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Analytical and Numerical Approaches for Design of Stone Pavers in Urban Shared Areas

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Abstract. Existing statistical data show that the use of pedestrian block pavements is increasing. This paper compares two approaches used to analyse a block pavement in an urban shared area. In presence of occasional heavy traffic roads, the pavement should be verified using methods currently used for road pavements. The analytical theory of Westergaard and the commercial finite element (FE) software Abaqus® were used to calculate the response of the pavement when subjected to different loading, and geometrical configurations. In all the examined cases, the results obtained from the analytical theory of Westergaard were higher than those obtained from the adopted static FEMs. Therefore, a parametric study was performed in order to use the analytical method as an alternative to the costly FEM approach introducing a Dynamic Amplification Factor (DAF). The results of comparison gave interesting results, valid for hexagonal pavers: it is possible to estimate analytically with good approximation the stresses induced by heavy loads applied to natural stone blocks. This is an interesting result since the analytical theory provides an inexpensive procedure for the analysis of modular pavements.

1. Introduction

Block or modular pavements are urban structures composed of pre-formed modular pavers successfully used worldwide for low-traffic-volume roads. In the last couple of decades, the use of this type of structures has increased, especially for pedestrian zones, cycle paths, residential driveways, parking lots, and historical city centres [1,2]. In these applications, modular pavements have revealed to have both good technical performances and low life cycle costs [3].

In historic city neighbourhoods and towns, modular pedestrian pavements are often used because of their architectural and environmental impact [4]. These pavements differ from traditional rigid or flexible structures because of the dimension and shape of their modules. Geometrical characteristics of the blocks strongly affect the strain-stress distribution under the load. Moreover, the shape of the individual blocks could contribute to lock the blocks and, consequently, to better distribute the tensile stresses caused by the applied loads at their bottom (Soutsos et al. [5]). In general, the experience gained in this topic shows that longer sides are related to higher stress concentrations and, therefore, thicker blocks are required, as confirmed by the analytical solutions proposed by Westergaard [6]. Therefore, as for traditional continuous pavements, the success of block pavements mainly depends on the correct definition of the selected input data during the design stage [7,8]. Available materials and their corresponding properties, the load bearing capacity of the subgrade in the area where the pavement will be built, and ordinary and accidental traffic loads [9] should be considered.

Particularly, in pedestrian priority or space sharing systems it is important to define correctly the expected loads. This is because [10] emergency vehicles and other heavy vehicles (i.e. full load weight over 30 kN) are exceptionally admitted for parking or circulation at speeds lower than 40 km/h.

In the literature, empirical and mechanistic methods and catalogues of modular structures are available to design modular pedestrian concrete pavements mainly because the structural response of their elements is relatively easy to estimate. Moreover, these empirical approaches and catalogues literature do not offer practical methods for designing stone block pavements when it is appropriate to consider occasional heavy loads. Under such conditions, the use of FEM is necessary, long, and costly. For this reason, the authors carried out a parametric study to evaluate a more efficient method to design stone modular pavements. The study focused on pedestrian pavements composed of hexagonal basalt pavers to be used in pedestrian and urban low-volume traffic pavements. The proposed approach was based on the Westergaard's analytical theory, commonly used for the analysis of concrete slab pavements. A comparison between the maximum tensile stress values obtained through the analytical approach and those obtained by mean the FEM commercial software Abaqus® was performed. The mechanical performance verification analysis included the evaluation of the examined structure under occasional passages of commercial and heavy loads that may occur during the service life of the structure.

2. Materials and methods

A common method to analyse a block pavement consists on using a finite element model to represent modular blocks laid on the bottom layers of the examined pavement. Wheel loads are modelled as a tire pressure uniformly distributed within a circular area on the top surface of the pavement [11]. In presence of widespread blocks without interlocking between them, it is possible to apply the load over a single block.

Usually static analyses are performed to calculate stresses induced by traffic on a block pavement: in the literature, a Dynamic Amplification Factor (DAF) near 1.4 takes into account the dynamic effects of traffic loads [12,13,14]. The software Abaqus® has been used for the verification of the mechanical response of a single hexagonal block. Hexahedral elements with a dimension (dx) fixed equal to 0.02 m composed all the pavement's layers. The stresses from numerical approach were compared to those obtained using the analytical approach of Westergaard's theory, which is based on the theory of thin slabs (i.e. the transversal dimension of the slab, or thickness, is smaller than its length and width dimensions), and provides theoretical closed-form solutions for concrete slabs subjected to a uniform circular load [6].

The examined block pavements were composed of:
- regular hexagonal-shape basalt blocks, without jointing sand;
- 2 cm-thick bedding sand (washed river sand) layer;
- 15 cm-thick cement stabilized base course;
- 15 cm-thick aggregate base course;
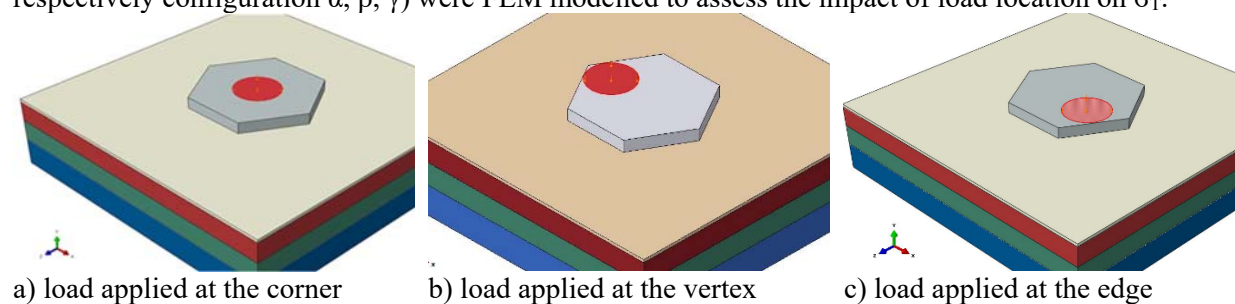- 15 cm-thick compacted subgrade.

All the performed analyses considered the same layers under the blocks.

Table 1 lists the mechanical properties of the pavement materials. These values were obtained from laboratory and on-site tests.

Table 1. Mechanical properties of the pavement materials

Material	Thickness (cm)	Young's modulus (MPa)	Poisson ratio	Reaction modulus (MPa/m)
Basalt	various	80,000	0.20	
Bedding sand	2	150	0.35	
Cement bound base course	15	500	0.20	-
Aggregate subbase course	15	300	0.35	-
Subgrade	infinite	100	0.40	40

Several analyses were performed to compare the maximum tensile stress (σ_T) at the bottom of the blocks, obtained using the two approaches. Particularly, three load positions (figure 1a, b, c respectively configuration α, β, γ) were FEM modelled to assess the impact of load location on σ_T.

a) load applied at the corner   b) load applied at the vertex   c) load applied at the edge

Figure 1. Example of a finite element model of a block pavement with hexagonal pavers.

Several analyses were performed to compare the values of σ_T obtained using the FEM approach and the Westergaard's theory. The role of three parameters was investigated:

- block thickness (h_b),
- wheel load (P), and
- the ratio (r_0) between the radius of the circle inscribed in the hexagon and the radius of the load footprint.

Five values of h_b (5, 8, 10, 12, and 15 cm), three values of P (table 2) (50, 20, and 5 kN), and six values of r_0 (1.71, 2.05, 2.40, 3.08, 3.77, 4.45) were examined.

Table 2. Input wheel loads

Notation of P	P (kN)	Tyre pressure (MPa)	Footprint Area (m^2)	Radius (m)
P_1	50	0.75	0.067	0.146
P_2	20	0.75	0.033	0.103
P_3	5	0.25	0.020	0.080

A single basalt block laid on the pavement layers was implemented in the FEM software Abaqus[®] because the pavers were not interconnected. The boundary conditions adopted in the model were: restrained horizontal displacements on the sides of the model, and fully constrained bottom layers according to previous sensitivity analyses carried out by the authors [RIF].

3. Results

The first analysis was related to the comparison of the results obtained through the Westergaard's theory and the FEM approach, having the critical wheel load P1 and varying the block thickness.

For all the three FEM configurations (figure 1), the authors compared the values of σ_T when P_1 is applied on a hexagonal block with 42 cm-long sides (figure 2). The stress results were very close to each other, as confirmed in figure 2, where differences are less than 12%. The results demonstrated that in the FEM models the loading position does not significantly affect σ_T.
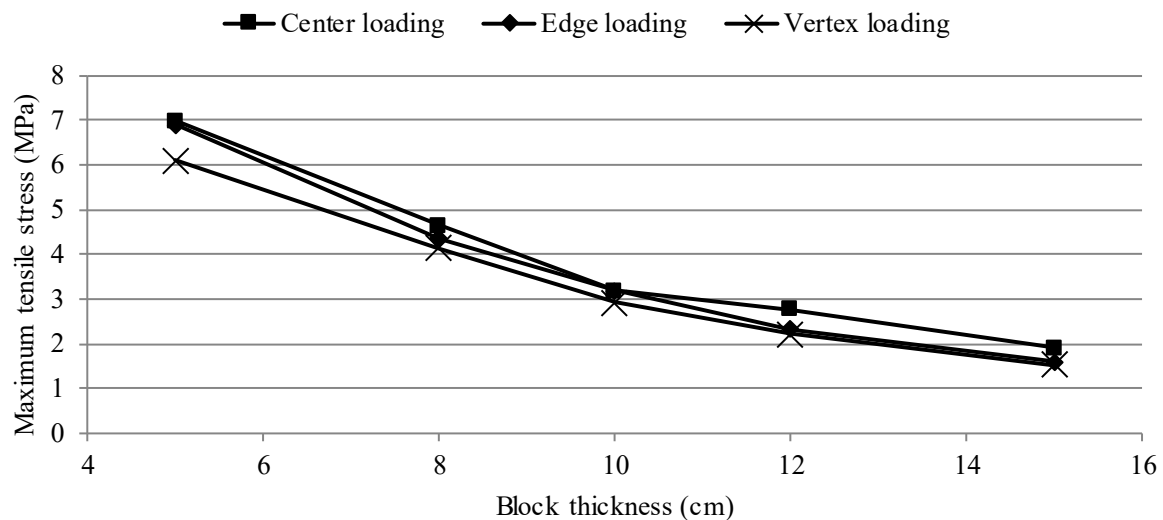
Figure 2. Maximum tensile stress calculated through FEM for different loading positions of P_1.

Table 3 lists the obtained σ_T for different block thickness and load configurations using the two approaches. For each combination of loading configuration and block thickness, the values of σ_T tend to converge with increasing the block thickness.

Table 3. Comparison of analytical and numerical results for different conditions

Block thickness (cm)	σ_T (MPa)					
	configuration α		configuration β		configuration γ	
	W^a	A^b	W^a	A^b	W^a	A^b
5	14.37	6.97	9.64	6.89	17.21	6.10
8	7.19	4.63	7.51	4.36	9.53	4.12
10	5.08	3.17	5.78	3.17	6.95	2.92
12	3.80	2.76	4.52	2.33	5.31	2.21
15	2.65	1.89	3.25	1.60	3.78	1.52

[a] "W" means the use of Westergaard's theory; [b] "A" means the use of FEM software Abaqus

However, σ_T calculated according to the Westergaard theory for configurations β and γ are about twice the ones given by the FEM model. The shape of the examined block, which is far from the assumption of a square slab considered in the Westergaard's theory, could cause this difference. Therefore, the results in figure 2 and table 3 lead to conduct a parametric study considering the configuration α, which gave the closest results between approaches W and A, and was the most critical one.

Figure 3 compares the results obtained through numerical and analytical methods when P_1, P_2 and P_3 are applied at the centre of a 42 cm-long sides block.
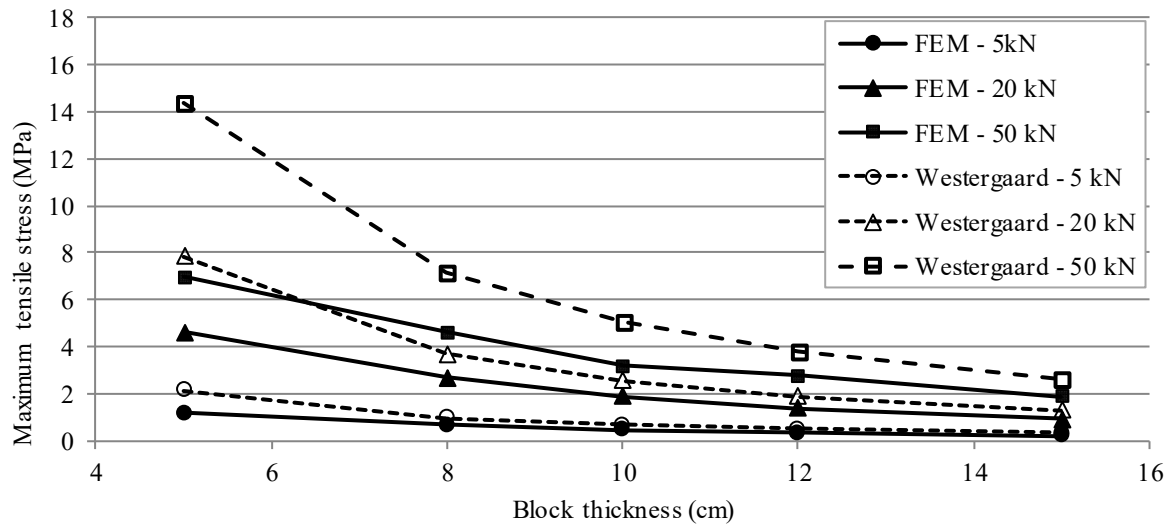
Figure 3. Maximum tensile stress for P_2 and P_3 in the configuration α

Figure 4 presents the values of σ_T for different side lengths, the load P_1, and 8 and 15-cm thick blocks. According to the Westergaard's theory, the extension in plant of the slab does not affect the calculation of the maximum tensile stress, which explains the constant values depicted in figure 4. However, the observed trend is affected by the block thickness. For 8 cm-thick blocks, no meaningful differences between W and A results are found when the hexagon sides are more than 0.52 m (i.e. r_0 is 3.08): under such conditions, the percentage differences tend towards a constant value close to 50%); for 15 cm-thick blocks, the observed trend is more linear and step.
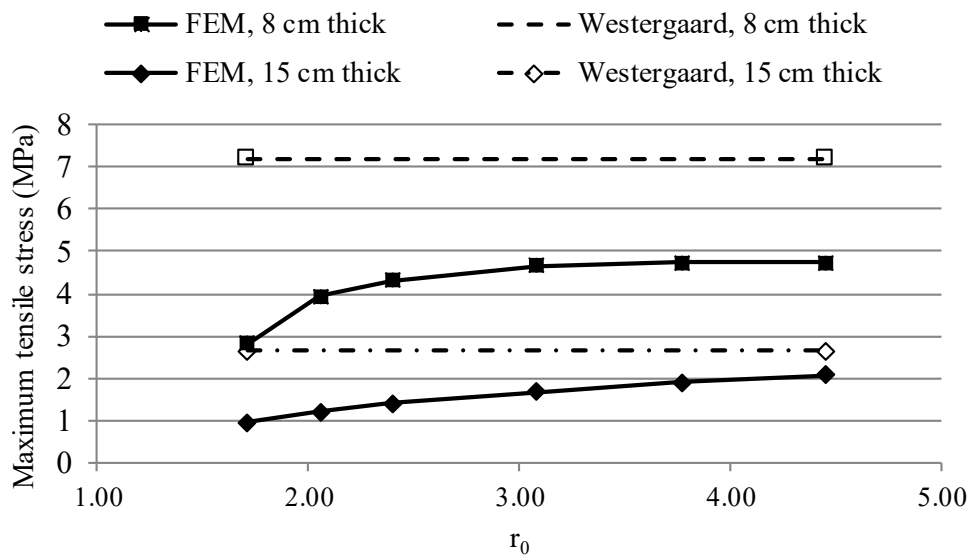
Figure 4. Maximum tensile stress for different ratio r_0 values

The curves in figure 4 suggest that for values of r_0 beyond 4.5 and block thickness more than 8 cm it is possible to obtain close results through the two methods. Indeed, increasing the block thickness and its dimensions in plant leads to a pavement configuration closer to that assumed in the Westergaard's theory (Ioannides et al., 1999). Therefore, a better agreement between analytical and numerical methods was found for thicker blocks.

Finally, the authors applied a DAF equal to 1.4 to all the values of σ_T calculated with the FEM approach. Table 4 lists the results of the comparative analysis. For each loading condition, the authors and presents their absolute percentage differences according to Equation 1.

$$APD = \left| \frac{\sigma_{T,Westergaard} - \sigma_{T,FEM} \times DAF}{\sigma_{T,FEM} \times DAF} \right| \cdot 100 \qquad (1)$$

Where $\sigma_{T,Westergaard}$ and $\sigma_{T,FEM}$ are the maximum tensile stress values respectively obtained through the analytical and numerical approach.

Table 4. Comparison of σ_T calculated through FEM and Westergaard methods introducing a DAF.

Input data			σ_T (MPa)		APD (%)
Wheel load (kN)	Hexagon edge size (m)	Block thickness (m)	$\sigma_{T,FEM}$	$\sigma_{T,Westergaard}$	
50	0.42	0.05	6.97	14.37	47.3
		0.08	4.64	7.19	10.8
		0.10	3.18	5.08	14.4
		0.12	2.76	3.80	1.7
		0.15	1.90	2.65	0.3
20	0.42	0.05	4.61	7.85	21.5
		0.08	2.68	3.70	1.5
		0.10	1.91	2.56	4.1
		0.12	1.40	1.89	3.4
		0.15	0.92	1.29	0.3
5	0.42	0.05	1.17	2.13	29.4
		0.08	0.66	0.99	7.5
		0.10	0.46	0.68	5.6
		0.12	0.33	0.50	7.3
		0.15	0.23	0.34	6.0
50	0.29	0.08	2.81	7.19	82.8
	0.35		3.93		30.8
	0.40		4.51		13.9
	0.52		4.66		10.2
	0.64		4.74		8.5
	0.75		4.98		3.2
50	0.29	0.15	0.95	2.65	99.1
	0.35		1.20		57.0
	0.40		1.40		34.8
	0.52		1.68		12.7
	0.64		1.86		1.6
	0.75		1.89		0.03

The results of the parametric analyses show that Westergaard's theory consistently provides maximum tensile stress values that are larger than those obtained through the FEM static approach, which overestimates the mechanical response of the hexagonal block pavement. The use of a DAF leads to a convergence between the two approaches: indeed, it provides APDs values that are lower than 6% for largest configurations (i.e. hexagon edges longer than 0.40 m) and thickest blocks (i.e. not less than 10 cm thick).

In conclusion, the proposed DAF equal to 1.4 could be used to adjust the results offered by the Westergaard's theory to perform a valid preliminary design analysis of the hexagonal block pavement

studied in this work. Undoubtedly, this alternative is more cost-efficient than using the FEM model. This correction factor has been validated for the specific hexagonal shape, pavement structure, wheel loads, and block thicknesses herein evaluated. Similar parametric analyses could be conducted to allow designers to efficiently and confidently use the Westergaards' analytical approach to verify the mechanical response of different and widespread geometries of pavers.

4. Conclusion

Existing statistical data show that the use of pedestrian block pavements is increasing. These structures are often constructed in pedestrian priority or space sharing systems, where heavy and commercial vehicles are admitted under ordinary (e.g. parking lots) or exceptional (e.g. emergency or public order situations) conditions.

This paper examined pedestrian basalt pavers with hexagonal shape loaded by occasional commercial traffic. The analytical theory of Westergaard and numerical static models performed by the software Abaqus® were used to calculate the maximum tensile stresses induced by the traffic. Several configurations of loads and pavers have been considered to compare the values of maximum tensile stress. The results highlighted the analytical method overestimates the mechanical response of the examined hexagonal pavers. A DAF equal to 1.4 could be applied to the maximum tensile stress results provided by the static models of Abaqus® to obtain results coherent to those provided by the Westergaard theory. Under such condition, the results from both approaches are comparable. Therefore, the Westergaard's theory can be used, as efficient alternative to costlier FEMs, in order to estimate the mechanical response of pavers. Indeed, the analytical theory provides an inexpensive procedure for the analysis of block pavements. Parametric analyses similar to that presented could be conducted for other paver geometries, until a list of correction factors useful to adopt the Westergaard's approach with confidence instead of having to develop costly FEM models.

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