

THE INFLUENCE OF THE CARBO-GLASS GEOGRID-REINFORCEMENT ON THE FATIGUE LIFE OF THE ASPHALT PAVEMENT STRUCTURE

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This paper describes the analyses of the fatigue life of the asphalt pavement reinforced with geogrid interlayer under traffic loading. Finite Element ANSYS package with using nCode applications, as well as macros specially designed in APDL programming script and VBA were used to model the considered problem. Our analysis included computation of stress, fatigue life, damage matrix and rainflow matrix. The method applied was the one of fatigue calculation: stress – number of cycles in short S-N. On the basis of the performed high cycle fatigue analysis, the influence of the location of the used geogrid and of its bond with asphalt layers on the fatigue life and the work of the asphalt pavement structure were determined. The study was carried out for three temperature seasons i.e. spring and fall (assumed as one season), winter and summer. The variability of the traffic conditions were taken into account by assuming weekly blocks of traffic loading. The calculations were made using the real values of loading measured in field tests on the German highways by means of HS-WIM weighing system. As a result of the performed tests, it was proved that the use of geogrid-reinforcement may prolong the fatigue life of the asphalt pavement. However, it is required that: the geogrid should be located in the tension zone as low as possible in the structure of the asphalt layers. Moreover, it is necessary to provide high stiffness of the bond between the geogrid and the asphalt layers.

Key words: geogrid, asphalt pavements, discrete and finite element modeling, fatigue, geogrid-reinforcement, contact of layers, stress–number of cycles.

1. INTRODUCTION

A significant growth in heavy load traffic is a currently observed in many European countries. For instance in Poland during the last decade the number of heavy vehicles travelling on the roads has doubled and the permissible single axle load value was also increased. The main European road network has been designed for the axle loading of 115 kN, which for our country is a major challenge, because so far the majority of roads in Poland have been designed for loading of 80 kN and 100 kN per axle.

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Searching for new ways to increase the durability of their asphalt pavement one should consider their reinforcement with selected kinds of geogrids or composites (a combination of geogrid and unwoven material) which are characteristic for their stiffness and the stiffness of the bonding to the asphalt layers [1], [2], [3], [6], [7], [11], [18]. This feature is a new approach, because the geogrid was almost always applied as the stress relieving interlayer to repair the reflection cracks created as a result of the discontinuities in the lower layers of the pavement structure.

Reinforcing the asphalt pavement in such a way that the discontinuity in the lower layers is eliminated results, first of all, in improvement of the fatigue life of the whole structure and so in the increase of the number of the loadings carried by the construction before it is damaged, or the decrease in the thickness of the designed layer while maintaining the level of desired fatigue life. Since this technology is still in the process of development, there is a number of issues that still wait for consideration. One of them is the question of the choice of the type of geogrid-reinforcement as well as its location, and the method of how to build it in. So far the studies dealing with these issues have had an experimental character and to in less range, the theoretical one [8], [9], [14], [17].

These conditions were taken into account, in certain research on the fatigue life of the asphalt pavement reinforced with a geogrid consisting of the carbo-glass fibre with relation to various kinds of interlayer bonding submitted to traffic loading and with relation to the temperature seasons characteristic for the selected, south region of Poland.

The studies correspond to the papers described in the FHWA report [12] on numerical analyses of the asphalt pavement reinforced with the geogrid located in the aggregate subbase. However, location of the geogrid in the asphalt layers and the evaluation of the fatigue life of such a structure required application of different numerical methods.

2. NUMERICAL ANALYSES

2.1. VARIANTS OF PAVEMENT STRUCTURES USED IN THE ANALYSES

The subject of the analysis was the asphalt pavement structure for heavy traffic load i.e. with the daily traffic load of 2000 equivalent axles of 100 kN. The pavement structure was reinforced with a geogrid spread over the entire width of the carriageway. In the numerical model the reinforcement layer was located in three different places i.e. on the aggregate subbase with the use of the 3 cm thick asphalt levelling layer (i.e. located at a depth of 31 cm), in the middle of the asphalt base layer (located 22 cm deep) and at the bottom of the asphalt binder layer (at a depth of 13 cm). The asphalt pavement structure presenting the location of the geogrid is shown in Fig. 1.

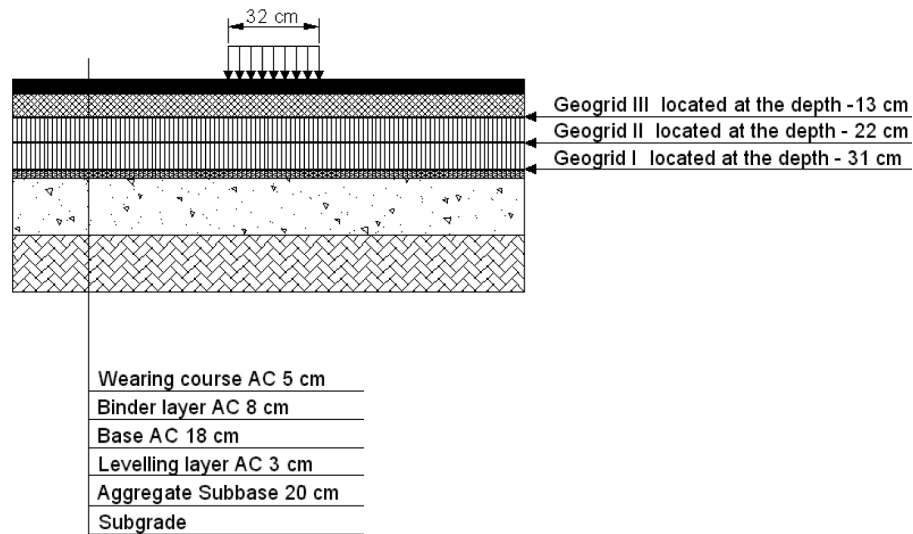


Fig. 1. The system of the layers in the analyzed asphalt pavement showing the variant locations of the geogrid-reinforcement.

Rys. 1. Układ warstw analizowanej nawierzchni z zaznaczonymi wariantowymi lokalizacjami pośredniej warstwy zbrojącej, tj. geosiatki

The analyses were carried out for several variations of the pavement structure which differed not only in the location of the geogrid-reinforcing but also in the way of bonding between layers. The variants of the contact conditions between layers used in the models of pavement structure are listed in Table 1.

Until now laboratory tests have indicated the decrease in bonding between layers due to the presence of the geogrid in comparison to the bonding without geogrid (what was compensated by growth of fatigue life) [9]. For this reason the contact zones between geogrid and asphalt layers were described by Coulomb's law. Several values of the friction coefficient were assumed and the fatigue life of the pavement structure in relation to this parameter was determined. The material parameters of the structure layers and subgrade used for the numerical calculations are listed in Table 3. Material and geometric parameters for the geogrid-reinforcement were determined in the laboratory tests using uniaxial tension method of the wide samples and extraction of the fibers [5]. The numerical analyses were made for all seven variants of the bonding between layers in three locations of the geogrid in the pavement structure.

The values of the numerical analyses are listed below.

For comparison purposes additional analyses for the following two cases of the structure without geogrid-reinforcement were carried out. The results are presented in Table 2.

Table 1

Variants of bonding between layers of the asphalt pavement structure reinforced with the geogrid-reinforcement.
Warianty połączenia międzywarstwowego w modelach konstrukcji nawierzchni zbrojonej geosyntetykiem

<i>Symbol</i>	<i>Type of bonding between the layers of the structure</i>
B – case 1	Full bonding between all the layers and between the asphalt layers and the geogrid-reinforcement (continuity of all the components of the displacement vector)
F=0.00 – case 2	No bonding between the geogrid and the asphalt layers in the tangent direction (bonding only in the direction normal to the contact area), the coefficient of the Coulomb model friction is F=0.00. The remaining layers of the pavement structure were in full bonding.
F=0.25 – case 3	No bonding between the geogrid and the asphalt layers in the tangent direction (bonding only in the direction normal to the contact area), the coefficient of the Coulomb model friction is F=0.25. The remaining layers of the pavement structure were in full bonding.
F=0.50 – case 4	No bonding between the geogrid and the asphalt layers in the tangent direction (bonding only in the direction normal to the contact area), the coefficient of the Coulomb model friction is F=0.50. The remaining layers of the pavement structure - full bonding.
F=0.75 – case 5	No bonding between the geogrid and the asphalt layers in the tangent direction (bonding only in the direction normal to the contact area), the coefficient of the Coulomb model friction is F=0.75. The remaining layers of the pavement structure were in full bonding.
F=1.20 – case 6	No bonding between the geogrid and the asphalt layers in the tangent direction (bonding only in the direction normal to the contact area), the coefficient of the Coulomb model friction F=1.20. The remaining layers of the pavement structure were in full bonding.
F=0.00* – case 7	Full bonding between the geogrid and asphalt levelling layer, between the geogrid and the base layer - no bonding in the tangent direction (bonding only in the direction normal to the contact area), the coefficient of the Coulomb model friction is F=1.20. The remaining layers of the structure were in full bonding.

Table 2

Variants of bonding between layers of the asphalt pavement structure without the geogrid-reinforcement.
Warianty połączenia międzywarstwowego w modelach konstrukcji nawierzchni niezbrojonej geosyntetykiem

<i>Symbol</i>	<i>Type of bonding between the layers of the structure</i>
ZW – case 1	Full bonding between all layers of the pavement structure (continuity of all the components of the displacement vector)
BZW – case 2	No bonding between asphalt layers (the friction coefficient = 0.00) but with the full bonding between the contact area of the aggregate subbase and subgrade and also at the full bonding between the base and aggregate subbase.

2.2. MODEL AND MATERIAL PARAMETERS

The elastic multi-layers system where the geogrid is modeled as reinforcement by a membrane with only tensile stiffness was assumed as a physical model of the pavement and subgrade. Besides, it was also assumed that with one exception the full bonding

does not exist between the membrane and the asphalt layers. The Coulomb friction model in the tangent directions to the surface of the contact was introduced. It is characterized by friction coefficient μ defined as (2.1):

$$(2.1) \quad \mu = \frac{\tau_k}{p_k}$$

where: τ_k is shear stress on the contact surface, p_k is normal stress to the contact surface.

At the normal direction to the contact surface, the continuity of the components of the displacement vector was assumed. For the remaining layers between which the geogrid was not placed, the full bonding was assumed (the continuity of the displacement). The conditions of the geogrid-reinforcement binding with asphalt layers for top and for the bottom of the geogrid were described by one value of the friction coefficient μ .

The constitutive models for all materials of which the pavement structure was composed, were assumed for the fatigue analyses as linear elastic (Hooke's model). The values of the stiffness modulus for the asphalt layers, which are the function of the speed at which the vehicles travel (relating to the time of loading) and the temperature, were assumed on the basis of the temperature profiles and the average speed of the vehicles for specific temperature seasons (Fig. 2). The stiffness modulus of asphalt layers replaces Hooke's modulus, what is the certain simplification in analyses. Numerical calculations were made for material parameters listed in Table 3. The geogrid-reinforcement was modeled by the equivalent orthotropic continuum layer – a membrane with only tensile stiffness and the thickness of 0.06 mm. Elastic modulus determined in laboratory tests were: $E_{XX} = 150811$ MPa (carbon fibers), $E_{ZZ} = 59092$ MPa (glass fibers) [5], where X and Z are the directions of the orthotropic location of glass and carbon fibers consistent with the global coordinates XYZ of the FEM model. Equal values of shear modulus and the major Poisson's ratio were assumed: $G_{XZ} = 0.20$ GPa and $\nu_{xz} = 0.20$ respectively.

Table 3

Material parameters for the pavement layers in the specific seasons:
SPRING/FALL, SUMMER, WINTER.

Przyjęte stałe materiałowe warstw nawierzchni dla poszczególnych sezonów:
WIOSNA/JESIEŃ, LATO, ZIMA

The layer	Stiffness Modulus E [MPa]	Poisson's ratio ν	The Thickness of the Layer [cm]
Wearing course AC	dependant on the temperature (changing with the depth), Figure 2	0.30	5
Binder layer AC		0.30	8
Base AC		0.30	18
Aggregate Subbase	400	0.35	20
Subgrade	100	0.35	450

Besides, it was assumed, that in the subgrade at the depth of 450 cm the bedrock was situated and it did not affect the results of analyses.

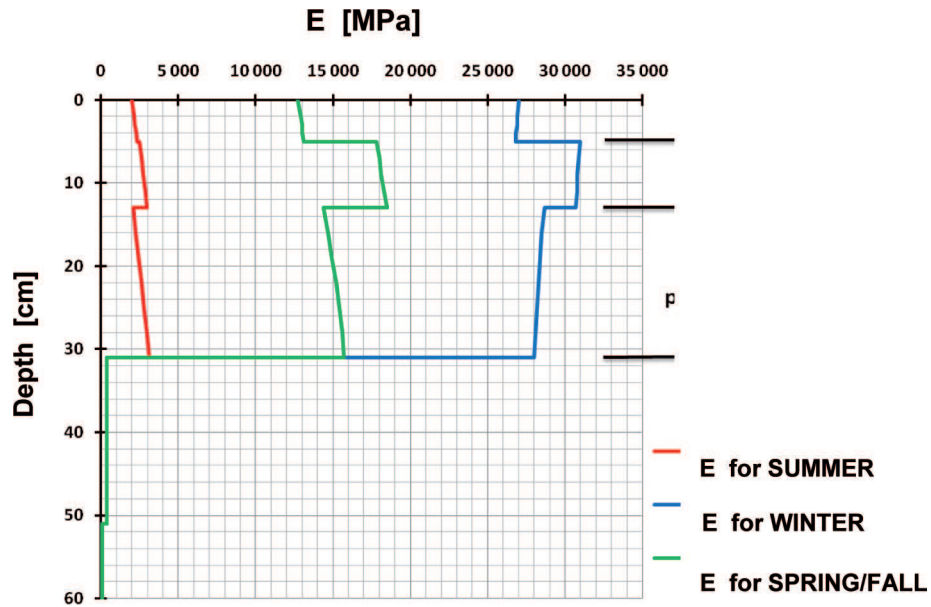


Fig. 2. The graphic representation of the elastic modulus E of the asphalt layers, aggregate subbase and subgrade for specified temperature seasons, distributions assumed for the numerical analyses.

Rys. 2. Wykresy wartości modułów sztywności sprężystej E warstw asfaltowych, kruszywa i podłoża gruntowego dla poszczególnych sezonów temperaturowych, rozkłady przyjęte do analiz numerycznych

For simplification, the wheel loads were reduced to vertical load only neglecting the horizontal forces, and they were modeled as the pressure of time dependent value and applied to the surface on a disc with the diameter of 0.32 m (Fig. 5a). The variability of the load in specified seasons was closed in blocks and ascribed to three temperature seasons: SPRING/FALL, WINTER, SUMMER. Types of vehicles for specified seasons were collected in field tests on German highways [15] and prepared for fatigue analysis by ICE-flow system (Fig. 3). Types of vehicles in the selected weeks for specified seasons are presented in Fig. 4.

Because of the symmetry of the static model of the construction in the fatigue analysis, only a quarter of the three-dimensional model of the pavement structure was taken into consideration, Fig. 5.

It was assumed that evaluation of the fatigue life of the asphalt layers structure (N_{str}) consists in determining the smallest number of cycles after which the damage of at least one of the materials may occur: asphalt concrete (N_p), the material of the geogrid-reinforcement (N_s), or the adhesion layer – the bonding between the geogrid and the asphalt layers (N_{adh}). The geogrid stops playing the role of the reinforcement

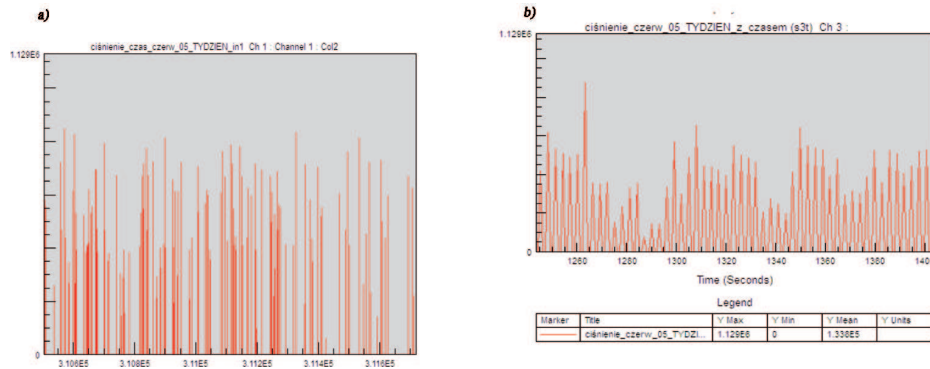


Fig. 3. An example of a sample load history in the SUMMER temperature season [Pa] for vehicle wheels a) measured in field tests [15], b) prepared for FEM-fatigue analysis using the ICE-flow application.
 Rys. 3. Przykładowy fragment przebiegu czasowego obciążenia z sezonu temperaturowego LATO [Pa] od kół poruszających się pojazdów a) pomierzony w badaniach polowych [15], b) przygotowany dla analiz zmęczeniowych MES z wykorzystaniem aplikacji ICE-flow

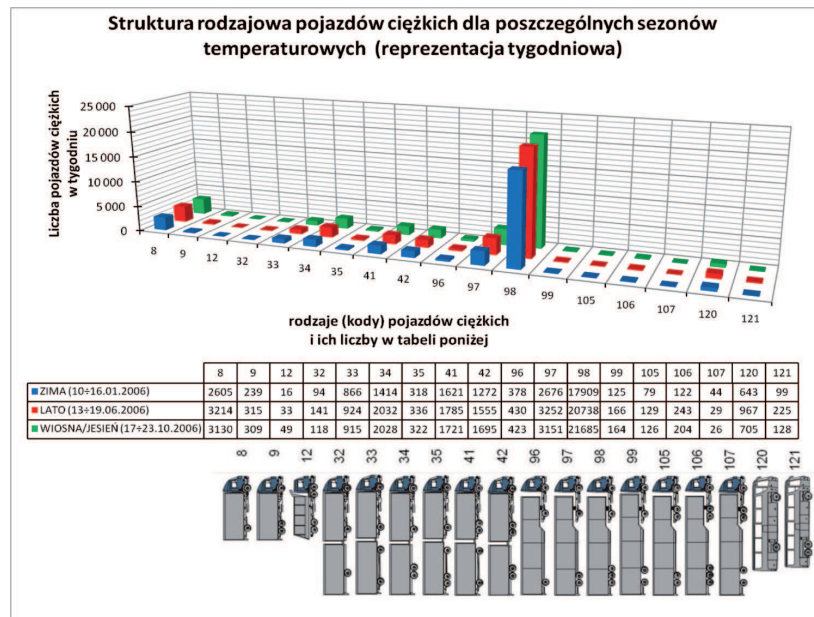


Fig. 4. Types of vehicles for the specified temperature seasons determined on the basis of the field tests [15]
 Rys. 4. Struktura rodzajowa pojazdów ciężkich dla poszczególnych sezonów temperaturowych, wyznaczona na podstawie badań polowych [15]

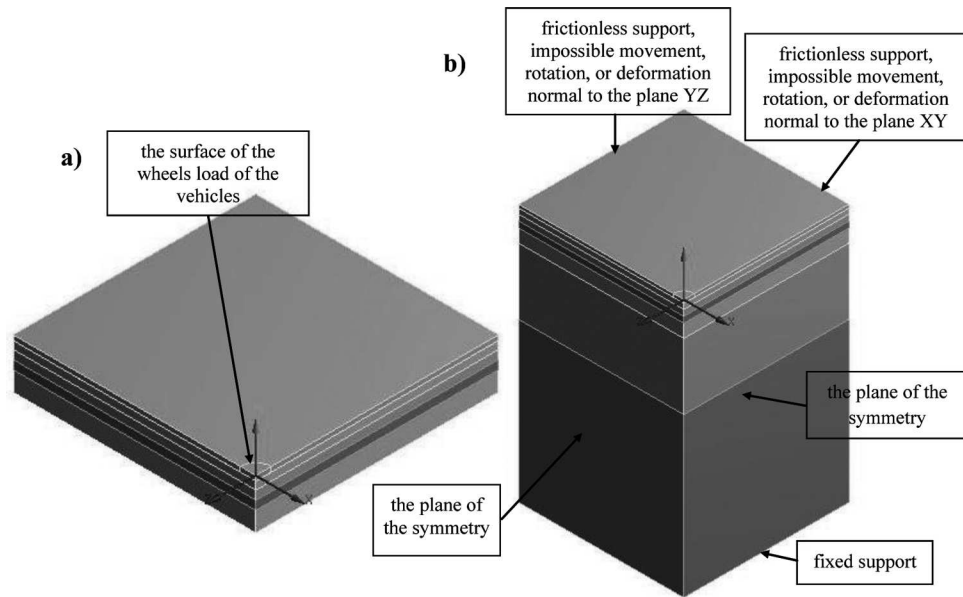


Fig. 5. a) Geometric model of the asphalt pavement structure showing the area where the contact pressure from the heavy vehicle's type is applied, b) geometric model of the pavement structure and subgrade taken for FEM analyses – the XYZ the global coordinate system.

Rys. 5. a) Model geometryczny konstrukcji nawierzchni z zaznaczoną powierzchnią działania ciśnienia kontaktowego od opony pojazdu ciężkiego, b) model geometryczny konstrukcji nawierzchni i podłoża gruntowego przyjęty do obliczeń, XYZ – globalny układ współrzędnych

in the structure. Therefore the fatigue life of the asphalt structure reinforced with a geogrid can be described by the following equation (2.2):

$$(2.2) \quad N_{str} = \min(N_p, N_s, N_{adh})$$

At this phase of the study, it was assumed that only the fatigue material properties of the asphalt concrete (N_p – the minimal value in the set) play the role in evaluation of the fatigue life of the pavement structure. It was assumed that the conditions of the contact between all the layers of the structure do not change during the service. Also, it was assumed that the fatigue life of the structure does not indicate the period of time until the entire structure is damaged but only the period of time till local fatigue cracks are initiated and macro-cracks appear (the criterion of fatigue damage).

The fatigue life of all the variants (N_{str}) was calculated on the basis of the *Palmgren-Miner* hypothesis of the linear summing of the fatigue damage for the specified temperature seasons, according to the equations (2.3–2.6):

$$(2.3) \quad D_c = 2 \cdot D_{\frac{SPRING}{FALL}} + D_{SUMMER} + D_{WINTER}$$

$$(2.4) \quad D_{\frac{SPRING}{FALL}} = \frac{n_1}{N_{T1}}$$

$$(2.5) \quad D_{SUMMER} = \frac{n_2}{N_{T2}}$$

$$(2.6) \quad D_{ZIMA} = \frac{n_2}{N_{T2}}$$

where (2.3–2.6):

D_c is fatigue damage for all temperature seasons [–], $D_{SPRING/FALL}$ is fatigue damage for temp. season SPRING/FALL [–], D_{SUMMER} – fatigue damage for temp. season SUMMER [–], D_{WINTER} is fatigue damage for temp. season WINTTR [–], n_i is the number of the load blocks in a given temperature season – the number of weeks [–], N_{Ti} is the damaging number of load blocks (weeks) for a given temp. season [–].

If the sum D_c in equation (2.3) reaches the value 1, the pavement structure is damaged according to the assumptions given above.

2.3. THE FINITE ELEMENT MODEL OF THE PAVEMENT STRUCTURE WITH GEOGRID-REINFORCEMENT FOR THE FATIGUE ANALYSES

The following elements at the ANSYS code were used from the software ANSYS in FE modeling of the pavement structure: 20-node, solid element SOLID186, 8-node SURF154, the contact surfaces between the layers were modeled with 8-node elements of the TARGE170 and CONTA174. The final mesh of the model is presented in Fig. 6a. The geogrid was modeled by the 4-node anizonomic 2-dimentional elements SHELL41, which enabled functioning of this layer only with the membrane stiffness and with the tensile stiffness Fig. 6b.

FEM model of the asphalt pavement structure was subjected to empirical verification. The verification was carried out in the Federal Highway Research Institute in Germany for the variant of the structure without the geogrid in the asphalt layers and submitted to the static load of the vehicle [5]. The results were satisfactory, what enabled the authors to perform further analysis employing the FEM model.

2.4. THE FATIGUE MATERIAL PROPERTIES OF THE ASPHALT LAYERS

The stress-life (SN) relations for the asphalt layers i.e. the wearing course layer, binder layer, base layer were determined on the basis of the fatigue test results for uniaxial tension at controlled force and carried out at the Braunschweig University by *Mollenhauer* [10]. These tests were the continuation of the study by *Rubach* in the 1990's, [13].

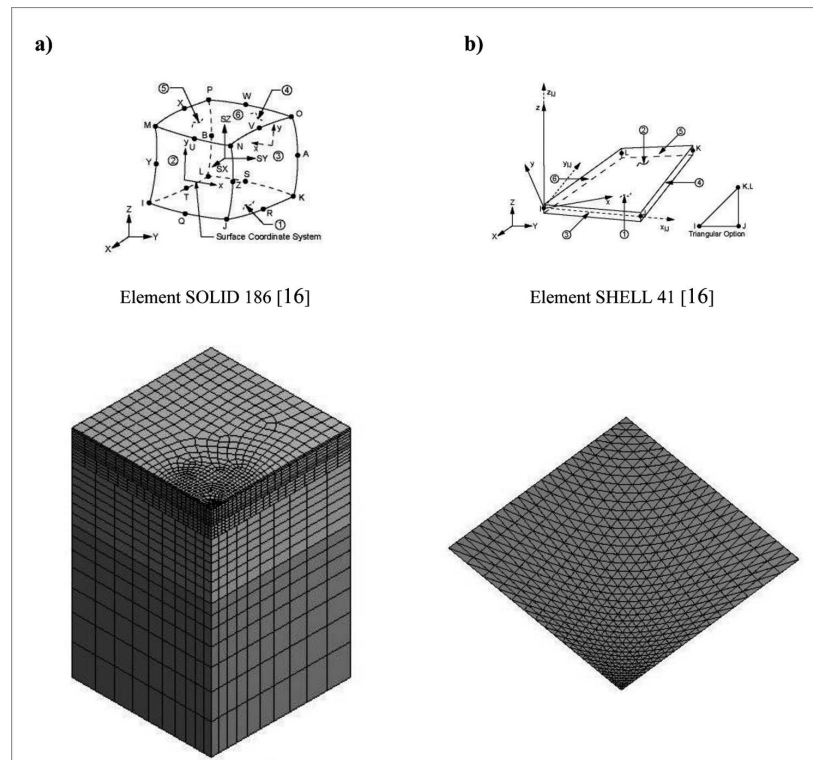


Fig. 6. The mesh of the FE model of pavement structure and subgrade with the SOLID 186 element, b) The final mesh of the FE model of the geogrid-reinforcement built into the asphalt pavement with the SHELL 41 element.

Rys. 6. a) Siatka MES przyjętej konstrukcji nawierzchni drogowej i podłoża gruntowego z głównym elementem SOLID 186, b) Ostateczna siatka MES geosyntetycznej warstwy zbrojącej wbudowanej w układ warstw nawierzchni z elementem SHELL 41

The experimental fatigue data described by the general correlation (2.7) were reformulated to formula (2.8) by means of *Goodman* correction (mean stress effects) taking into account the average temperature of the specified temperature profiles: SPRING/FALL, SUMMER, WINTER for the specific layers of the structure. The temperature correction was made according to the algorithm described in the literature [10]. Due to the lack of the following correlation $\sigma_a = f(\sigma_m)$, and taking into account the mean stress, the *Goodman* theory recommended for the situation where the influence of σ_a on the fatigue life of the material is not established in the laboratory tests (2.9).

$$(2.7) \quad N_{macro} = K_1 \cdot \Delta\sigma^{-K_2}$$

$$(2.8) \quad \sigma_a = SF \cdot K'_1 \cdot (N_{macro})^{K'_2}$$

where: K_1, K_2, K'_1, K'_2 are material constants [-], N_{macro} is the number of the load cycles till macro-cracks appears [-], $\Delta\sigma$, is the range of the stress [Pa], σ_a is the alternating stress of the cycle respectively [Pa], SF is Shift factor [-].

The fatigue curves established this way (Figs 7-8) with the asymmetry coefficient of the cycle $R - Ratio = -1$ were used for the fatigue calculations using the DesignLife and the ANSYS software. The shift factor of the laboratory test results corresponds to the real life results, SF , based on the initial analysis was assumed arbitrarily by author for all the asphalt layers at $SF=3.66$. The value is only a rough one, it needs a separate investigations in relation to the Polish conditions of traffic loads, climate and execution methods. The values of the tensile ultimate strength R_m for asphalt concrete of all the asphalt layers of the pavement structure in the uniaxial tension tests were determined on the basis of *Goodman* theory (Formula 9) and are listed in Table 4.

Table 4

Tensile ultimate strength AC for the asphalt layers analysed structure and specified temperature seasons. The test of the uniaxial tension [10].

Wytrzymałości na rozciąganie AC dla warstw asfaltowych analizowanej konstrukcji nawierzchni i poszczególnych sezonów temperaturowych. Próba jednoosiowego rozciągania statycznego [10]

Asphalt layers	Tensile ultimate strength [MPa] for equation (9)		
	SPRING/FALL	SUMMER	WINTER
Wearing course AC	1.82	0.54	5.30
Binder layer AC	1.95	0.57	4.50
Base AC	1.50	0.70	3.15

In the fatigue analysis of the pavement structure for the cross-referencing of the measured fatigue curves, the so called equivalent alternating stress σ_{ekw} (equation 2.9) was used. It included the correlation in respect to the mean stress effects (*Goodman* theory) and the equivalent stress of the *Galileo* hypothesis converted the multiaxial stress state to the uniaxial one [4].

$$(2.9) \quad \sigma_{ekw} = \frac{\sigma_{G,a}}{1 - \frac{\sigma_{G,m}}{R_m}}$$

where: σ_{ekw} is the equivalent alternating stress [Pa], $\sigma_{G,a}$ is maximum principal stress – amplitude value [Pa], $\sigma_{G,m}$ is maximum principal stress – mean value [Pa], R_m is tensile ultimate strength AC [Pa], according to Table 4.

3. RESULTS OF THE FATIGUE ANALYSES

The models were analysed as non-linear issues, due to the contact between pavement layers phenomena and the membrane stiffness type. Solutions were computed by the iterative *Newton-Raphson* procedure. The contact between geogrid and asphalt layers

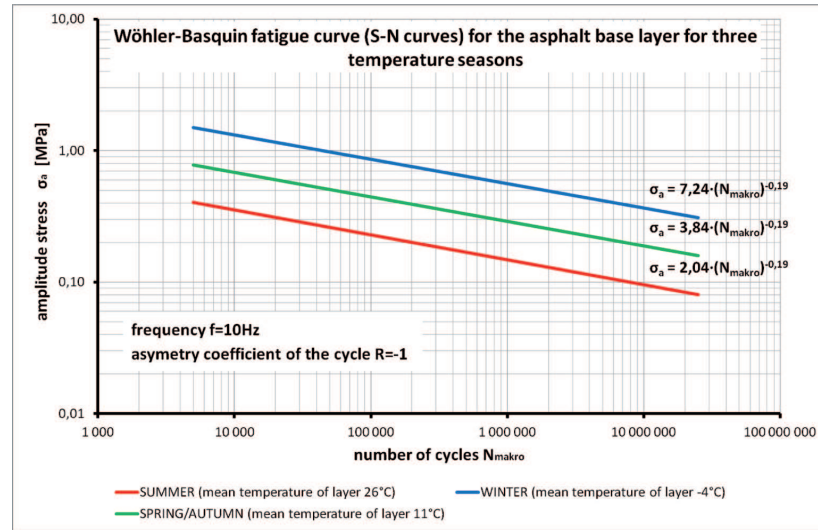


Fig. 7. Wöhler-Basquin fatigue curves (S–N curves) for the asphalt base layer of the analysed pavement structure for three temperature seasons.

Rys. 7. Wykresy zmęczeniowe Wöhlera-Basquina dla warstwy podbudowy związanej analizowanej konstrukcji nawierzchni, dla trzech sezonów temperaturowych

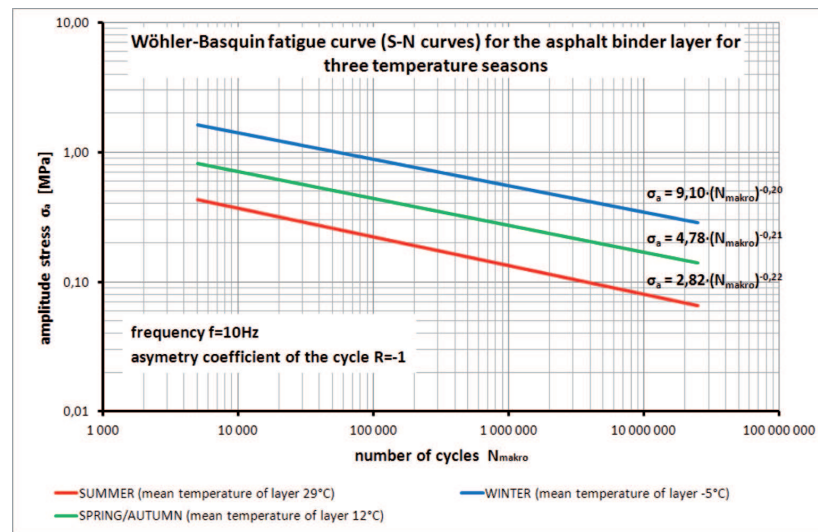


Fig. 8. Wöhler-Basquin fatigue curves (S–N curves) for the asphalt binder layer of the analysed pavement structure for three temperature seasons.

Rys. 8. Wykresy zmęczeniowe Wöhlera-Basquina dla warstwy wiążącej analizowanej konstrukcji nawierzchni, dla trzech sezonów temperaturowych

was solved for by *Pure Penalty* method [16]. The range of the numerical calculations included determination the values for all the variants of the analysed construction as follows:

- rainflow and damage matrices on the asphalt layers surface,
- the maximum equivalent alternating stress for the most strained elements of the structure,
- the minimal fatigue life of the asphalt layers of the pavement structure.

Table 5

Calculated fatigue life of the pavement structure for various values of the friction coefficient μ and for various locations of the geogrid.

Obliczona trwałość zmęczeniowa konstrukcji nawierzchni dla różnych wartości współczynnika tarcia μ , i różnej lokalizacji geosyntetyku

Fatigue life N_{str} [years] of the asphalt pavement structure with the carbo-glass geogrid reinforcement for variants of bonding between layers of the asphalt pavement structure			
case - symbol	contact conditions between asphalt layers (cases without geogrid-reinforcement)	N_{str} [years]	N_{str} with relation to N_{str} of case ZW [%]
ZW	full bonding between all layers	14,4	100,0%
BZW	no bonding between all layers	<1	-

case - symbol	contact conditions between asphalt layers and geogrid	location of the geogrid in pavement structure:		
		I location (depth of 31cm)	II location (depth of 22cm)	III location (depth of 13cm)
		N_{str} [years]	N_{str} [years]	N_{str} [years]
B	full bonding	25,5	15,8	10,0
F=0.00	friction coeff.=0.00	1,2	<1	<1
F=0.25	friction coeff.=0.25	4,0	1,7	1,3
F=0.50	friction coeff.=0.50	9,4	3,0	2,6
F=0.75	friction coeff.=0.75	15,4	7,9	4,8
F=1.20	friction coeff.=1.20	22,3	9,7	8,3
F=0.00*	one-side bonding	1,6	<1	<1

case - symbol	contact conditions between asphalt layers and geogrid	N_{str} with relation to N_{str} of case ZW [%]	N_{str} with relation to N_{str} of case ZW [%]	N_{str} with relation to N_{str} of case ZW [%]
B	full bonding	177,3%	110,0%	69,6%
F=0.00	friction coeff.=0.00	8,0%	-	-
F=0.25	friction coeff.=0.25	27,8%	11,5%	9,2%
F=0.50	friction coeff.=0.50	65,1%	21,0%	18,4%
F=0.75	friction coeff.=0.75	106,8%	54,7%	33,2%
F=1.20	friction coeff.=1.20	154,9%	67,7%	57,9%
F=0.00*	one-side bonding	11,0%	-	-

case - symbol	contact conditions between asphalt layers and geogrid	depth of macro-cracks appearance in the pavement structure *)		
B	full bonding	PD	PD	PD
F=0.00	friction coeff.=0.00	PD	PG	W
F=0.25	friction coeff.=0.25	PD	PG	PD
F=0.50	friction coeff.=0.50	PD	PG	PD
F=0.75	friction coeff.=0.75	PD	PG	PD
F=1.20	friction coeff.=1.20	PD	PG	PD
F=0.00*	one-side bonding	PD	PG	W

*) macro-cracks location:

PD – at the bottom of the asphalt base = 31 cm depth,

PG – at the bottom of the asphalt base = 22 cm depth,

W – at the bottom of the binder layer = 13 cm depth.

The results expressed as the fatigue life of the asphalt pavement N_{str} reinforced and non-reinforced with the geogrid as well as the locations of the first macro-cracks in the structure are listed in Table 5. Additionally, in Fig. 9 the graphs of the fatigue life of the structure for various conditions of the layer contact (coefficient of friction μ) were shown along the locations of the reinforcement.

The analyses results confirm the practical observations according to which good bonding the geogrid with the asphalt layers is the prerequisite of the effective functioning of the geogrid in the pavement structure. The complete lack of the bonding or its insufficient value makes it impossible to incorporate the geogrid into the functioning of the layer structure and causes the increase of the effective stress in the asphalt layers, which results in the faster damage of the pavement structure, Table 5.

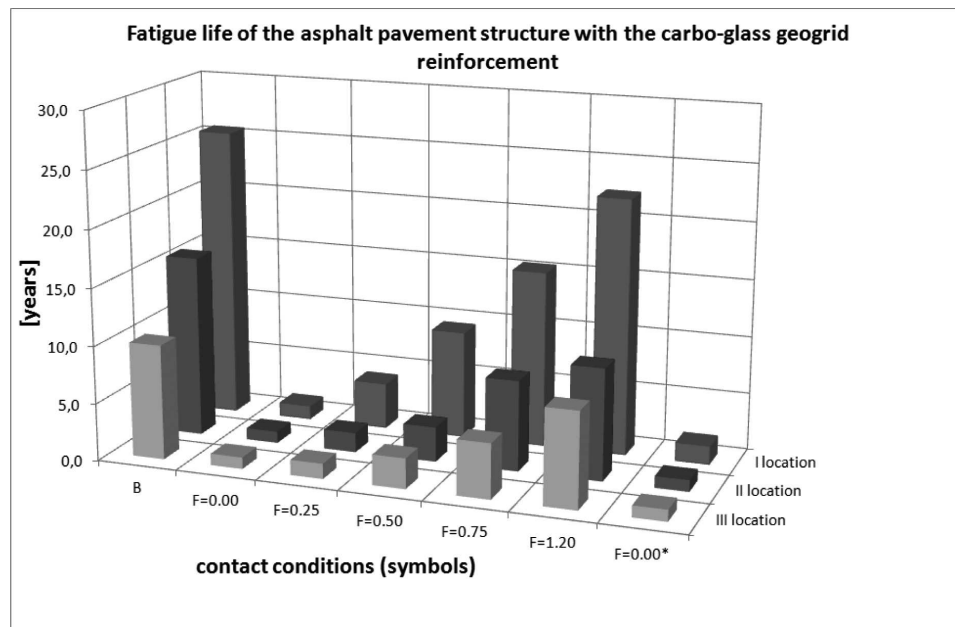


Fig. 9. The graph showing the change of the fatigue life [years] of the asphalt pavement reinforced with the carbon–glass geogrid with respect to conditions of the bonding between the asphalt layers and geogrid and the location of the reinforcement.

Rys. 9. Wykres zależności trwałości zmęczeniowej [lata] asfaltowej nawierzchni drogowej zbrojonej geosiatką węglowo-szklaną w zależności od warunków związania międzywarstwowego i lokalizacji zbrojenia

4. CONCLUSIONS AND SUMMARY

In general, it was concluded that using the structure of the asphalt layers with the geogrid interlayer of the geogrid is an effective method of prolonging the fatigue life

of the asphalt layers but only when the described requirements concerning location of the geogrids and the kind of the bonding between the layers are satisfied. The effectiveness of such layers depends on the following factors:

1. *With respect to the influence of the bonding parameter (friction coefficient μ) between the geogrid and the asphalt layers:*
 - the complete lack of the bonding between one or two sides of the geogrid and the asphalt layers, regardless of the location of the reinforcement in the layers of the pavement structure (variant $F=0.00$ and $F=0.00^*$, Table 5), causes a significant decrease in the fatigue life, defined as the period of time before macro-cracks appear in the asphalt layers,
 - at the intermediate values of the friction coefficient 0.00–1.20 the fatigue life assumes medium values as presented in Fig. 9,
2. *With respect to the influence of the location of the geogrid in the asphalt pavement structure:*
 - the degree of the increased fatigue life of the pavement structure when the geogrid was applied at the full bonding (as a consequence of the decrease in the effective stress of the asphalt layers) is strongly related to the location of the reinforcement in the layers of the structure,
 - at the full bonding between the geogrid and the asphalt layers for all season temperatures (for the assumed temperature profiles), the fatigue life for the spectrum loading assumed for the highway (Fig. 3) has got the highest value for the lowest locations of the geogrid in the asphalt layers of structure (at a depth of 31 cm),
 - at the full bonding and the higher locations of the geogrid in the asphalt layers of the structure, the fatigue life is smaller and for the location under the binder layer (at a depth of 13 cm, in the compression zone), it exhibits a lower value of the fatigue life than in the case when no geogrid is applied. The effectiveness of the geogrid as reinforcement increases with the distance down from the neutral surface in the asphalt layers,
 - the highest value of the fatigue life was observed for the geogrid located in the position I, at the bottom of the asphalt layers system and at the full bonding; it was greater than 25 years, i.e. it increased by over 70% in comparison to the non-reinforced structure. In the case of location II, it was equal to 16 years (increase by 10%) and for location III at full bonding it was equal to 10 years (the decrease by 30% in comparison to the non-reinforced structure).

To summarize, it needs to be emphasised that the application of the geogrid reinforcement may contribute to the increase in the fatigue life of the asphalt pavement, but the following requirements need to be satisfied:

- the stiffness of the bonding between the geogrid and the asphalt layers should be the highest available,
- the geogrid should be located in the pavement structure in the tension zone as low as available in the asphalt layers of the structure,

- additionally, the geogrid (as a product) should exhibit the highest possible stiffness [5].

It should be underlined, that FEM showed the essential efficiency in fatigue analyses. It allows to study fatigue properties in composed loading states. Current FEM systems permit also the easier implementation of fatigue hypotheses, on the basis of stress and strain tensor components, what makes the adaptation of FEM to multiaxial fatigue analysis needs possible.

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WPLYW ZBROJENIA SIATKĄ WĘGLOWO-SZKLANĄ NA TRWAŁOŚĆ ZMĘCZENIOWĄ ASFALTOWEJ NAWIERZCHNI DROGOWEJ

Streszczenie

W artykule opisano badania trwałości zmęczeniowej asfaltowej nawierzchni zbrojonej geosyntetyczną warstwą pośrednią poddanej zmiennym obciążeniom od kółporuszających się pojazdów. Badania te zrealizowano wykorzystując numeryczny model nawierzchni opracowany z użyciem metody elementów skończonych w systemie ANSYS z wykorzystaniem aplikacji firmy nCode oraz przygotowanych specjalnie makropoleceń w językach skryptowych APDL (ANSYS Parametric Design Language) i VBA (Visual Basic for Applications). Analizy obejmowały wyznaczenie naprężeń, trwałości zmęczeniowej, macierzy zniszczeń oraz macierzy rainflow. Zastosowano metodę obliczeń zmęczeniowych: naprężenie – liczba cykli (czas życia), w skrócie S-N.

Na podstawie przeprowadzonych wysokocyklowych analiz zmęczeniowych określono, jaki wpływ na pracę i trwałość nawierzchni drogowej ma lokalizacja wbudowanego geosyntetyku oraz jego związanie z warstwami asfaltowej nawierzchni. Analizy przeprowadzono dla trzech sezonów temperaturowych, tj. wiosny i jesieni (łącznie – jeden sezon), zimy oraz lata. Zmienność warunków ruchu uwzględniono przyjmując tygodniowe bloki obciążeń. Do obliczeń wykorzystano rzeczywiste wartości obciążeń z pomiarów połowych przeprowadzonych przez Federal Highway Research Institute w Kolonii na niemieckich autostradach z wykorzystaniem systemu ważenia pojazdów w ruchu HS-WIM. Dane te obejmowały naciski poszczególnych osi, strukturę rodzajową i prędkości przejeżdżających pojazdów ciężkich z trzech miesięcy reprezentujących różne pory roku: styczeń, czerwiec i październik.

W efekcie przeprowadzonych analiz stwierdzono, że stosowanie zbrojenia geosyntetycznego może wydłużyć trwałość zmęczeniową nawierzchni asfaltowej. Wymagane jest jednak, aby: geosyntetyk zlokalizowany był w strefie rozciągania, możliwie jak najniżej w układzie warstw asfaltowych. Ponadto konieczne jest zapewnienie wysokiej sztywności połączenia geosyntetyku z warstwami asfaltowymi.

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