Fatigue performance of flexible pavements with Cement-Bound Granular Material (CBGM)

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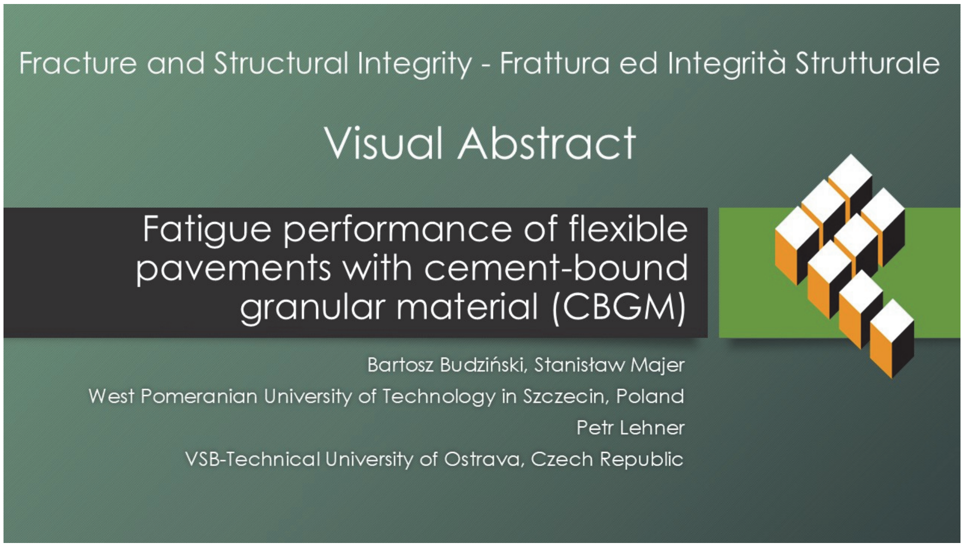

Fracture and Structural Integrity - Frattura ed Integrità Strutturale

Visual Abstract

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INTRODUCTION

In Poland, flexible pavement structures are among the most commonly designed types of road surfaces. These structures typically consist of two to three asphalt layers placed on a granular base. Frequently, a cement-bound granular mixture (CBGM) is designed beneath the granular base, serving as a subbase layer. Currently, flexible and semi-rigid pavements are most often designed using the mechanistic-empirical approach, supported by national catalogues and structural design standards [1,2]. In mechanistic pavement analysis, a linear elastic multilayer system is typically used as the structural model. This model consists of horizontally infinite, homogeneous, and isotropic layers of constant thickness representing the pavement structure and improved subgrade, along with a semi-infinite homogeneous, isotropic layer representing the natural subgrade soil. Such a model allows for estimation of stress and strain in each structural layer under traffic loading. Pavement layers are modeled as elastic bodies, with each layer treated as a material characterized by specific mechanical properties (layer thickness, elastic modulus, and Poisson's ratio). Using specialized computer programs, the values of stresses and strains at critical points in the pavement structure under the vehicle wheel load are determined (Fig. 1). This forms the basis for fatigue life assessment based on chosen failure criteria.

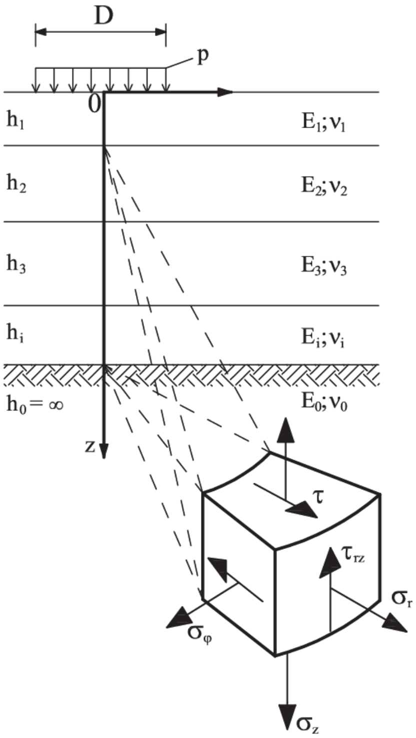

Figure 1: Elastic layered half-space model [1].

Based on the calculated strains and stresses, and using fatigue criteria derived from empirical relationships, the fatigue life of the pavement is determined - that is, the number of equivalent single axle loads (ESALs) until a condition defined by a given fatigue criterion is reached. In the design of flexible pavements, two primary fatigue criteria are used:

- The criterion of asphalt layer cracking,
- The criterion of permanent deformation (formation of structural rutting).

The first criterion is related to tensile strains at the bottom of the asphalt layers, which can lead to cracking of these layers. The second one refers to the accumulation of permanent deformations in the pavement structure and subgrade, primarily associated with vertical compressive strain at the subgrade level. However, for cement-bound layers, another relevant form of fatigue—such as vertical crushing—may be considered depending on the layer configuration. In the case of hydraulically bound layers, most often cement-bound, used both in the main base (in semi-rigid pavements) and in the subbase, their mechanical behavior can be divided into several characteristic phases (Fig. 2). Two main working phases are typically distinguished: before cracking and after cracking [3,4]. In the uncracked phase, the cement-bound layer behaves like a plate with a length several times its thickness. In the second phase, several stages can be identified: the layer cracked into large blocks (where the spacing between cracks is close to the layer thickness), cracking into small blocks, and a final stage where the material is so fragmented that it behaves similarly to an unbound granular layer.

The progressive fragmentation and structural breakdown of the cement-bound layer affect both its stiffness modulus and Poisson's ratio. These changes directly influence the magnitude of strains and deformations within the entire pavement structure. Tab. 1 presents the stiffness modulus values depending on compressive strength, as reported by Judycki based on a comprehensive literature review, taking into account the working phase of the cement-bound layer.

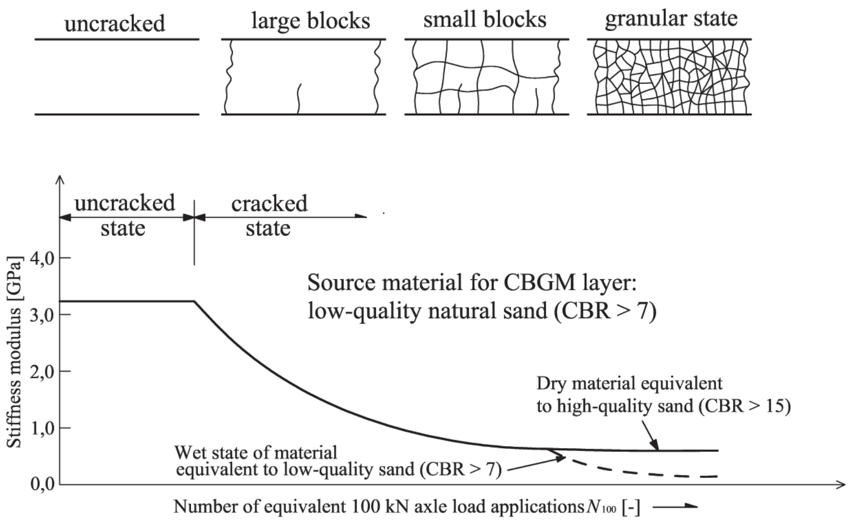

Figure 2: Definition of the stages of breakdown of weakly cemented layers [5].

Strength [MPa]	Type of aggregate	Uncracked state [GPa]	Cracked state [MPa]	
			Large blocks	Small blocks / aggregate
6 – 12	Crushed stone aggregate	14 (7–30)	3 000	500 – 600
3 – 6	Crushed stone aggregate	10 (4–14)	2 500	300 –500
1,5 – 3	Natural aggregates CBR > 45	4.5 (3–9)	2 000	160 – 350
1.5– 3	Sand CBR> 7	3 (2–6)	1 200	90 – 200
0.75 – 1.5	High-quality sand	3.5 (2–6)	2 000	160 – 300
0.75 – 1.5	Low-quality sand	1.5 (0.5 –3)	500	70 – 150

Table 1: Stiffness modulus of CBGM [6]

For the design calculations presented in the 2014 Catalogue of typical flexible and semi-rigid pavement structures [7] the stiffness modulus values for hydraulically bound mixtures (HBM) in semi-rigid pavements were adopted as shown in Tab. 2. However, in the case of cement-bound subbase layers, the uncracked phase was omitted from consideration. For strength classes C3/4 and C5/6, the modulus was assumed as corresponding to the cracked state with small blocks, according to Tab. 2. For the C1.5/2 mixture, a stiffness modulus of E = 200 MPa and Poisson's ratio ν = 0.3 was assumed, this value is approximately half of that adopted for crushed aggregate. In pavement designs based on the California Bearing Ratio (CBR) method, this layer is assigned a structural coefficient at least equal to that of an aggregate layer with a CBR ≥ 80. The lack of transition from the uncracked to the cracked phase under construction traffic is also confirmed by static plate loading tests (plate diameter 30 cm) performed on granular layers placed over CBGM. Depending on traffic load, a secondary modulus value between 130 and 180 MPa is expected, whereas field tests frequently show values between 300 MPa and even 500–600 MPa, indicating that the CBGM layer remains in the first, uncracked phase. The adoption of such low stiffness values—particularly for the C1.5/2 mixture placed beneath a crushed aggregate base—results in considerable reserves in fatigue life. During the development of the catalogue, the authors indicated that it would be more rational to adopt stiffness modulus values in the second working phase somewhere between the states of large and small block cracking. The article further demonstrates that for CBGM layers of greater thickness or protected by an aggregate cover, there is a significant fatigue life reserve before the transition to the small block cracking phase occurs.

RC Class [MPa]	Uncracked state		Cracked state			
			Large blocks		Small blocks	
	E [MPa]	ν [-]	E [MPa]	ν [-]	E [MPa]	ν [-]
C5/6	7 200	0.25	2 500	0.3	500	0.3
C3/4	4 800	0.25	2 000	0.3	400	0.3

Table 2: Stiffness moduli and Poisson's ratios of HBM adopted for the 2014 Catalogue design [7]

COMPARISON OF THE SELECTED FATIGUE CRITERIA FOR CBGM LAYERS

The fatigue criterion for hydraulically bound layers refers to the number of equivalent single axle loads (ESALs) after which cracking occurs at the bottom of the layer. A comprehensive review of commonly used fatigue criteria for hydraulically bound layers in pavement design was carried out by Pełczyńska and Gajewski in 2018 [8]. Most of these criteria define fatigue life using parameters indirectly related to material fatigue behavior, such as tensile strength or ultimate tensile strain. In the case of hydraulically bound materials, there is also a relatively poorly understood phenomenon known as "mortar training," which refers to the temporary increase in strength during the early life of the material [9,10]. The analysis of fatigue criteria revealed that for low traffic loads, the Dempsey criterion yields the lowest fatigue life values. This criterion has been used in the fatigue life calculations of semi-rigid pavement structures in Poland. Dempsey and his team recommended using a modified formula originally proposed by the Portland Cement Association (PCA) in 1966 for the design of concrete pavements [11]. This approach takes into account the tensile strength of the hydraulically bound layer Rf and the tensile stress at the bottom of the layer σt. In the absence of direct test data, Dempsey proposed assuming a tensile strength value equal to one-fifth of the compressive strength RC.

$$\log N_f = 11.782 - 12.1212 \cdot \frac{\sigma_t}{R_f} \tag{1}$$

Among the fatigue criteria that provide significantly higher fatigue life estimates for hydraulically bound layers under low traffic loads—and which have been calibrated through field testing—is the criterion developed by De Beer [12]. He calibrated his fatigue life formula based on test sections loaded using the Heavy Vehicle Simulator (HVS). This criterion considers the ratio of tensile strain εt at the bottom of the hydraulically bound layer to the failure strain ε_b, along with the influence of shrinkage-induced cracking, represented by a coefficient d. The value of d ranges from 1.1 for materials of lower strength and thicknesses below 20 cm, to 1.4 for higher-strength materials and thicknesses above 20 cm.

$$\log N_f = 7.19 \cdot \left(1 - \frac{d \cdot \varepsilon}{8 \cdot \varepsilon_b}\right) \tag{2}$$

MATERIALS AND METHODS

To calculate strains and stresses in the layers of the pavement structure (Fig. 3), the BISAR 3.0 software was used [13]. This program, based on the theory of multilayer elastic half-space, is designed for mechanistic pavement design. It has been and continues to be widely used in pavement structure dimensioning, including for the structures presented in the 2014 Polish Pavement Design Catalogue [7]. The calculations were performed for a CBGM C1.5/2 layer with a compressive strength R_C=2.4 MPa and varying thickness, placed on subgrades with bearing capacities of 80 MPa and 25 MPa, and a Poisson's ratio ν=0.35. For fatigue life calculations corresponding to the first (uncracked) working phase, the following parameters were assumed for the CBGM layer: stiffness modulus E=2500 MPa and ν=0.3. In practical applications, it is common to place an unbound aggregate layer (with E=400 MPa and ν=0.3) on freshly laid CBGM. This is primarily for technological reasons: to ensure proper curing by preventing moisture loss and to protect the layer from construction traffic. The latter is particularly critical, as heavy construction traffic may cause premature cracking of the

CBGM layer, forcing it into the second working phase before subsequent structural layers are placed. In such cases, it is justified to assume that the layer will operate in its cracked phase throughout its service life.

It should be emphasized that in all the analyzed configurations, the CBGM layer is covered with an unbound aggregate layer. This aggregate cover plays a dual role: it supports proper curing of the cement-bound material by limiting moisture loss and, more importantly, it protects the CBGM against vertical stresses induced by construction traffic. As a result, the crushing-type fatigue failure of the CBGM layer, which may occur when asphalt layers are placed directly on top of CBGM, is not expected in our case. Furthermore, the intensity and duration of construction traffic before placing the upper layers are limited, and therefore insufficient to induce such failure. This protective layer effectively mitigates premature cracking and preserves the CBGM in its uncracked state during construction. For the analysis, a wheel load of 50 kN and a contact pressure of 850 kPa were assumed.

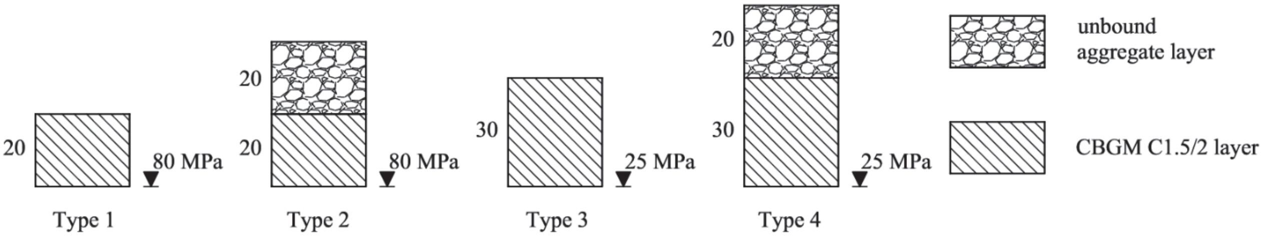

Figure 3: Layer structure adopted for calculations.

RESULTS AND DISCUSSION

The fatigue life calculations for CBGM, according to Dempsey, were carried out using his proposed relationship, in which the flexural strength Rf is assumed to be 0.2 of the compressive strength R_C, resulting in Rf=0.48 MPa. For the De Beer criterion, a failure strain of ε_b=125 με and a shrinkage cracking factor d=1.2 were adopted. Tab. 3 presents the obtained stress and strain values for various pavement layer configurations, along with the corresponding fatigue life calculated according to the criteria proposed by Dempsey and De Beer. In configurations Types 1–3, the calculated tensile stresses exceed the assumed flexural strength of the CBGM layer, indicating immediate cracking and thus no fatigue life in the sense of progressive damage. This behavior is marked in the table as instantaneous failure (-*). Such results highlight the limitations of these configurations under repetitive loading and suggest they may be inadequate in terms of structural durability, particularly under construction or early-life traffic. In contrast, Type 4 presents significantly lower tensile stress and strain values, with σt=0.40 MPa and ε=85.06 με, which are well below the critical thresholds. Consequently, this configuration yields a nonzero fatigue life under the Dempsey model (48 load repetitions), and a substantially higher fatigue life under the De Beer model (2,858,260 load repetitions). This discrepancy illustrates the conservative nature of Dempsey's method compared to the more field-calibrated De Beer approach, which has been validated using Heavy Vehicle Simulator (HVS) testing. As such, De Beer's criterion may offer a more realistic prediction of the CBGM layer's performance under actual service conditions, particularly during early trafficking stages. These results underline the importance of proper structural configuration and layer thickness when using CBGM materials in pavement design. While thinner or more heavily loaded configurations may appear structurally efficient, they can lead to premature cracking if not properly verified through fatigue analysis. Furthermore, the significant discrepancies observed between the fatigue life predictions based on Dempsey's and De Beer's criteria highlight the ongoing uncertainty in the fatigue characterization of cement-bound granular mixtures. This underscores the need for continued research aimed at developing and validating appropriate fatigue criteria that accurately reflect the mechanical behavior of CBGM under realistic loading and environmental conditions.

Type [-]	Stress st [MPa]	Strain [με]	Dempsey Nf	De Beer Nf
Type 1	1.01	235.6	-*	143 000
Type 2	0.65	137.8	-*	1 002 450
Type 3	0.70	148.6	-*	808 870
Type 4	0.40	85.06	48	2 858 260

*- instantaneous cracking (no fatigue life)

Table 3: Fatigue Life Calculation Results.

CONCLUSIONS AND FUTURE REMARKS

The article analyzed the mechanical behavior of CBGM mixtures used in pavement structures during the construction phase. The conducted calculations enabled the assessment of the risk of damage to cement-bound layers caused by construction traffic. Fatigue life evaluation of hydraulically bound materials remains challenging due to the wide variety of existing criteria and the diversity of research approaches across different countries. The following conclusions were drawn:

- According to the Dempsey criterion, only the layer configuration classified as Type 4 would not crack under construction traffic. In contrast, based on the De Beer criterion, none of the analyzed structures are expected to fail due to technological traffic loads.
- In pavement design practice in Poland, stiffness modulus values for CBGM layers are typically assumed to be twice as low as those for crushed aggregate. This approach may be unjustified. Using overly conservative, reduced stiffness values in mechanistic calculations can result in an overdesigned pavement structure.
- Future research should focus on defining fatigue criteria and material parameters specific to the regions where the road pavement structures are being designed and constructed.

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