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THERMAL STRESS IN CONCRETE SLAB OF THE AIRFIELD PAVEMENT

Termiczna odporność betonowych nawierzchni lotniskowych i jej skutki dla procesu użytkowania

Abstract: *Stress occurring in concrete pavement slab changes on daily and annual basis. Daily changes of air temperature in between environments depend on the following: latitude where the structure is located and season. Change of air temperature causes the variable thermal stress of a slab and consequently change of its linear dimensions (slab extension or shortening. "Thermal balance of pavement" prepared for individual structure solutions, should be the basis for construction design and geometric solutions concerning air field structure. This publication refers only to natural changes of temperature conditions of the environment. Other phenomena occurring on concrete airfield pavement under the influence of imposed thermal loads will be the subject of another publication in this regard.*
Keywords: concrete pavement, thermal balance of the surface, daily and annual cycles of temperature changes, amplitude of temperature changes

Streszczenie: *Stan naprężenia w betonowej płycie nawierzchni zmienia się w cyklu dobowym i rocznym. Dobowe zmiany temperatury powietrza zalegającego na granicy środowisk zależą od: szerokości geograficznej, w której położony jest obiekt, i pory roku. Zmiana temperatury powietrza powoduje zmienny stan naprężenia termicznego płyty i w konsekwencji zmianę jej wymiarów liniowych (wydłużanie lub skracanie płyty). „Bilans termiczny nawierzchni" sporządzony dla indywidualnych rozwiązań konstrukcyjnych, stanowić powinien podstawę projektu konstrukcyjnego i rozwiązań geometrycznych obiektu lotniskowego. W publikacji uwzględniono tylko zmiany naturalne warunków temperaturowych otoczenia. Inne zjawiska zachodzące w lotniskowej nawierzchni betonowej pod wpływem wymuszonych obciążeń termicznych będą przedmiotem opracowania w innej kierunkowej publikacji z tego zakresu.*
Słowa kluczowe: nawierzchnia betonowa, bilans termiczny nawierzchni, dobowy i roczny cykl zmian temperaturowych, amplituda zmian temperaturowych

1. Introduction

Stress condition in case of concrete pavement slab is caused by two factors: external loads onto the slab surface caused by aircraft wheels and the temperature influence which is considered the other type of special load. The temperature impact on concrete pavement of airfield slab is of dual nature, e.g. the temperature resulting from environmental climatic conditions typical for the region of laminar, slowly variable heat transfers, which refer to annual and daily cycles of these changes. The other type of thermal stress which impacts the pavement is: the imposed, dynamic influence of hot air streams of massless, impulse nature which come from the discharged hot exhaust gas streams generated by aircrafts engines. The publication presents the selected problems concerning slowly variable natural heat flow changes in pavement structural arrangement. Changes of slab thermal effort are determined not only by average variations of external temperature but also the amplitude of these changes and other factors which influence intensity thereof.

2. Thermal balance in structural arrangement of pavement

The basis for stress condition analysis, in case of the considered slab depth "z" and the duration time "t" from temperature influence on concrete slab surface, where z = 0, i.e. function $t_{0,\tau} = f(\tau)$. Mutual impact of ambient temperature on slab surface can be [3] provided in the heat balance equation for the considered structural arrangement of the pavement.

$$R + P + V + (M \times Q) = 0 \tag{1}$$

where:

R – refers to solar radiation understood as the difference between absorbed of short-wave solar radiation, ranged from 0.3 to 3.0 μm, and waves of greater length measured by slab surface,

P – refers to heat amount obtained and consumed while touching the slab surface as a result of heat transfers of turbulent nature,

V – refers to the amount of volumetric heat which is between slab surface and lower structural layers of pavement or the ground,

(M × Q) – refers to amount of heat changing into water vapour or water vapour condensation in the course of changing evaporation mass M into evaporation heat Q.

In case of concrete pavements the heat flux occurring as a result of evaporation or vapour condensation (M x Q) during bright, sunny, summer days is close to zero value.

Equation (1) refers to the principle of conservation of energy in thermodynamic processes, together with heat distribution process, which takes place on the slab surface or the surrounding ground under the influence of solar radiation.

According to the conclusions of the [1, 3], the basic summand of equation (1) is radiation factor which can be presented in the form of

$$R= Q + q - \Theta - E_{ef} \quad (2)$$

where:

Q, q, Θ – are forms of linear, reflected and shortwave radiation,

E_{ef} – refers to effective radiation of slab surface or the ground, determined on the basis of the relationship $E_{ef} = E_n - qE_d$.

Taking into consideration the heat flux and focusing on energy-related aspects, the reflection ability of the considered surface a_0, can be assessed, which should be understood as dispersion of radiation R_0 from the reflective surface of the slab or the ground surrounding the slab. According to the equation (2) after conversions, the form of radiation can be obtained

$$R = (Q + q)(1 - a_0) - E_{ef} \quad (3)$$

In case of concrete pavements the heat flux (M × Q) occurred during the evaporation or vapour condensation process on sunny days is close to zero. In such a situation, thermal balance equation concerning the concrete pavement for summertime

$$(Q + q)(1 - a_0) - E_{ef} + P_0 + F_0 = 0 \quad (4)$$

Summands included in the equation (4) can be determined in the course of field or theoretical measurements.

Equation (1) includes the summand P, which can be determined based on the relationship (5). This parameter includes the phenomenon of turbulent heat flow amount within the contact area of the following: pavement slab and the air surrounding thereof.

$$P = a_k (t_{pow} - t_{ekw}) \quad (5)$$

where:

a_k – convective volume heat coefficient,

t_{pow} – surface temperature near the ground,

t_{ekw} – coefficient of equivalent temperature rise according to the relationship,

ϱ – coefficient of material heat capacity,

j – solar radiation intensity related to slab surface heating,
ʎ – coefficient of material thermal conductivity.

Analysing the issue of thermal balance of the pavement, it should be referred to longitude and latitude. Determining changes of heat flowing within 24 hours, they can be specified as follows:

$$P_\tau = P^d_{śr} + A_p \cos \omega (\tau - 14) \quad (6)$$

where:
P_τ – amount of flowing heat of turbulent nature within 24 hours,
A_p – amplitude of thermal volume changes (P_{max} - P_{min}):2,
$P^d_{śr}$ – average daily heat of the structure.

Temperature of slab surface can be determined as the total of air temperature and equivalent temperature t_{ekw} = f(P). Heat flow within the pavement in uneven. There are differences between temperatures of upper and lower slab surface. Thermal condition of a slab on the considered upper and lower surface thereof, is also uneven. Such a situation is caused by the following: differences within zone surface humidity, absence of material structural homogeneity, its density. Therefore, analysing the phenomenon of heat relocation within concrete pavement, the relationship between slab surface temperature t_p, temperature gradient should be found (t_p - t_{sp}) thermal resistance in case of heat transmission (thermal wave impedance). These phenomena should be considered for:

- night time

$$t_n = t_p ((a_k \cdot h) : (\lambda + a_k \cdot h - j \cdot \lambda)) \quad (7)$$

- daytime

$$t_d = (t_p + t_{ekw}) \cdot ((a_k \cdot h) : (\lambda + a_k \cdot h - j \cdot \lambda)) \quad (8)$$

3. Heat relocation within pavement structural arrangement

Temperature of upper slab surface contains ambient air temperature and equivalent temperature. The occurred temperature difference of upper and lower slab surface results in stress condition of the structure. The issue of thermal stress of the pavement can be considered as wave issue. Practical aspect of wave process occurring in case of layer type of road or airfield structures made of cement concrete proves the occurrence of refraction within the area of component layers of pavement structural arrangement. Using proper selection of impedance of thermo elastic layers of structural arrangement, it is possible to influence temperature distribution in this regard and, as consequence, the extent of the occurred thermal stress. It provides the opportunity to minimize negative effects of thermal influence on the pavement and, first of all, on the slab deformation and consequently other parameters thereof, among others, bearing capacity. Coefficient j introduced in case of relationship (5), takes into consideration changes of slab heating intensity or weakening of this process. Slab heating intensity **j** can be presented as the relationship in the formula

$$j = (a_k \cdot h) : (\lambda + a_k \cdot h - j \cdot \lambda) \tag{9}$$

Consequently, during summertime and daytime, we obtain various slab heating intensity, when $j \leq 1$, while in case of night-time $j \geq 1$. Explaining the issue of heat flow in case of pavement it can be observed that if $t_p \geq t_{sp}$, then $j \leq 1$ and then the heat will be transferred from slab surface to its lower layers and accordingly for the relationship $t_p \leq t_{sp}$ then $j \geq 1$ then the heat will flow from lower layers of the slab towards its surface. At various times during the year, temperatures of the slab surface and its lower layers are diversified in terms of plus and minus. Fig. 1 presents visual diagram of this condition.

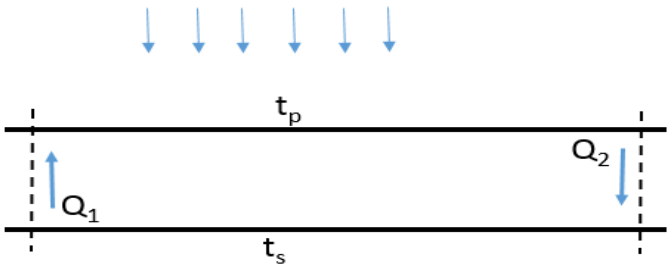

Fig. 1. The heat relocation: Q1 – heat will flow from lower layers of the slab towards its surface, Q2 – heat will be transferred from slab surface to its lower layers

The issue of heat flow discussed on the basis of the example **j** refers to temperature changes occurring in case of the pavement within 24-hour-cycle. In order to determine stress in concrete pavement, annual changes should also be analysed, however the scope of this analysis is very complex.

The problem of heat relocation within the pavement structure can be analysed for two situations:

1. On slab surface, then the heat flux Q* can be presented as the relationship in the formula (10)

$$Q^* = - K \text{ grad } T + \Theta (T - T_0) \tag{10}$$

where:

ϴ – refers to thermal conductivity coefficient, according to Newton,

T_0 – outer air temperature.

2. Within the contact area of layers, assuming that thermal energy flows on a permanent basis, temperatures equality and equality of heat flow will be maintained, according to Fourier's law. Consequently, solving this problem, wave parameters should be taken into consideration which are typical for heat distribution, including: thermal wave impedance I, wave reflection coefficient r, and refraction coefficient w. These values are described in the following relationships: $r = I_2 / I_1$, informs about the amount of reflected heat within the range from 0 to ∞, is within the range from -1 to 1 - $w = (1 - r_T) / (1 + r_T)$, determines the amount of reflected heat in comparison to heat which penetrated another layer, J – thermal wave impedance according to [5], can be presented in the formula

$$J = \varrho\, c_v\, \lambda \tag{11}$$

where:

ϱ – is the density of the medium responsible for heat flow process,

c_v – medium heat capacity,

ʎ – amount of heat conductivity.

Thermal refraction coefficient occurs in the airfield pavement, together with mechanical wave coefficient.

4. Temperature of pavement structure during one side heating

In order to analyse this issue, the following assumptions were made: the pavement is isotropic body and its thermal characteristics is uniform. Influence of the temperature on the slab is perpendicular to its surface, slab deformations can occur in both directions x and y. Heat transfer through lateral surfaces of the slabs and expansion cracks during the first stage of the analysis may not be taken into consideration. Appropriate pavement slab density and its dimensions are the problem during concrete setting. It is exothermic process which, according to this publication, was not considered earlier as completed. Therefore, it is not taken into account in further considerations of this publication. Investigating the stress problem in case of concrete pavements, the issue of the "massive nature of pavement structure" should be taken into consideration. Massive nature of the pavement, in this case, should be understood as the ratio of the total size of pavement slab surface with regard to its volume. It was recognized that concrete pavements in case of which this ratio is $M_n \leq 2$ accordingly are massive type of structures taking into consideration these values within the following range from $2 \leq M_n \leq 15$. These structures are considered of average massive nature and, in reality, the airfield concrete pavement structures are like that. Structures of mass coefficient higher than 15 are not considered mass structures in thermal regard. Temperature distribution, according to which thermal reaction field on the pavement stabilizes, is the consequence of heat conductivity

$$dQ = ʎ\ dt/dz \tag{12}$$

where:

dt – refers to the change of temperature influence extent,
dz – direction of heat distribution,
dQ – flowing heat amount.

Heat flow in elementary volume dV = 1cm^3, within unit of time dτ = 1, equals heat flux increase (δ (δ Q)) : δ z . In cases of periodical slab heating and cooling and as a result of influence of air temperature and solar radiation, the course of these phenomena is of trigonometric function nature (sine and cosine), in such a situation equation concerning the slab temperature changes within its upper surface in the considered period of time τ and it is as follows:

$$t_{0,\tau} = t_{śr} + t_p^m \cos \omega\tau \tag{13}$$

where:

$t_{śr}$ – average temperature of slab surface,
t_{mp} – maximum temperature deviation from its average value,
ω – frequency of temperature fluctuations on slab surface within the considered area determined according to the relationship ω = 2π / T.

Relationship (13) is the limiting condition which allows using differential equation of thermal conductivity in the form of $\delta t/\delta\tau = (a\ \delta^2 t) / (\delta z2)$ for the assumed criteria. The solution of this equation was presented in the publication [2] and it is as follows

$$t_{z,\tau} = t_{śr} + t_p^m\, e^{-\sqrt{\frac{\omega}{2a}}} \cos\left(\omega\tau - z\sqrt{\frac{\omega}{2\lambda}}\right) \tag{14}$$

According to the relationship, the following conclusion can be drawn: the highest temperatures occur when τ = 0 and then we receive the following:

– for the upper surface, where: z = 0, → $t_{0,0} = t_{śr} + t_p^m$
– for the lower surface whwn: z = h, → can write a dependency:

$$t_{h,0} = t_{śr} + t_p^m \, e^{-} \sqrt{\frac{\omega}{2a}} \quad \cos\left(- h \sqrt{\frac{\omega}{2a}} \right) \tag{15}$$

Data required to consider climatic phenomena for a given region, should be approved in accordance with the information provided by the relevant weather stations.

According to the analyses presented in the publication (4) water vapour and migration thereof occurs in structures. However, its influence on the amount of volumetric heat, in case of hardened concrete is unnoticeable. Within the hardened concrete, there is approximately 3% to 4%, of free water vapour and its amount cannot significantly influence the course of further thermal processes in the pavement.

5. Design temperatures in case of airfield and road concrete pavements

The analysis of phenomena resulting from relationship (14) allows presenting some practical observations addressed mainly to those who use this type of pavements. These observations include the following occurrences:

1. Intensive solar radiation and stress of concrete pavement caused thereby as a result of which significant slabs relocation may occur, both horizontal x, as well as vertical y. Vertical slab relocation – warping, is caused by the occurrence of significant temperature gradient. Currently, temperature distribution at the depth **z** during time **τ** decides about the nature and extent of slab deformation, defined as "curling". Together with the increased considered layer, on a certain slab depth, the reduction of temperature can be observed. This phenomenon takes place in accordance with the relationship.

$$U = \sqrt{\frac{\pi}{aT}} \quad \exp\left(- z \quad \right) \sqrt{\frac{\pi}{aT}} \quad = \exp(- z) \tag{16}$$

Disappearing of slab temperature at its depth takes place in case of value **u = 0** where **z**→∞. Analysing the aforementioned, the following observations can be made: disappearing of temperature is more intensive when pavement slab is less thick, **u** $\neq$ **0**.

Faster temperature changes occur when the value of thermal conductivity coefficient is lower, which is referred to thermal properties of materials used for layers. In case of majority of materials which form structural layers of airfield-road pavements, in most situations noticeable temperature fluctuations take place at the depth of 0.5 to 0.6 m and they disappear at the depth of 0.8 to 1.0 m. Observations regarding annual changes prove that temperature disappearance occurs at greater depth of some or a dozen or so metres.

2. The length of thermal wave in case of l_T pavements determined, assuming the time of temperature change **τ** and variation period **T (τ = T),** results in the amplitude of temperature change, which in these conditions reaches maximum values and occurs when the fluctuation amplitude is maximum $\cos(\omega\tau - z\sqrt{\frac{\omega}{2a}})$ is suitable for **z=l.**

3. The velocity of thermal wave propagation equals the wave length (wave distance) divided by the fluctuations period τ = T. The essence of this phenomenon can be presented as follows

$$V_T = L_T, \qquad T = 2 = 2\sqrt{2\pi T_{a:}} \quad : \; T = 2a\omega \tag{17}$$

4. The time related to the delay of maximum temperatures on a variable slab depth

$$\tau_\phi = Z{::}\, V_l = z, \qquad \tau_\phi = \sqrt{\frac{1}{2a\omega}}\; z \tag{18}$$

The discussed factors, such as: temperature disappearing within a slab refer to its depth, thermal wave length $\mathbf{l_T}$**,** velocity of its propagation $\mathbf{v_T}$ and the time related to the delay of its course are functional relations: u = f (z, a), l_T = f(a), τ_ϕ = f (z, a) and l_x = f (a) prove that the presented considerations of thermal waves propagation within a complex layer medium remain in close connection with the component elements – layers of structural arrangement, they were made of: structural layer, base course and subgrade. It is clear that the intensity of propagation in layers is related to the time of the day, it can be observed especially in case of annual changes cycle. Accuracy of operation in case of the designed pavement depends not only on structural slab thickness, but it is closely related to geometric surface arrangement thereof, based on optimum division into single elements (slabs) of certain size. Justified tendency in case of pavement design based on extending distance between cracks (contraction type or expansion cracks) within slabs, requires taking into consideration the phenomenon of "spatial slab stability". This phenomenon refers to the excessive limitation of cracks number – mainly expansion cracks. The consequence of such solutions are oversized slabs which, even at significant slab thickness and moderate and stable air temperatures, results in "spatial pavement deformation" even when slab edges are combined with one another by means of appropriate connectors. Field tests [2, 4] proved that the temperature of concrete pavement slab is lower by approx. 5°C than the temperature of the subgrade being part of structural pavement arrangement. These temperature values are close to each other. During heat flux flow, some local discontinuities (surface coarseness or micro cracks) occur on pavement surface, which are a kind of heat accumulator on slab surface and the close vicinity thereof.

6. Conclusions

Phenomena of thermal and mechanical wave refraction play significant role in layer type of structures, such as road and airfield pavements. Introduced in the publication and described by means of relationships: refraction coefficient, thermal wave impedance or wave reflection coefficient and relations between thereof allow analysing the influence of the applied materials on temperature distribution within structural pavement arrangement and the extent of thermal stresses occurring within the slab. Determining refraction coefficient of the complex medium the value of which is w = 0, we can obtain – wave impedance matching coefficient of concrete pavement slab and lower layers, together with subgrade. Practically, this means that matching properly material properties distinguished by: anticipated thermal capacity, thermal conductivity coefficient and medium density, we can eliminate the occurrence of interlayer thermal and mechanical reflection. If thermal refraction coefficient is w = 0, then also mechanical refraction coefficient is of the same value. Therefore, complete recognition of wave processes of thermal and mechanical nature can significantly limit negative effects caused by aircrafts traffic on concrete airfield pavements and those caused by vehicles traffic on concrete road pavements. The necessity to prepare individual thermal balance of the pavement, suggested in the publication, results from the fact that in case of our country, geographic location of airport or traffic routes significantly influence the pavement condition in the course of technical durability thereof.

7. References

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