect of the synthetic wax F-T on the dynamic viscosity at 60°C and 135°C bitumen 35/50 subjected to technological aging (Figs. 6-7). Viscosity is one of the fundamental rheological properties of bitumen [2, 9]. It should be noted that it is one of the most important parameters to assess the behavior of bitumen in the case of long-term asphalt load of pavement surface by vehicle as well as the parameter indicating the possibility of the production of asphalt mixture at low temperatures.

The results of changes bitumen 35/50 in the value of dynamic viscosity at 60°C and 135°C are shown in Figures 6 and 7.

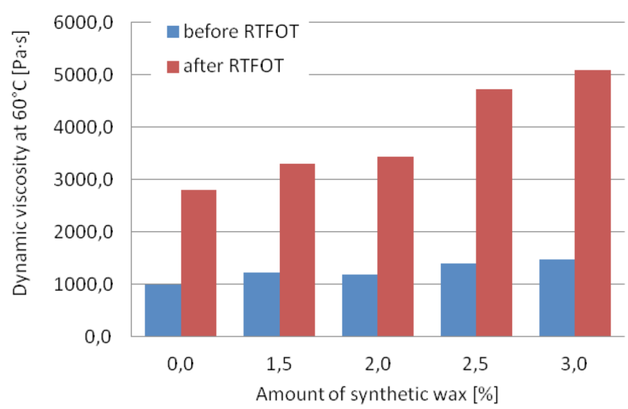

Fig. 6. Dynamic viscosity of bitumen 35/50 at 60°C before and after aging RTFOT

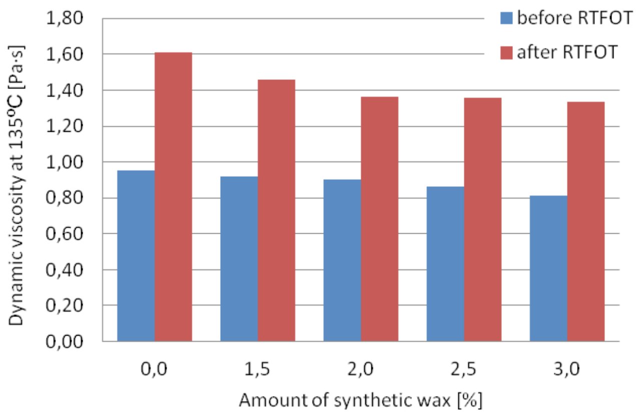

Fig. 7. Dynamic viscosity of bitumen 35/50 at 135°C before and after aging RTFOT.

Based on analysis of the test results shown in Figure 6 and 7, it can be seen that with increasing content of synthetic wax at 60°C a significant increase occurs in the dynamic viscosity of the bitumen by RTFOT aging in relation to the dynamic viscosity before aging. In the case of temperature of 135°C with increasing amounts of synthetic wax after aging a decrease in viscosity is observed, thus contributing to the proper coating of binder aggregate. The amount of synthetic wax 2–3% causes the lowest viscosity increase in after aging compared to the reference bitumen.

3. Conclusions

On the basis of research of bitumen 35/50 with the addition of synthetic wax F-T subjected to the aging process the following conclusions can be drawn:

- technological aging causes a decrease in the penetration and softening temperature rises resulting in hardening of bitumen with increasing amounts of synthetic wax F-T,
- addition of synthetic wax F-T in the amount of 2.0% causes a slight increase in Fraass breaking point of bitumen after aging,
- increase in the amount of synthetic wax addition leads to an increase in the thermal sensitivity of the bitumen as a result of aging by increasing penetration index and plasticity range of temperature increase,
- taking the viscosity increase as the assessment measure of aging, it can be concluded that bitumen modified with 2.0% synthetic wax F-T is most resistant to changes of the rheological properties.

References

[1] Błażejowski K., Styk S.: *Technologia warstw asfaltowych*, WKiŁ, Warszawa 2009.

[2] Gaweł, J., Kalabińska, M., Piłat J.: *Asfalty drogowe*, WKiŁ, Warszawa 2001.

[3] Hurley G., Prowell B.: NCAT report 05-06. *Evaluation of Sasobit for use in warm mix asphalt*. Auburn, 2005.

[4] Iwański M., Mazurek G.: *Asphalt Concrete with Low-Viscosity Modifier*. Proceedings 2nd International Conference of Transport Infrastructures. São Paulo, Brazil, 4-6 August 2010, pp.167–176

[5] Iwański M., Mazurek G.: *The influence of the low-viscosity modifier on viscoelasticity behavior of the bitumen at high operational temperature*. 8th International Conference. Environmental Engineering. May 19-20, 2011, Vilnius, Lithuania, pp. 1097–1102.

[6] Iwański M., Mazurek G.: *Rheological charakteristics of syntetic wax-modified asphalt binders*. Polimery 2012, 57, nr 9, pp. 661-664

[7] Judycki J., Stienss M.: *Mieszanki mineralno-asfaltowe na ciepło – przegląd dodatków*. Drogownictwo nr 7-8, 2010, s. 227–232.

[8] Piłat J., Radziszewski P.: *Nawierzchnie asfaltowe*, WKiŁ, Warszawa 2010.

[9] Radziszewski P.: *Wpływ modyfikacji elastomerem SBS na właściwości reologiczne lepiszczy asfaltowych*. Polimery nr 7–8, 2008, s. 559–563.

[10] Trzaska E.: *Laboratoryjne metody badania procesu starzenia lepiszczy asfaltowych, symulujące starzenie technologiczne i eksploatacyjne*. Nafta-Gaz, czerwiec 2010, s. 500–506.

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Wpływ wosku syntetycznego F-T na starzenie asfaltu drogowego 35/50

1. Wprowadzenie

W Polsce opracowuje się obecnie technologie umożliwiające wyprodukowanie mieszanek mineralno-asfaltowych w technologii na ciepło WMA (ang. Warm Mix Asphalt) [4, 7]. Jedną z metod obniżenia temperatury wytwarzania mieszanki jest zastosowanie tzw. lepiszczy niskotemperaturowych. Są to asfalty drogowe zawierające dodatkowe składniki obniżające lepkość asfaltu w wyższych temperaturach. Jednym z takich składników jest wosk syntetyczny otrzymywany w procesie syntezy Fischera-Tropscha (F-T) [3, 5, 6, 7]. Jego zastosowanie umożliwia obniżenie temperatury produkcji i wbudowywania mieszanki mineralno-asfaltowej o około 30°C. Dzięki temu uzyskuje się oszczędność energii podczas produkcji mieszanki mineralno-asfaltowej oraz wpływa na obniżenie emisji lotnych związków asfaltu. Należy zaznaczyć również, że trwałość nawierzchni asfaltowych w dużym stopniu zależy od przebiegu procesów starzeniowych związanych z oddziaływaniem wysokiej temperatury na lepiszcze asfaltowe, w wyniku których następuje obniżenie wartości jego parametrów fizykochemicznych i reologicznych [10].

Najintensywniejsze procesy starzenia asfaltu zachodzą w czasie wytwarzania mieszanki mineralno-asfaltowej, kiedy lepiszcze łączy się z kruszywem w mieszalniku otaczarki. Oddziałująca temperatura jest wtedy najwyższa (wynosi około 160–180°C), a błonka asfaltu na kruszywie jest najcieńsza [2, 8, 9]. W konsekwencji występuje proces odparowania frakcji olejowych i szybkie utlenianie związków asfaltu [1, 2], powodując utratę jego właściwości lepko-sprężystych.

W artykule przedstawione wyniki badań laboratoryjnych wpływu wosku syntetycznego F-T na właściwości asfaltu drogowego 35/50 poddanego starzeniu technologicznemu za pomocą metody RTFOT.

2. Metodyka i rezultaty badań

Badaniach wpływu wosku syntetycznego F-T na zmianę właściwości lepiszcza wykonano wykorzystując asfalt drogowy 35/50. Wosk syntetyczny F-T dozowano do lepiszcza w ilości 1,5%, 2,0%, 2,5% i 3,0% w stosunku do jego masy. Następnie określono następujące właściwości asfaltu 35/50 modyfikowanego woskiem F-T:

- penetrację w temperaturze 25°C, zgodnie z PN-EN 1426,
- temperaturę mięknienia wg metody „Pierścień i kula”, zgodnie z PN-EN 1427,
- temperaturę łamliwości wg Fraassa, zgodnie z PN-EN 12593,
- lepkość dynamiczną w temperaturze 60°C i 135°C.

Modyfikowane lepiszcze z różnymi zawartościami wosku syntetycznego F-T poddano procesowi symulującemu starzenie technologiczne w warunkach laboratoryjnych, stosując metodę RTFOT (Rolling Film Over Test) wg normy PN-EN12607-1. Jako kryterium oceny wpływu dodatku wosku syntetycznego F-T na proces starzenia asfaltu 35/50 przyjęto zmianę jego właściwości przed i po oddziaływaniu czynnika temperaturowego.

2.1. Wpływ dodatku na podstawowe parametry asfaltu po procesie starzenia

Zmiany podstawowych właściwości asfaltu po procesie starzenia tj. penetracji i temperatury mięknienia w zależności od ilości modyfikatora (wosku syntetycznego F-T) przedstawiono na rysunkach 1-2.

Na podstawie analizy uzyskanych wyników badań można stwierdzić, że wzrost ilości dodatku wosku syntetycznego powoduje zmianę badanych właściwości asfaltu. Proces starzenia powoduje usztywnienie lepiszcza charakteryzowane obniżeniem penetracji oraz proporcjonalny wzrost temperatury mięknienia. Można stwierdzić, że obniżenie penetracji asfaltu 35/50 wraz ze wzrostem ilości dodatku wosku syntetycznego jest znacznie mniejsze niż w przypadku asfaltu referencyjnego. Najmniejszy spadek penetracji po procesie starzenia odnotowano dla asfalt 35/50 z zawartością 2,0% wosku syntetycznego. Natomiast największy wzrost temperatury mięknienia uzyskano dla zawartości wosku F-T w zakresie od 2% do 3%.

Wyniki zmiany temperatury łamliwości asfaltu 35/50 modyfikowanego woskiem syntetycznym F-T po starzeniu przedstawiono na rysunku 3.

Na podstawie analizy wyników badań można stwierdzić, że wartość temperatury łamliwości rośnie wraz z ilością dodawanego wosku. Asfalt referencyjny po starzeniu metoda RTFOT charakteryzuje się podwyższoną temperaturą łamliwości o 2,5°C. Zastosowanie dodatku wosku syntetycznego w ilości 2,0% do asfaltu 35/50 cechuje się najmniejszą zmianą jego temperatury łamliwości w zakresie około 1°C po procesie starzenia.

2.2. Indeks penetracji

Na podstawie wyników oznaczenia penetracji w temperaturze 25°C, temperatury mięknienia oraz temperatury łamliwości określono indeks penetracji (PI), będący miarą wrażliwości termicznej asfaltu.

Zamianę indeksu penetracji (rys. 4) określono zgodnie z normą PN-EN 12591 za pomocą wzoru (1). Następnie obliczono temperaturowy zakres plastyczności modyfikowanego asfaltu 35/50 (TZP) charakteryzowany zakresem temperatur, w których lepiszcze zachowuje właściwości lepko sprężyste (wzór (2)).

Zmiany wartości indeksu penetracji oraz temperaturowego zakresu plastyczności asfaltu 35/50 modyfikowanego woskiem syntetycznym przedstawiono na rysunkach 4 i 5.

Badania wykazały, że wraz ze wzrostem ilości dodatku wosku F-T nastąpił wzrost indeksu penetracji lepiszcza. W przypadku asfaltu referencyjnego po procesie starzenia RTFOT wzrost ten jest nieznaczny. Największy wzrost indeksu penetracji po starzeniu uzyskał asfalt 35/50 z zawartością 1,5–2,0% wosku syntetycznego. Temperaturowy zakres plastyczności po starzeniu we wszystkich zakresach dozowania wosku syntetycznego F-T do asfaltu 35/50 uległ wzrostowi. Tym samym zwiększył się zakres temperatur, w których modyfikowany asfalt zachowuje swoje właściwości lepko sprężyste. Należy zaznaczyć, że asfalt 35/50 modyfikowany woskiem syntetycznym w ilości powyżej 1,5% uzyskał temperaturowy zakres plastyczności powyżej 60°C.

2.3. Lepkość dynamiczna

Istotnym elementem badań była ocena wpływu dodatku wosku syntetycznego F-T na lepkość dynamiczną w temperaturze 60°C i 135°C asfaltu 35/50 poddanego starzeniu technologicznemu (rys. 6-7). Lepkość jest jedną z podstawowych właściwości reologicznych asfaltu [2]. Należy zauważyć, że jest ona jednym z najważniejszych parametrów oceny zachowania się lepiszcza w przypadku wystąpienia długotrwałych obciążeń nawierzchni drogowych ruchem pojazdów jak również parametrem decydującym o możliwości produkcji mieszanki mineralno-asfaltowej w obniżonej temperaturze.

Na podstawie analizy uzyskanych wyników badań (rys. 6-7) można stwierdzić, że wraz ze wzrostem zawartości wosku syntetycznego F-T w temperaturze 60°C następuje znaczny wzrost lepkości dynamicznej asfaltu 35/50 po starzeniu asfaltu metodą RTFOT w stosunku do jego lepkości dynamicznej przed starzeniem. W przypadku temperatury 135°C wraz ze wzrostem ilości wosku syntetycznego po procesie starzenia następuje spadek parametru lepkości, przyczyniając się tym samym do poprawnego obtoczenia ziaren kruszywa lepiszczem. W zakresie ilości od 2 do 3% dozowanego wosku syntetycznego F-T do asfaltu 35/50 lepkość charakteryzuje się najmniejszym przyrostem wartości po procesie starzenia w stosunku do asfaltu referencyjnego.

3. Podsumowanie

Na podstawie wykonanych badań asfaltu drogowego 35/50 z dodatkiem wosku syntetycznego Fischera-Tropscha poddanego starzeniu technologicznego RTFOT można sformułować następujące wnioski:

- starzenie technologiczne wraz ze wzrostem ilości wosku syntetycznego F-T powoduje spadek penetracji oraz wzrost temperatury mięknienia powodując usztywnienie asfaltu 35/50 niezależnie od ilości modyfikatora,
- dodatek wosku syntetycznego F-T w ilości 2,0% powoduje niewielki wzrost temperatury łamliwości asfaltu 35/50 po procesie starzenia,
- wzrost ilości dodatku wosku syntetycznego F-T powoduje zwiększenie wrażliwości termicznej asfaltu w wyniku starzenia, poprzez wzrost indeksu penetracji, jak i wzrost temperaturowego zakresu plastyczności,
- przyjmując za ocenę starzenia asfaltu przyrost lepkości dynamicznej można stwierdzić, że najbardziej odporny na zmiany reologiczne jest asfalt 35/50 modyfikowany 2,0% wosku syntetycznego.


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EXPERIMENTAL DETERMINATION OF THE WORKING FLUID VOLUME FOR OPTIMAL FUNCTION OF THE LOOP HEAT PIPE

Abstract
This experiment is concentrated on the working fluid of the heat pipe. The working fluid is an important part for the function of the heat pipe regarding the transfer of the heat. The measurements point out the appropriate quantity of the working fluid regarding the correct function of the loop heat pipe in the cooling of electronic components.

Keywords: loop heat pipe, heat transfer, cooling, working fluid

1. Introduction

Pass-heat device used in this experiment is called a loop heat pipe (LHP). It is a specific type of heat pipe in which the evaporator and condenser are separated and between them is transferred the operating liquid through the pipe. After the successful demonstration of the ability and reliability of heat transfer in space applications, the loop heat pipes experienced the attention of the world in 1990 [1]. Loop heat pipes are used in the space industry for cooling of electrical equipment on spaceships now [2]. Loop heat pipes are capable of passive cooling of equipment at normal operating conditions [3]. This phenomenon is often made use of in the design of solar water heaters, particularly of small capacities, too [4]. The first published analysis of thermosyphon solar water heater circuit was by Close [5]. There have been many other publications on the analysis of these systems but they are all based on the original formulation. For verifying the theoretical results, he tested two thermosyphon systems with different characteristics and the results conformed well to those predicted. Gupta et al. [6] modified the model of Close to take into account the heat exchange efficiency of the collector absorber plate, and thermal capacitance. Ong [7] extended the work of Close and Gupta et al. by using a finite difference solution procedure. The theoretical prediction of flow rate has been compared with the measured flow rate using dye trace inject. Zerrouki et al. [8] considered natural circulation of a compact thermosyphon solar water heating system produced and commercialized in Algeria. Their calculations and measurements were performed on mass flow rate, temperature rise and fluid and absorber temperatures inside the thermosyphon of parallel tube design. An increasing volume of data obtained by testing loop heat pipes in applications developed on Earth, scientists can work around the world in the development of loop heat pipes.

2. Designee of loop thermosyphon

The aim of the experiment is to compare the cooling effect, depending on the volume of filling. At the experiment loop thermosyphon was used, which is shown on Figure 1. The loop thermosyphon is composed of evaporator, condenser and transport pipeline. Evaporator is located in the lower part of the device. It composes of alumina of dimensions 115 x 80 x 30 mm (HxWxD), inside there is a system of four vertical holes of diameter 5 mm, hole pitch 15 mm. On the sides of the evaporator are holes of diameter 10 mm, for the inlet and outlet of the working substance. On the evaporator semiconductor device is mounted and connected to a laboratory power supply voltage and current, whose actions generate heat. To increase the heat transfer between semiconductor devices and evaporator heat conductive paste is used. Between the evaporator and semiconductor device the thermometer is located for temperature control of semiconductor devices as the prevention of heat failure. The condenser section is located at the top of the device. For this application heat exchanger was used, which composes of copper pipe with the ribs from sheet of steel. Dimensions of the heat exchanger: length 740 mm, width 140 mm, height 30 mm, 3 mm rib pitch. Pipe has a length of 1.5 m, diameter 10 mm and wall thickness of the pipe is 1 mm. The volume of the pipe is calculated as 301.6 ml. Transport pipe is composed from copper pipes, copper and brass fittings and thoroughfares, which are connected to evaporator and condenser with the soft solders and soldering technology. Diameter of a copper pipe is 10 mm, wall thickness 1 mm. The total length of the transfer pipe, including fittings and thoroughfares is 1 m. Pipeline volume is 50.3 ml

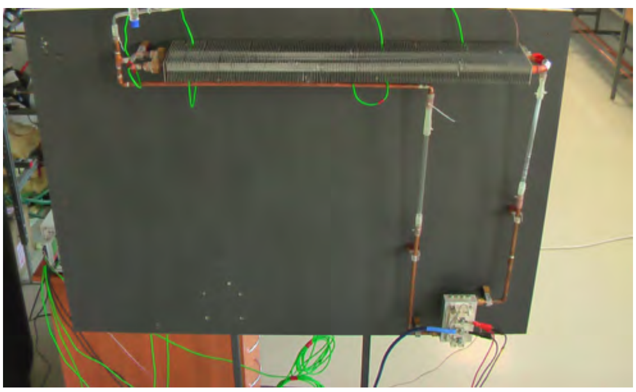

Fig. 1. Loop heat pipe

3. Characteristics of working substance

Working substance used in loop heat pipe is controlled by the range of operation temperature. Depending on operate temperature, the loop heat pipe are sorted in four classes: cryogenic (4 – 200 K), low (200 – 550 K), medium (550 – 750 K), high (750 K and more) operate temperature. Most of applications from loop heat pipe are ranked in low range of operate temperature [9]. Next important point at choosing type of working substance is the compatibility between the working fluid and the material of loop heat pipe. Whichever chemical reaction between the working fluid and the material loop heat pipe creates a non-condensable gas in the system. The existence of non-condensable gas in the system markedly reduces the performance of loop heat pipe. For more information about the compatibility between metal and working substance can be found in the literature [9]. Volume of working fluid filled in system may have critical impact on the performance of loop heat pipe. Directive exists that after there you have to make headway. Let us assume the loop heat pipe at the lowest temperatures is out of order, when transportation pipelines and condenser are fully filed with fluid. At that time there has to remain enough of operate fluid in evaporator. This pour minimal volume filling of operates fluid into loop heat pipe. Another aspect is that when the loop heat pipe is at the highest temperature out of order, volume of liquid has to be smaller than the sum of pipe's volume and evaporator. After analysis, if the minimum value of the working fluid is greater than the maximum value, then the physical size of the components must to be re-designed. This condition is usually achieved by increasing the size of the components [10, 11]. Working fluid used in this experiment is called fluorinert FC-72. Theory of the working fluid is grounded on dielectrics, which ensures the prevention of short circuits and damage to electrical equipment parts.

4. Experiment and results

To realize the experiment it is necessary to achieve equilibrium, which occurs after evaporation of the working fluid to the desired percentage amount. At steady state, the heat pipe was allowed to cool to room temperature (approx. 20°C). After cooling, the temperature data logging was turned on using the monitoring software on the computer, turned on the power source and the output power was set to an initial value of 80 W. Using the computer temperature data on the evaporator are recorded as well as on the inlet to the condenser, the condenser on the ribs, at the outlet of the condenser and the ambient air. After stabilization of the temperature at the evaporator, where there is a thermal oscillation applied, the current value and increase of the output power by 20 watts, on 100 W. Procedure described in this paragraph shall be repeated until output power is 300 W, or is not achieved at evaporation temperature of 100°C, the upper limit of the temperature of the evaporator. In experimental determination of optimal working fluid volume for loop thermosyphon, it was used quantity of working fluid in the range 30–70% of loop thermosyphon volume. The temperature values of the evaporator wall by varying quantity of the working fluid are shown in Table 1. Figure 2 shows a comparison of the cooling effect, depending on the quantity of working fluid filling.

Table 1. Measured values on the wall of the evaporator at various filling quantities

Heat load [W]	Volume of the working fluid [%]				
	30%	40%	50%	60%	70%
81	41	42	43	46	46
100	44	46	45	51	50
121	49	51	49	54	54
140	52	52	53	57	56
161	58	56	56	61	59
181	65	59	60	63	62
200	76	63	62	65	65
221	84	66	65	68	68
241	92	69	67	70	69
260	100	73	70	72	71
280		79	71	75	73
298		82	75	76	77

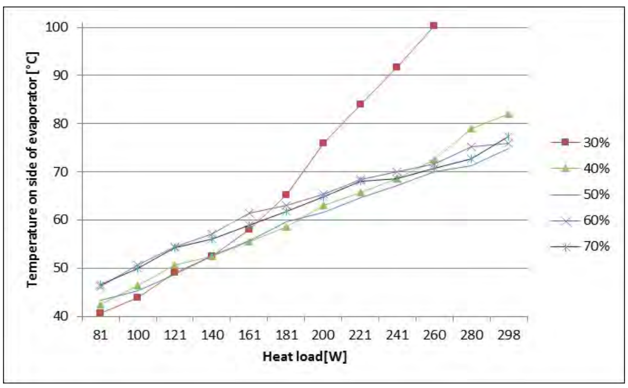

Fig. 2. Comparison of the cooling effect on the quantity of filling

In the figure it is seen the worst condition – response curve with points in the shape "X" at the quantity 30% of filling, when it is not possible to achieve a higher value of forward power 260 W. The loop thermosyphon reaches best cooling effect with working fluid volume 50%, as shown in graph by blue curve without the symbols. Although in some places this curve intersects with another curves, but then these curves show worst results. According to the graph created by measured data, we recommend50% amount of working fluid for optimal function of loop thermosyphon.

5. Conclusions

This experiment dealt with the influence of the amount of working fluid filling on the cooling effect of the loop heat pipe. The experimental measurements and calculations show the worst results for 30% of working fluid filling when it is not possible to reach a value of forward power greater than 260 W. The best results are achieved with 50% volume of working fluid. This experiment has shown the suitability of 50% filling with working fluid of loop heat pipe for the effective removal of heat from electrical components. For precise analysis of an appropriate amount of working fluid filling, we suggest to examine the scope of working fluid volume in the range of 40–60%.

Acknowledgements

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References

[1] Cheung M.K. et al.: *Thermal Performance and Operational Characteristics of Loop Heat Pipe*, Proceedings of the 28th International Conference on Environmental Systems, Society of Automotive Engineers, Paper No. 981813, 1988.

[2] Kaya T. et al: *Investigation of Low Power Start-Up Characteristics of Loop Heat Pipe*, Space Technology and Applications International Forum, CP458, 1999, pp. 799–804.

[3] Huzvar J., Nosek R.: *Impact of fuel supply to concentrations of emissions in domestic boiler*. In: Power control and optimization, proceeding of fourth global conference: 2–4 December 2010, Kuching, Malaysia, 2010.

[4] Riahi A. et al.: *Experimental Investigation on the Performance of thermosyphon solar water heater in the south caspian see*, THERMAL SCIENCE, Vol. 15, No. 2, 2011, pp. 447–456.

[5] Close D.J.: *The Performance of Solar Water Heaters with Natural Circulation*, Solar Energy, 6, 1, 1962, pp. 33–40.

[6] Gupta C.L., Garg, H.P.: System Design in Solar Water Heaters with Natural Circulation, Solar Energy, 12, 2, pp. 163–182, 1968.

[7] Ong K.S.: *A Finite-Difference Method to Evaluate the Thermal Performance of a Solar Water Heater*, Solar Energy, 16, 3–4, 1974, pp. 137–147.

[8] Zerrouki A., Boumedien A., Bouhadef K.: *The Natural Circulation Solar Water Heater Model with Linear Temperature Distribution*, Renewable Energy, 26, 4, 2002, pp. 549–559.

[9] Faghri A.: Heat *Pipe Science and Technology*, Taylor & Francis, Washington DC, 1995.

[10] Lenhard R.: *Numerical simulation device for the transport of geothermal heat with forced circulation of media*, Proceedings of the Power control and optimization, 4, 2010.

[11] Kapjor A., Kosecová A., Papučík Š.: *Influence of construction parameters to heat output of floor convector*, Proceedings of the TRANSCOM, 6, 2005, pp. 69–72.

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ASSESSMENT OF THE INTERNAL MICROCLIMATE USING THE QUESTIONNAIRES SURVEY

Abstract
This paper considers the subject of the applicability of survey research as an essential element for the assessment of the indoor microclimate. The results of the survey research are presented and compared with the experimental results performed in residential buildings.

Keywords: building physics, indoor air quality, indoor climate, questionnaire surveys

1. Introduction

Currently conducted studies to determine the quality of the indoor microclimate use systems based on advanced technological solutions. During the research, usually only a few basic parameters that describe the quality of the indoor environment are monitored and measured constantly. Additionally, measurements are used in a limited number of sensors that are placed at specific locations, and the measuring range is determined by the upper and lower detection limit. Therefore, each additional source of information about the state of the indoor environment can provide highly relevant data to analyze the quality of the indoor microclimate. Especially when it collects and analyzes data in a different manner than usually applied technological sensors (Table 1). One such source of information can be a questionnaire survey of flat-users. In conjunction with the results of the measurement systems they create full spectrum of information on the quality of the internal microclimate. Surveys, in addition to the description of operation of the technical solutions used in the building, also give information on individual behavior and user experience [4].

2. Subject of research

The indoor microclimate affects thermal comfort of users [5] and, as a results, is a crucial factor. The study consisted of registration of changes of parameters describing the typical indoor climate. At the same time, among the dwelling users questionnaire surveys were performed. Then, the results of the study were compared with the results of measurement surveys. During a measurement study authors focused their attention on identifying the variability in parameters of indoor air. The measurements conducted during

Table 1. Comparison of the possibility of collecting information by users and sensors

Information source	
Buildings users	Sensors
It is possible to a large number of users	Number of sensors usually limited
Variable location	Fixed location
Receiving multiple signals at the same time	Limited number of measured parameters
A wide range of sensitivity	Fixed range
The possibility of mutual communication and exchange of information	The data transferred to the control or data recording
Possible large variation in sensitivity over time	The relatively small variation in sensitivity on time
The possibility of integration of multiple parameters	Usually ignore the impact of other parameters

the recording of the basic parameters describing the microclimate of premises: the concentration of carbon dioxide, temperature and relative humidity of the air. Measurements were carried out at the temperature of outside air -10°C to 0°C and the wind speed 0 to 6.5 m/s. In rooms where exhaust ducts were located the speed and direction of air flow through each ducts of the natural ventilation were also recorded. The analyzed parameters were measured for two weeks with measuring step of 30 minutes. For each apartment at least two series of measurements were done.

Buildings selected for the study were made in the traditional technology or big plates, which have walls warmed with styrofoam. All buildings are equipped with natural ventilation system. Based on the analysis of existing questionnaires sheets on indoor air quality (Table 2) the scope and subject of the questionnaire used in the study were defined. The survey contained 48 questions. It contained questions about thermal comfort, problems in the operation of natural ventilation and symptoms of SBS. Primary objective of the survey was to determine subjective assessment of indoor air quality. Also identified was the knowledge level of users on the development of indoor air quality and its impact on the mood of the inhabitants.

Table 2. The number of questions in each thematic groups in the questionnaires of air quality

Questions group	A	B	C	D	E
Basic questions	1	4	1	0	2
Background factors	4	5	4	3	4
Physical factors affecting the indoor environment	36	12	13	30	12
Psychosocial work environment factors	5	4	4	11	4
Questions about the disease	5	4	3	2	2
Symptoms of SBS	20	13	13	17	13
Comments	0	1	1	1	1
Number of all the questions	71	43	41	64	38

Comments :
A – Swedish Council for Building Research [8]
B – MM-Questionnaire Orebo Medical Center Hospital [8]
C – Nordtest Report 204 Indoor Climate Questionnaire [8]
D – Hong Kong Polytechnic Library Survey [8]
E – Kielce University of Technology

The analysis included 65 apartments and 21 single-family houses, which collected 177 questionnaires.

3. Research results

The results of the measurement study showed that in majority of the analyzed dwellings problems with the system of natural ventilation occured. These results were presented by the authors in detail in the articles [7, 9, 10]. In short they are presented in Table 3. It shows percentage of the number of units, which reported incorrect microclimate values. The values above the recommended adopted minimum or maximum values were considered as incorrect.

Table. 3. Percentage of dwellings with reported incorrect microclimate values – a method of measuring

Name of the parameter	Kind of building	
	Single family	Multifamily
Indoor temperature	37.3	51.2
Relative humidity	35.6	54.1
CO_2 concentration	20.6	44.7
Air flow velocity	48.9	69.7
The direction of air flow in ventilation ducts	61.3	78.4

The analysis of the data presented in Table 3 shows that in the majority of the analyzed objects natural ventilation does not work properly. This causes abnormalities in the development of microclimate. In the majority of cases these abnormalities did not occur alone. A thorough analysis of the results indicates that the irregularities did not affect only 10–15% of all surveyed dwellings in each group of buildings.

Given such large-scale problems the authors have tried to analyze individual user experience of the surveyed dwellings based on questionnaire surveys.

The group of questions about physical factors affecting the indoor environment was 12 questions. Respondents could answer in the affirmative or negative way. The results have been provided in Figure 1. It presents the percentage of respondents confirming the existence of the parameter. Although the answers are dependent on the individual preferences in many areas they agree with measurements. This includes parameters which are easy to define by users such as temperature and feelings within. With some questions the respondents had some problem to answer (eg humidity).

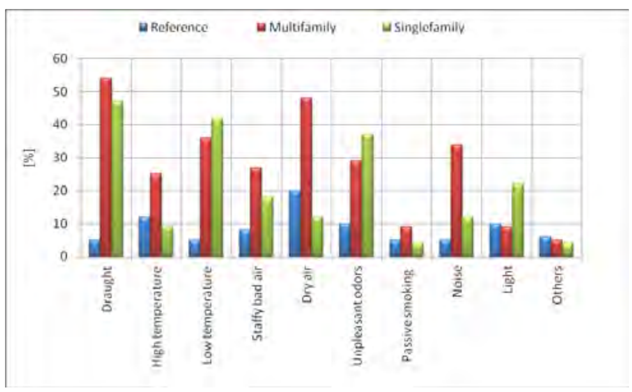

Fig. 1. Wrong assessment of the physical characteristics of microclimate by sensations of respondents, percentage

Another set of questions were questions regarding the occurrence of the sick building symptoms. In this part of the questionnaire users were asked 13 questions. Users could answer in the affirmative or negative way. The results are shown in the Figures 2–4. Figure 2 shows the percentages of members of apartments and houses, who declared the most common of SBS symptoms – separately for single-family and multi-family buildings. Figure 3 shows the percentages of users of the same objects declaring the presence of SBS symptoms according to gender, and age Figure 4 of the respondents.

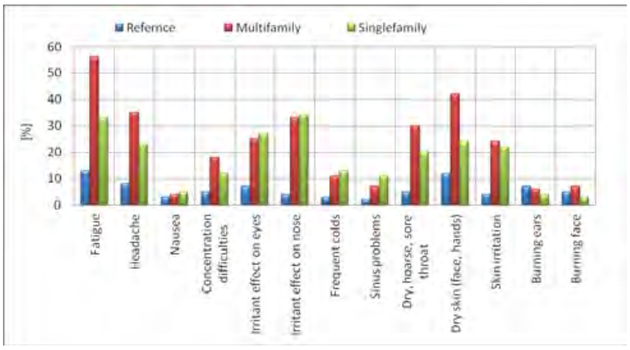

Fig. 2. The occurrence of SBS symptoms in the analyzed users apartments and single-family households

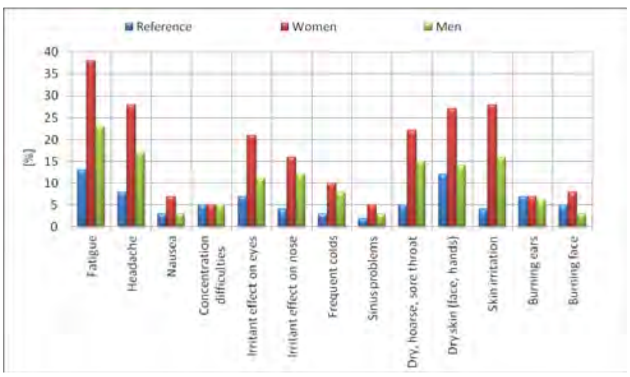

Fig. 3. The occurrence of SBS symptoms in relation to sex

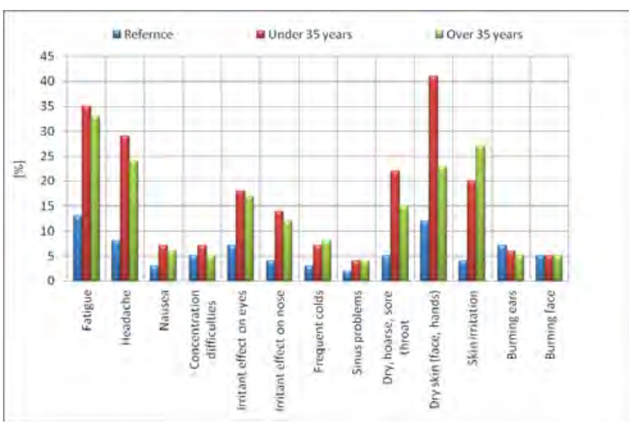

Fig. 4. The occurrence of SBS symptoms in relation to age

4. Analysis of results

The results clearly show that the surveys are a source of additional information about the functioning of the building. In a large part they allow to determine the impact of unmeasured parameters (odors, cigarette smoke, etc.) on the users and medical symptoms of SBS.

A major problem in the analysis of the results of research based on questionnaires is to establish reference levels. Only for some parameters (temperature, draft) levels have been established [5] and can be determined by calculation (PMV, PPD, DR). Due to the lack of accepted reference levels authors indicated in Figures 1 through 4 levels of reference of available publications [1, 2, 3]. These levels have been established for different types of buildings and should be considered only as a guide. Also, the period of calculation of the values, the end of the last century, indicates the need for verification. The authors found, however, that it is sufficient for the execution of a preliminary assessment of the results.

Analyzing the negative assessment of the physical characteristics that describe climate (Fig. 1) it should be noted that they are consistent with results from a measurement study (Table 3), both for single-family dwellings and multi-family houses.

Survey results indicate a much smaller percentage of people dissatisfied with the microclimate parameters in single family houses. They also less frequently complained about the typical symptoms associated with the syndrome SBS. This is due to the smaller number of observed disturbances in the operation of natural ventilation system, which was confirmed by measurements. It should be remembered that the assessment of some of the physical characteristics is dependent on individual preferences of residents. In some cases, we could be dealing with a „habit" of users to specific microclimate parameters. An example would be a smaller number of people complaining about the low temperature in houses even though tests have shown that it is on average up to 2 to 4°C lower as compared to apartments in multifamily buildings. Another important factor is the size of the facilities per inhabitant. In the case of single-family houses space per user is several times larger than the area of multi-family buildings. In this situation the concentration of indoor air pollution is more complex and, thus the negative feeling by the respondents is limited.

Very interesting part of the questionnaire concerns the presence of the symptoms associated with SBS. Number of people complaining about the various symptoms has been presented Figure 1 and amounts from a few to several dozen percent of respondents. It should be noted that a large number of respondents complained about more than one symptom. Over 40% of houses users complained about at least one of the symptoms of SBS, in apartment buildings, it was over 45% of users. Undoubtedly, these opinions should be verified by medical research. But the cost of execution and delivery time are not comparable to the method used in the questionnaire. Therefore, it must be held that the questionnaire surveys can be an instrument for the quick assessment of indoor air quality.

5. Conclusions

1. A well planned and carried out questionnaire survey can be relatively inexpensive, but could also be a good indicator of the quality of the microclimate just like the research using a complicated measuring equipment.
2. Questionnaires allow to collect large amounts of data in a relatively short period of time.
3. Proper preparation of the questionnaire and the analysis of results is an interdisciplinary task and requires the cooperation of specialists from many fields.
4. The advantage of survey research is to assess by the users an almost infinite number of indoor air parameters at the same time.
5. The movement of the people makes it possible to cover the entire studied area for the tests and not just certain areas characteristic for recording with the measurement apparatus.

References

[1] Andersson K.: *Management of the sick building – investigation strategies, Proceedings of the International Symposium on New Epidemics in Occupational Health*, Helsinki 1994, pp. 117–120.

[2] Andersson K.: Epidemiological Approach to Indoor Air Problems, Indoor Air Volume 8, Issue S4, 1998, pp. 32–39.

[3] Andersson K., Stridh G.: *The use of standardized questionnaires in building-related illness (BRI) and sick building syndrome (SBS) survey*, NATO/CCMS Pilot Study on Indoor Air Quality 1992, pp. 47–64.

[4] Engvall K., Norrby C., Sandstedt E.: *The Stockholm Indoor Environment Questionnaire: a sociologically based tool for the assessment of indoor environment and health in dwellings*, Indoor Air Volume 14, Issue 1, February 2004, pp. 24–33.

[5] Orman Ł.J., *Układy klimatyzacyjne – zagadnienia wstępne*, Wydawnictwo Politechniki Świętokrzyskiej, Kielce, 2012.

[6] PN-EN ISO 7730:2002 moderate thermal environment – Guidelines for PMV and PPD indices and establish conditions for thermal comfort (in Polish).

[7] Piotrowski J. Z., Koruba D, Telejko M.: *The possibility of supplementing ventilation airflow in terms of microbiological internal microclimate,* 55 conference proceedings of the Conference on Scientific and Technological KILiW PAN Sciences and Science Committee PZITB, Krynica – Kielce 20–25.09.2009, pp. 623–630 (in Polish).

[8] Sowa J.: *Using survey data to assess the quality of indoor environment*, Publishing Institute of Heating and Ventilation Technical University of Warsaw, Warsaw 2000 (in Polish).

[9] Telejko M. Piotrowski J.: *Influence the structure of a building for the distribution of ventilation air*, Rzeszów University of Technology Research Papers, Volume 58, No. 3/2011/III, Publishing University of Rzeszów, Rzeszów 2011, pp. 131–140 (in Polish).

[10] Telejko M., Piotrowski J.: *Air exchange in multifamily buildings equipped with aggregated ventilation ducts,* Rzeszów University of Technology Research Papers, Volume 59, No. 3/2012/III, Publishing University of Rzeszów, Rzeszów 2012, pp. 47–54 (in Polish).

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Badania nad jakością mikroklimatu wewnętrznego z zastosowaniem kwestionariuszy ankietowych

1. Wprowadzenie

Autorzy prowadzonych obecnie badań nad jakością mikroklimatu wewnętrznego wykorzystują w swoich pracach systemy oparte o zaawansowane technologicznie rozwiązania. Jednak w trakcie realizacji badań analizie poddawanych jest tylko kilka podstawowych parametrów opisujących jakość środowiska wewnętrznego. Pomimo, że dostępna obecnie aparatura pomiarowa daje możliwość monitorowania parametrów IAQ w sposób ciągły, to do pomiarów stosowane są ograniczone ilości czujników. Umieszczane są w określonej lokalizacji, a ich zakres pomiarowy jest ograniczony. Dlatego też badania takie warto uzupełnić dodatkowymi danymi, zwłaszcza jeśli sposób odbierania i monitorowania parametrów IAQ jest zgoła odmienny. Źródłem takich dodatkowych, bardzo istotnych, informacji o stanie środowiska wewnętrznego mogą być badania ankietowe użytkowników mieszkań. Wyniki badań ankietowych w połączeniu z danymi zebranymi przez systemy pomiarowe tworzyć będą pełny obraz jakości mikroklimatu wewnętrznego. Dodatkowo odpowiednio przeprowadzone badania ankietowe, poza opisem działania zastosowanych rozwiązań technicznych, pozwalają uzyskać informacje na temat zachowań oraz indywidualnych odczuć użytkowników.

2. Charakterystyka badań

Badania polegały na rejestracji zmian parametrów opisujących mikroklimat wewnętrzny oraz porównanie otrzymanych wyników pomiarowych z wynikami wykonanych, równolegle z pomiarami, badań ankietowych.

Analizą objęto 65 mieszkań i 21 budynki jednorodzinne, z których łącznie korzystało 177 osób. Ankieta zawierała 38 pytań koniunktywnych zawierających pytania dotyczące komfortu cieplnego, zaburzeń w działaniu wentylacji grawitacyjnej oraz występowania symptomów SBS. Głównym celem przeprowadzenia ankiety było sprawdzenie subiektywnej oceny jakości powietrza wewnętrznego przez użytkowników pomieszczeń.

3. Analiza wyników

Uzyskane wyniki badań jednoznacznie wskazują, iż wykorzystanie ankiet jest źródłem dodatkowych informacji na temat funkcjonowania budynku. Ich niezaprzeczalną zaletą jest fakt, że pozwalają na określenie oddziaływania na użytkowników parametrów niemierzalnych (zapachy, dym papierosowy itp.) oraz medycznych objawów SBS.

4. Wnioski

1. Odpowiednio zaplanowane i przeprowadzone badania ankietowe mogą być relatywnie tanim, ale równie miarodajnym wskaźnikiem co badania z wykorzystaniem skomplikowanej aparatury pomiarowej.
2. Zaletą badań ankietowych jest możliwość oceny przez użytkowników praktycznie nieskończonej ilości parametrów powietrza wewnętrznego w tym samym czasie.
3. Przemieszczanie się mieszkańców daje możliwość oceny całej rozpatrywanej przestrzeni.
4. Testy ankietowe pozwalają na zebranie dużej ilości danych w stosunkowo krótkim przedziale czasowym.
5. Prawidłowe przygotowanie kwestionariusza oraz analiza wyników jest zadaniem interdyscyplinarnym i wymaga współpracy specjalistów z wielu dziedzin.

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EFFECT OF FILLING RATIO ON THERMAL PERFORMANCE AND THERMAL PARAMETERS OF CLOSED LOOP PULSATING HEAT PIPES

Abstract

Improving the performance of electrical components needs higher heat removal from these systems. One of the solutions available is to use a sealed heat pipe with a throbbing filling, where development meets the current requirements for intensification of heat removal and elimination of moving parts cooling systems. Heat pipes operate using phase change working fluid, and it is evaporation and condensation. They have a meandering shape and are characterized by high intensity of heat transfer, high durability and reliability. Advantage of these tubes is that it is not necessary to create the internal capillary structure for transporting liquid and they need no pump to the working fluid circulation. They have a simple structure, low cost, high performance, and they can be used for various structural applications. The choice of working fluid volume and performance affects thermal performance. Distilled water, ethanol and acetone were used in the performance ranges of 0–80%.

Keywords: closed loop pulsating heat pipe, thermal performance, evaporation, condensation, filling ratio, thermal resistance, temperature.

1. Introduction

Pulsating heat pipes are one of the latest trends in heat pipe technology. In contrast to conventional types of heat pipes in which the working fluid circulation inside the tube is continuously done with capillary forces between the heat source and the heat sink in the form of counter flow, in the pulsating heat pipe working materials move in the axial direction. The basic mechanism of heat transfer is pulsatile fluid motion associated with phase change (evaporation and condensation) [1]. Akachi and Polasek describe the basic operation of these tubes. Pulsating heat pipes usually consists of copper capillary meandering shape. Pulsating heat pipes are filled with an optimum amount of fluid. Effect of surface tension creates columns of liquid phase, which are intermittent of vapor bubbles. The working fluid is evaporated in the evaporation section, where the heat input is. The effect of evaporation increases the vapor pressure inside the tube. Vapor bubbles in the evaporation section are growing and are pushing the liquid phase in the condensation section. Since the condensation part is cooled, the pressure is reduced, vapor phase is condensed and the vapor phase bubbles. This process between evaporation and condensation section is continuous and it occurs when there is the pulsating motion inside the tube. Heat is transferred through the latent heat in the vapor phase and sensible heat transported through the liquid phase [2]. Pulsating heat pipes can be divided into four groups (Fig. 1) [7]:

- closed pulsating loop heat pipe,
- closed pulsating loop heat pipe with check valve to ensure the movement of fluid in a particular direction,
- closed ends pulsating heat pipe, which is closed at both ends,
- pulsating heat pipe with open ends.

The parameters that affect the performance of the closed pulsating heat pipe, summed Groll. They are working fluids and their termo-physical properties, internal diameter of the pipe, total length of the pipe, length of condensation and evaporation section and inclination angle [3].

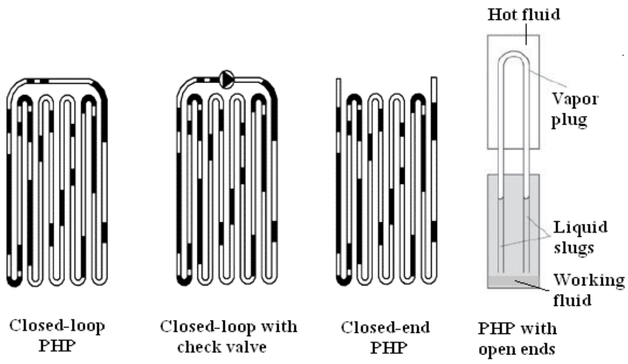

Fig. 1. Types of pulsating heat pipes [7]

A lot of parameters influence the formation of different phases in the evaporating section, such as the Bond number, defined by equation (1) must be less than ~2.

$$Bo = \frac{D_i}{\sqrt{\frac{\sigma}{g} \cdot (\rho_{liq} - \rho_{vap})}} \quad (1)$$

where σ – surface tension [Nm^{-1}], g – acceleration due to gravity [ms^{-2}], ρ_{liq} – density of liquid [kgm^{-3}], ρ_{vap} – density of vapor [kgm^{-3}].

The inner diameter of the tube is a parameter that affects the correct functioning of pulsating heat pipes. They work optimally only in a certain range of diameters. The value of the critical diameter can be determined from the equation (2) of Bond (Eötvös) number as [5]:

$$D_{crit} \approx 2\sqrt{\frac{\sigma}{g \cdot \left(\rho_{liq} - \rho_{vap}\right)}} \quad (2)$$

It is also worth noting that heat pipes can be produced with an internal structure on the inner surface. It is called a wick and can be made of different microstructures. Such metal coatings have been investigated in the pool boiling mode e.g. in [8, 9].

2. Proposal of a method for measuring the thermal performance of closed loop pulsating heat pipes

Closed loop pulsating heat pipe was constructed for investigating the performance parameters, which had 21 river meanders and the inner diameter was 1.8 mm. Distilled water, acetone and ethanol were used as the working fluid. The critical diameter for water is 5.34 mm, for acetone is 3.47 mm and for ethanol is 3.39 mm. The condition affected the proper operation of internal diameter has been satisfied. Orientation of the heat pipe was vertical. At the top of the heat pipe there were over T-pieces connected two capillaries. One was used to evacuate the air from the heat pipe and the other to carry the heat pipe (Fig. 2). Volume of the working substance ranged from 0–80%. Heat pipe dimensions 235 mm x 200 mm. The beginning of the measurement was set temperature of evaporating at 50°C, 60°C and 70°C and cooling water at 15°C. It also was determined length of evaporating, condensing and adiabatic section. Condensation section was placed in a heat exchanger. Exchanger was constructed of plexiglas and the coolant water was inside. Circulation of cooling water ensured Julabo Model SE.

Fig. 2. Pumping air through a pump and filling pulsating heat pipes

In the inlet and outlet of the heat exchanger temperature sensors NiCr-Ni were placed, which panned coolant temperature. Coolant flow was measured by an ultrasonic flowmeter KAMSTRUP. Evaporation section of pulsating heat pipe was heated with the water in heater thermostat. All thermometers and ultrasonic flow meter are connected to the input of measuring units AHLBORN ALMEMO (Fig. 3).

Fig. 3. Experimental measuring device

The control panel transmits information using special software to personal computer in the form of a Microsoft Excel spreadsheet.

3. Evaluation of the measured variables

The survey was carried on pulsating heat pipes in a vertical position. Calculation of the temperature difference of cooling water in evaporator scanned on entry and exit calculated according to equation (3) in the form:

$$\Delta \overline{t_i} = \overline{t_0} - \overline{t_p} \tag{3}$$

where $\Delta \overline{t_i}$ – the difference of middle temperatures of the cooling water in fixed state [°C], $\overline{t_0}$ – the middle value of output temperature of the cooling water [°C], $\overline{t_p}$ – the middle value of input temperature of the cooling water [°C]. The calculation of middle heat pipe power value from measuring values is determined (4):

$$\overline{Q} = \dot{m} c_p \Delta \overline{t_i} \tag{4}$$

where: $\overline{Q}$ – the middle power value in fixed state [W], ṁ – mass flow rate of cooling water [kgs^{-1}], c_p – the specific heat capacity at constant pressure [$Jkg^{-1}K^{-1}$], $\Delta \overline{t_i}$ – the difference of middle cooling water temperatures in fixed state [°C] [3].

4. Achievements

According to equation 4 thermal performance of pulsating heat pipes was calculated. Figures 4, 5 and 6 shows the thermal performances at all filling ratios and different temperatures of evaporation. There increasing thermal performance with increasing evaporation temperature of the pulsating heat pipe may be seen. Best values of thermal performances are achieved when the working fluid was distilled water (Fig. 4). It is influenced by the thermo-physical properties of water, a high value of latent heat of evaporation and also the value of the internal diameter of 1.8 mm. Pulsating heat pipes filled with acetone achieve the lowest thermal performance (Fig. 5).

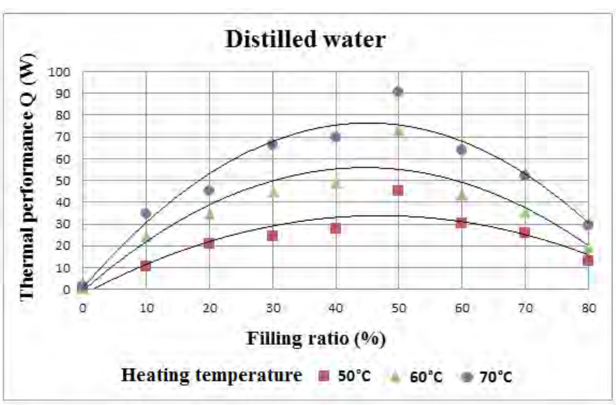

Fig. 4. Effect of filling ratio on thermal performance of CLPHP, working fluid: distilled water

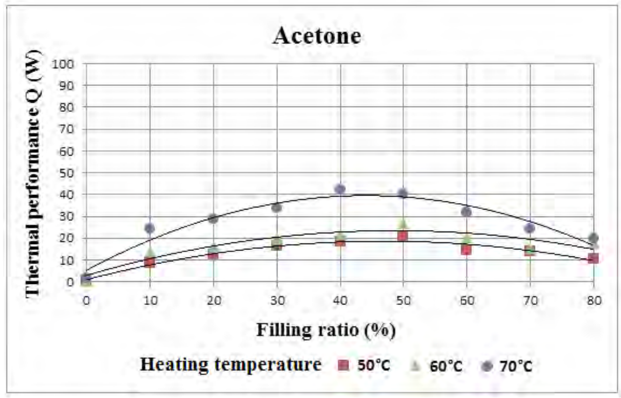

Fig. 5. Effect of filling ratio on thermal performance of CLPHP, working fluid: acetone

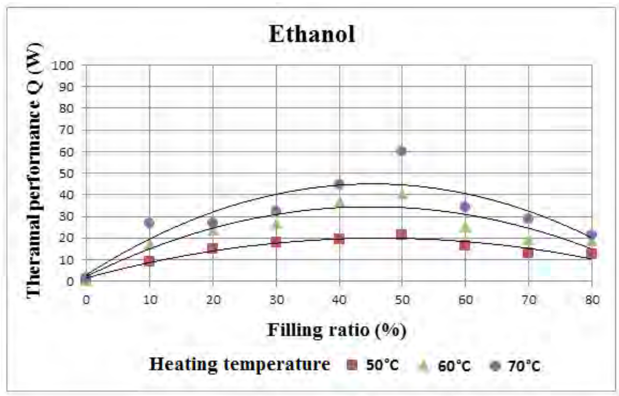

Fig. 6. Effect of filling ratio on thermal performance of CLPHP, working fluid: ethanol

Thermal resistance was also studied in experiment (Figs. 7, 8, and 9). Thermal resistance was evaluated as the mean value at each temperature of evaporation section. These values were kept constant for some time.

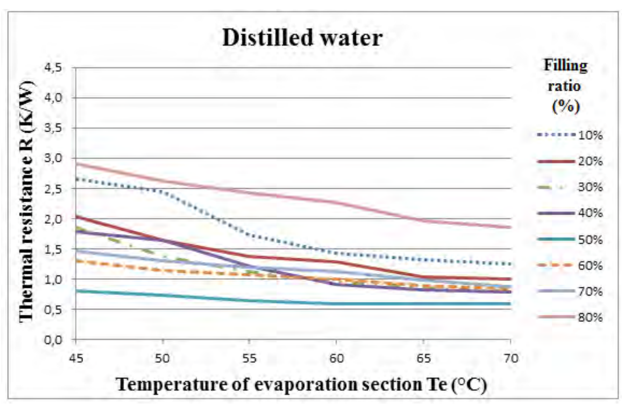

Fig. 7. Thermal resistance depending on the temperature of the evaporation section, working fluid: distilled water

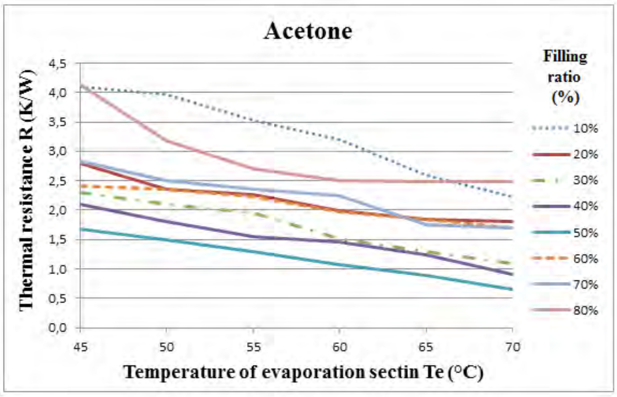

Fig. 8. Thermal resistance depending on the temperature of the evaporation section, working fluid: acetone

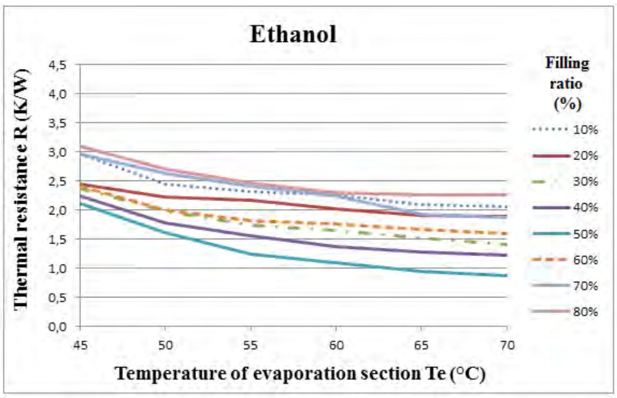

Fig. 9. Thermal resistance depending on the temperature of the evaporation section, working fluid: ethanol

5. Conclusions

The measurement results show that the thermal performance is dependent on the input heat flux. Higher temperatures of evaporation section could not be achieved due to the experimental device and evaporator design. Low temperatures of evaporation section were not able to generate enough vapor bubbles and their pumping activity was limited. This phenomena has led to a reduction in heat output and increased thermal resistance. Increasing the temperature of evaporation section reduced thermal resistance. Closed loop pulsating pipe filled with distilled water give the best performance, because thermo-kinetic water properties as thermal conductivity, latent heat of evaporation, constant pressure specific heat are better than the acetone and ethanol. The experiment shows that the lower volume filling of 30% or above 70% of the thermal performance is greatly reduced.

Acknowledgment

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References

[1] Akachi H.: Structure of a Heat Pipe, *US Patent, No 4,921,041*, 1990.

[2] Fasula, *Oscillating heat pipes*, Rhode Island: University of Rhode Island, May 2009, p. 46.

[3] Groll, Khandekar: *Roadmap to Realistic Modeling of Closed Loop Pulsating Heat Pipes*. In *9th* International Heat Pipe Symposium. Kuala Lumpur, Malaysia.

[4] Jandačka J., Nosek R., Holubčík M.: Analýza *vplyvu množstva spaľovacieho vzduchu na emisné a výkonové parametre zdrojov tepla*, Vykurovanie 2012, ročník 20, pp. 99–104.

[5] Reay D., Kew P,: *Heat Pipes Theory, Design and Applications*. UK: Fifth Edition, 2006.

[6] Nemec P., Čaja, Lenhard: *Influence working position of heat pipe on their thermal performance*, Experimental fluid mechanics, 2010, pp. 435-438.

[7] Zhang, Faghri: *Advances and Unsolved Issues in Pulsating Heat Pipes*, In Heat Transfer Engineering, 2008, Vol. 29, pp. 20–44.

[8] Orman Ł.J.: *Possibility of the application of microstructures in heating and ventilation systems*, Structure and Environment, No 1, Vol. 2, 2010. pp. 41–45.

[9] Orzechowski T., Orman Ł.J.: *Boiling heat transfer on surfaces covered with copper fibrous microstructures*, Proc of XI Int. Symposium „Heat Transfer and Renewable Sources of Energy", Szczecin, Poland, 2006, pp. 613–619.

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OPTIMIZATION OF HEAT TRANSFER ORIENTED SURFACES BY THERMOVISION AND USING CFD METHOD

Abstract
The paper presents applications of infrared measurements. It discusses the use of thermovision and CFD method in the analysis of heat transfer in experimental measurement with natural convection.

Keywords: heat transfer, natural convection, CFD method

1. Introduction

Infrared technology used to be an expensive testing method, nevertheless, today even small firms may buy simple IR equipment. The application ranges from heat losses determination in buildings (it is quite widespread due to the thermal performance analysis) to complex scientific measurements. The fundamental idea of the infrared technique is the radiation detection. Its intensity in the simplest form may be calculated with the Stefan – Bolzmann law. This radiation is comes from every body of temperature above zero Kelvin and depends on the temperature of the object to the forth order, emissivity (0 to 1) and the Stefan – Boltzmann's constant ($\sigma = 5{,}67 \times 10^{-8}\ W/(m^2K^4)$). During testing the detector obtains radiation coming from other sources too (not just from the observed element). As a result, correct calculation of temperature values requires consideration of other sources of radiation (radiation reflected from the element and emitted from some other sources in the surroundings as well as atmospheric radiation). This is done by the software of an IR system as data such as temperature of the things located in the vicinity, atmosphere, air humidity and other are input into the system [3, 4].

2. Examples of the measurements

2.1. Heat transfer from floor convector to surroundings

To recognise a mechanism of heat transfer from floor convector to surroundings by natural convection it is good to know the shape of flow and temperature distribution near the surface.

In our case the thermovision was used to visualize the heat output from the convector. It is known that by the help of the thermovision it is possible to visualize also small temperature differences. But the object must not be diathermal and the emission coefficient of its surface should be close to 0,9 because the air close to the surface of the floor convector heated through the natural convection is also diathermal, so it is invisible on the infra screenshots. From this reason the method of the heating of a thin, most often paper, foil was used for the visualization. The foil was placed at the surface so that the orientation of its surface was along the air streaming and so that it does not influence the natural convection. The foil is heated by the streaming warm air on temperatures close to the streaming air and the temperature profile in the closeness of the object is well visible as well as quantifiable. The way of placing the foil for the visualization in the thermostatic chamber is shown in Figure 1. The infracam MIDAS 320L was used and the pictures were evaluated by the help of the Pyrosoft software.

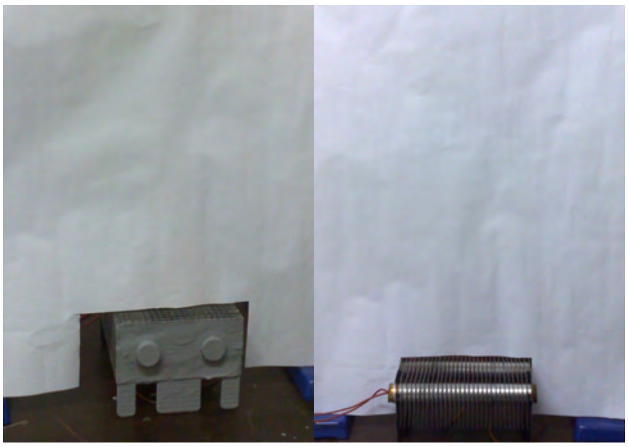

Fig. 1. The sample of floor convector in the thermostatic chamber

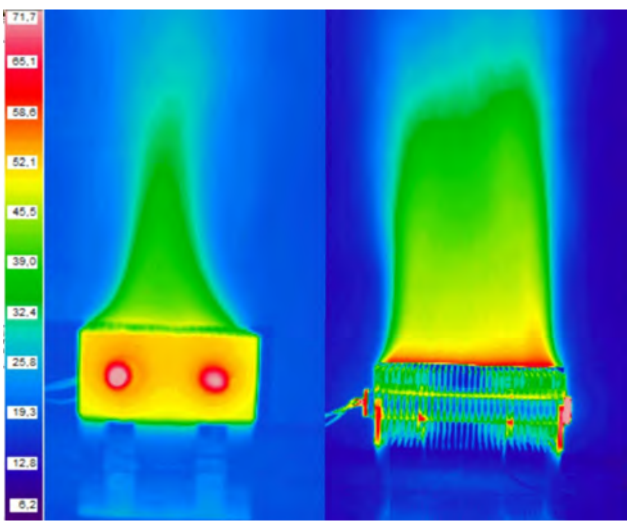

Fig. 2. Visualization of temperature fields

We also made measurements by CFD method on the same sample of floor convector as used in thermostatic chamber. The calculations were made in program Fluent. From CFD simulations in program Fluent Figures 3 and 4 were made. In Figure 3 we can see flow trajectory with velocity lines. While in Figure 4 we can see visualization of thermal field from a sample of a floor convector.

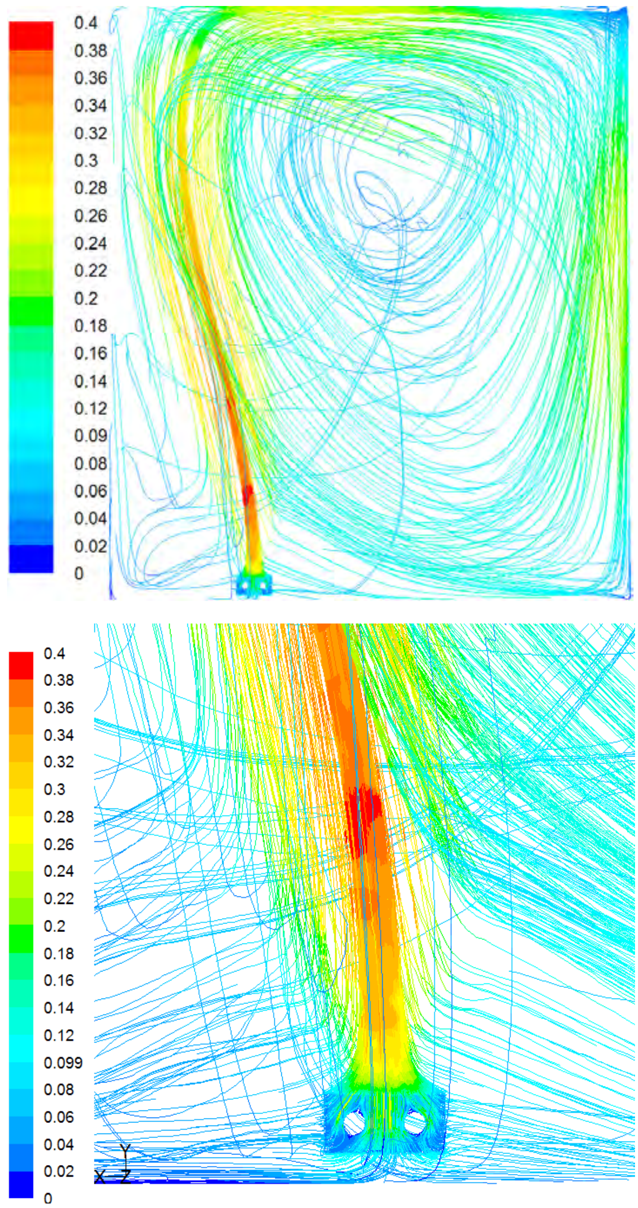

Fig. 3. Flow trajectory with velocity lines

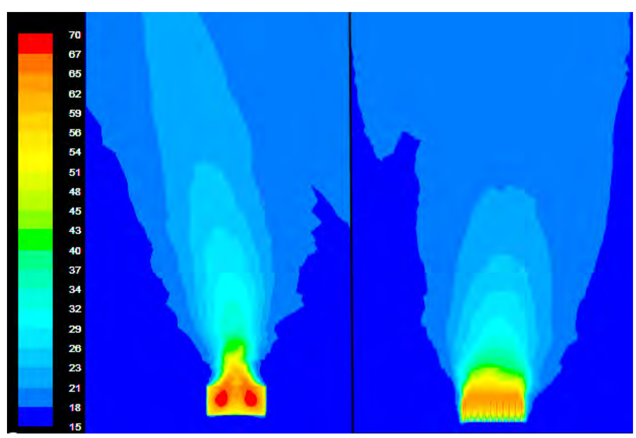

Fig. 4. Thermal field from a sample of a floor convector

2.2. Heat transfer from tubular heater

Another experimental measurement of heat transfer was made from tubular heater. Like in the previous case we compared heat transfer by CFD method and by thermovision.

The tubular heater was in thermostatic chamber as can be seen in Figure 5. Thermal gradient of tubular heater was 75/65°C and surrounding temperature was 20°C.

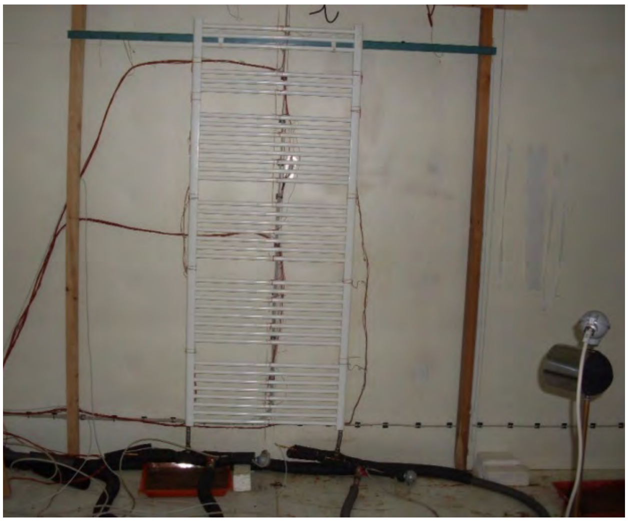

Fig. 5. Tubular heater in thermostatic chamber

When we achieved the equilibrium state (that was about 30 minutes), we made thermovision shots, which can be seen in Figure 6.

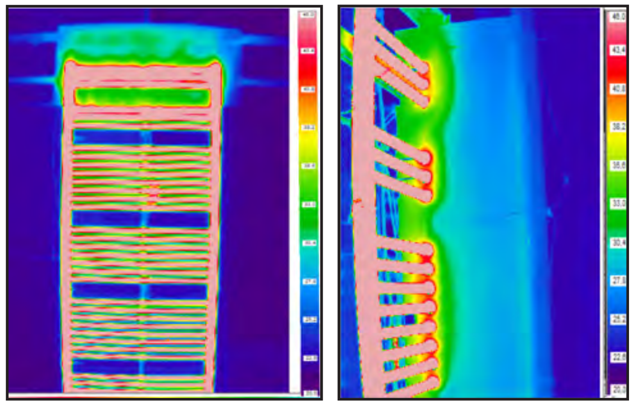

Fig. 6. Thermovision shots of tubular heater in thermostatic chamber

We also made heat transfer from tubular heater by CFD method in program Fluent. After the award of input conditions, like heating temperature, surrounding temperature and etc, the measurement started up. All of these parameters were similar as in case of measurement in thermostatic chamber. In Figure 7 screenshots of heat transfer form tubular heater by CFD method have been presented.

3. Conclusions

Infrared measurements become a widespread tool both in the industrial and science applications. The availability of IR systems caused mainly by their lower cost has enabled broader use of this method. Possible applications range from heat losses analysis

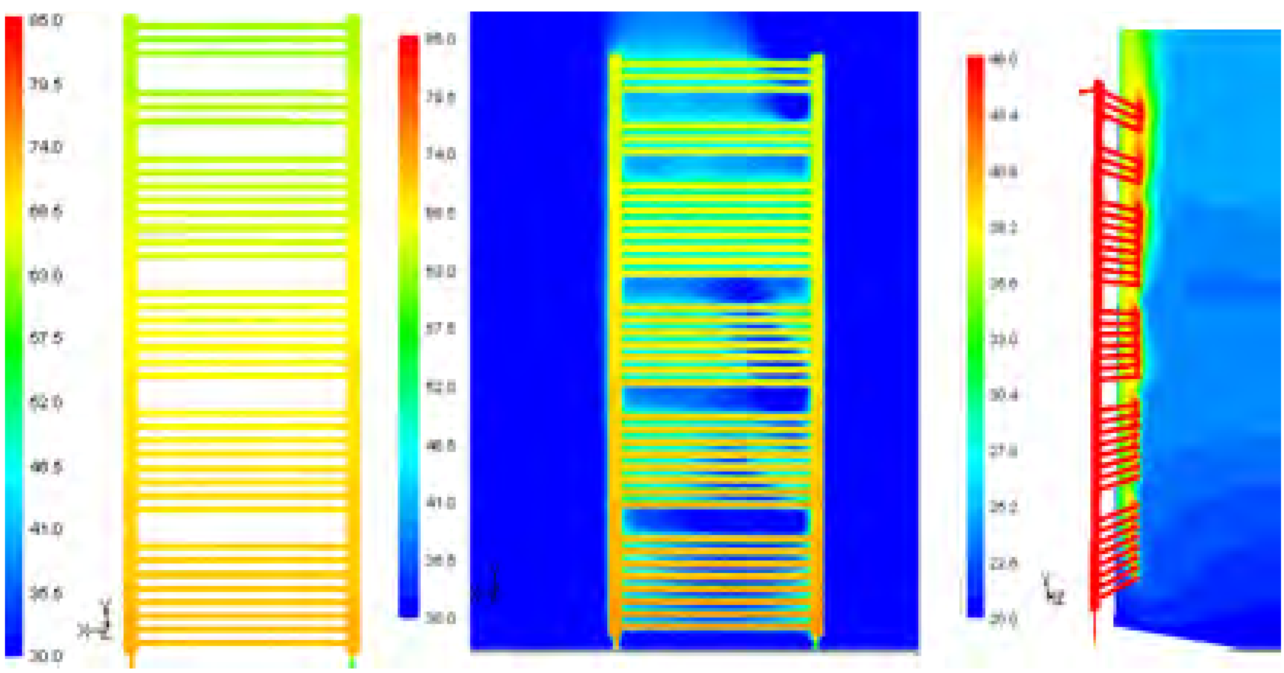

Fig. 7. Visualization of temperature fields in Fluent

in buildings (e.g. [3, 4]), heating systems [1], energy recovery systems [2] and other. The results of thermovision measurements can be compared with the calculations made in specialised computer finite element method programmes. Due to so many possible applications IR technology will surely be in even more widespread use in the future.

Acknowledgement

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References

[1] Lenhard R., Jandačka J., Malcho M.: *Modelovanie prestupu tepla na pasívnych chladiacich konvektoroch,* In: Vetranie a klimatizácia 2008: Energetická hospodárnosť vetrania a klimatizácie pri tvorbe vnútornej klímy : zborník prednášok z 11.

[2] Vantúch M., Jandačka J., Malcho M., Kasanický M.: *Measuring phase changes of CO_2 in a gravitational heat pipe on simulated depth borehole device,* TRANSCOM 2013 : 10-th European conference of young research and scientific workers : Žilina, June 24–26, 2013, Slovak Republic.

[3] Orman Ł.J.: *Badania termowizyjne w ocenie termoizolacyjności budynków*, Instal 4A, 2009, pp. 19–23.

[4] Orman Ł.J., Sułek M.: *Diagnostyka metodą termografii w podczerwieni w ocenie termoizolacyjności i charakterystyki energetycznej*, Proc. of Conf. "Terotechnologia 2009", pp. 325–330.

[5] Yakhot, V., Orszag, S.A., Thangam, S., Gatski, T.B., Speziale, C.G.: *Development of turbulence models for shear flows by a double expansion technique*. Physics of Fluids A 4, 1992, pp. 1510–1520.

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Abstract
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3	table	table	table

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3. Conclusions

References *(arranged in the citing order)*:

[1] Nowak M.: *Modelowanie konstrukcyjne (Structural modelling)*. Postępy Technologiczne 10 (2000), pp. 30-34.

[2] Zarylski R.: *Pomiary dynamiczne (Dynamic measurements)*. WNT, Warszawa 1971.

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