Experimental evaluation of the load transfer capacity of the block joints using the FWD in concrete block paving.

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Abstract: The use of paving blocks in Uruguay is common in storage areas, in ports and airports, in gas stations, in container storage areas, in parking areas, in secondary city streets and pedestrian roads. However, the technical know-how of the professionals in our country in their structural behaviour and particularly in the test techniques for the evaluation of existing pavements is limited. To contribute to this matter, this paper presents a test routine with the Falling Weight Deflectometer (FWD) and an analysis method for the evaluation of the load transfer capacity of the joint between paving blocks. This method includes the analysis of the deflections in sensors located on both sides of a joint, considering two and three positions of the test load. The load transfer capacity of the joint is necessary for a correct interlocking of the paving block and load spreading to larger areas of the wearing surface towards the lower layers in the concrete block paving (CBP).
Key Words: conocrete paving blocks; falling weight deflectometer; deflections; load transfer capacity

1. Introduction

Due to strength, durability, esthetical aspects, speed of manufacture and placement, it's common to use concrete block paving (CBP) in storages areas, in ports and airports, in gas stations, in container storage areas, in parking areas, in secondary city streets and pedestrian roads. Traditionally, the structural behavior of these pavements had been considered similar to flexible pavements. However, the wearing surface - made from small paving units, jointing and bedding of sand - make the principal difference. Beneath the bedding sand, the substructure is similar to the one of traditional flexible pavement [1] [2].

One of the main functions of the wearing surface is to transfer the load to the lower layers. Thus, the paving block must have an interlocking capacity. This means that when a load is applied an individual block, it should not act isolated, but together with their neighbors. This mechanism depends mainly on the characteristics of the block - shape, thickness, laying pattern -, of the jointing and bedding sand -, thickness, grading, maximum grain sizes and contents clay material – and of the edge restrictions. Particularly, the sand joint must be able to transfer the load from one paving block to another with a minimum relative movement between them [1] [2] [3].

The Falling Weight Deflectometer (FWD) is one of the equipment available in Uruguay that applies a non-destructive testing technique for evaluating the structural capacity of existing pavements. It's usually used for asphalt and concrete pavements. By applying a standardized load and evaluating the deflection on the pavements surface taken by sensors at progressive distances from the load application center, a deflection basin is determined. The closest sensor evaluates the upper layers deformation while the deflections in the furthest sensors are a consequence of the deformation of the deeper layers, including the subgrade [4] [5] [6].

Although the use of CBP is common in Uruguay, it is limited the knowledge about the structural behavior of these kind pavements and of the evaluation techniques of existing pavements. The Structures

and Transport Institute (IET) of the Engineering University (UdelaR) is working in this research line in order to contribute to knowledge in these areas. In this context, the aim of the present work is to propose a test routine with the FWD and the analysis of the deflections to determine the load transfer capacity of the joint between paving blocks. This is a must for a correct interlocking of the paving block and the load spreading capacity of the wearing surface in the CBP.

2. Method

2.1 The FWD test routine

The FWD test routine was applied to five different pavements – identified as PR1, PR2, H, FL, and B8 – where between eight to eleven consecutively numbered zones of each pavement were chosen. For a zone, the test routine consisted of locating the equipment in a sequence of positions, identified as pos1, pos2 and pos3. The Table 1 presents the general characteristics of the pavements tested.

Table 1. General data of the pavements tested

Id.	Place	Use	Pavement structure (1)		Dimension of the section evaluated	Number of zones tested
PR1	Montevideo Port-Rinconada 1	Areas of containers of the Montevideo Port. Circulation heavy vehicles	**wearing surface**	UniStone, e 10cm. H layer pattern (2)	Longitudinally, 62 m	10
			base	Cement-treated, 15cm		
			subbase	Granular material, CBR>60%, 15cm		
			subgrade	sand		
PR2	Montevideo Port-Rinconada 2	Areas of containers of the Montevideo Port. Circulation heavy vehicles	**wearing surface**	UniStone, e 10cm. H layer pattern (2)	Longitudinally, 63 m	10
			base	Cement-treated, 15cm		
			subbase	Granular material, CBR>60%, 15cm		
			subgrade	sand		
H	Access to the concrete precast plant	Circulation heavy vehicles	**wearing surface**	UniStone, e 8cm. H layer pattern (2)	Area of 15 m x 15 m	8
			base	Granular material, CBR>60%, 20cm		
			subbase	-		
			subgrade	CBR>5%		
FL	FIng-Landoni	Urban area of pedestrian and vehicular circulation.	**wearing surface**	UniStone, e 8cm. H layer pattern (2)	Longitudinally, 59 m	11
			base	Granular material, CBR>60%, 15cm		
			subbase	-		
			subgrade	CBR>5%		
B8	National Route 8, km 64	Waiting area of trucks at the entrance of a scale in national route	**wearing surface**	UniStone, e 10cm. S layer pattern. (3)	Longitudinally, 50 m	9
			base	Granular material, CBR>60%, 20cm		
			subbase	-		
			subgrade	CBR>5%		

Note 1: the pavement structure was informed by the contact manager

Note 2: H represents Herringbone layer pattern

Note 3: S represents Stretcher Bond layer pattern

The pavements PR1 and PR2 correspond to container areas the Montevideo Port, the pavement H is the access to concrete precast plant, FL is an urban pavement of vehicular and pedestrian circulation and B8 is a pavement in a waiting area for trucks at the entrance of a scale in national route. All the pavements were made of Unistone paving blocks, which is the most commonly used in Uruguay. PR1, PR2, H and FL have a laying pattern in herringbone (H) and B8 in stretcher bond (S). The joint sand and the bedding sand were made with natural sand.

The FWD used (https://www.fing.edu.uy/node/11852) is from the company KUAB (Sweden). The load is produced by dropping a large weight and transmitted to the pavement through a circular load plate of 300 mm diameter with damping system. A load cell mounted on top of the load plate measures the load impacted to the pavement surface. Deflection sensors mounted radially from the center of the load plate measure the deformation of the pavement at distances progressively in response to the load. The equipment is manually controlled or by a portable computer that used the FVO software.

A picture of the equipment is showed in Figure 1a) and Figure 1b) shows the detail of the load plate and the sensor used in the analysis. Although the equipment has nine displacement sensors, in the analysis only the deflection of three sensors were used: d0 (located at the center of the loading plate), d2 (at 200 mm from d0) and d3 (at 300 mm from d0). The deflection was standardized to a load of 40 kN. In each position before the test load, a load of 20 kN was applied for the accommodation of the measuring systems.



a) b)

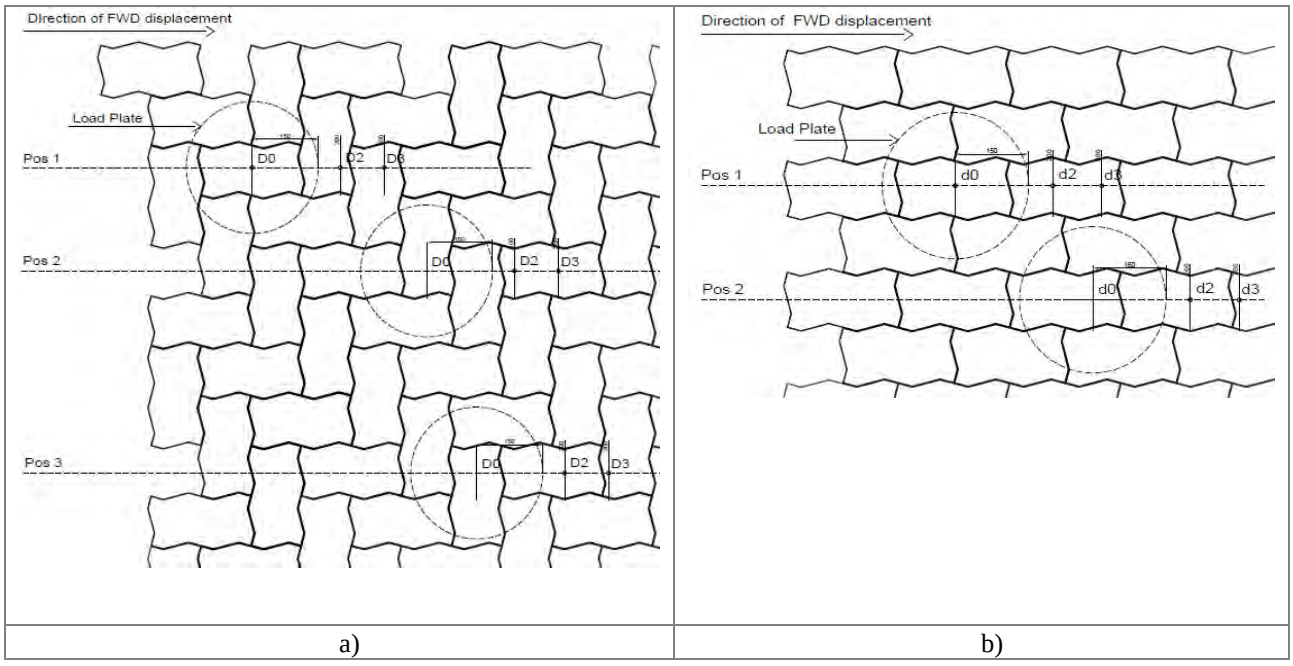
Figure 1. (a) Equipment used in the test; (b) detail of the loading plate and location of sensor d0, d2 and d3.

The deflection at d0 sensor corresponds to the maximum deflection in all the thickness of the pavement including the subgrade when it's subjected to load. The deflection of the sensors located at progressive distances evaluate the deflections of the deeper layers.

The Figure 2.a) shows the location of the load plate and sensors d0, d2, d3 in each test position (pos1, pos2 and pos3) for the layer pattern H and Figure 2.b) shows the pos1 and pos2 for layer pattern S. In both H and S layer pattern, the first position in the test routine (pos1) was defined locating the center of the load plate (d0 sensor) in accordance with the vertical axis of the paving block in its largest length which was aligned in the direction of FWD displacement. In this position and in H layer pattern, the d2 and d3 sensors were located on different paving blocks (Figure 2.a), while in the S layer pattern they were located on the same paving block (Figure 2.b).

In the second position of the test routine (pos2) at H layer pattern, d0 sensor was located on the next paving block – in the direction of displacement of FWD – at the crossing of its longitudinal axis following the longitudinal axis of the previous paving block. In this position both d2 and d3 sensors were located on the same paving block (Figure 2.a). However, in the pavements with S layer pattern at

pos2, the center of the loading plate was located on the same paving block, but at ¼ from its edge moving in its longitudinal axis. In this way the sensor d2 and d3 were on different pavement blocks (Figure 2.b).



a) b)

Figure 2. (a) Positions in the test routine for pavement with H layer pattern; (b) Position for S layer pattern.

Additionally, a third test routine (pos3) was performed on the pavement with H layer pattern, in which the d2 and d3 sensors were located on different paving blocks (Figure 2.a). In the H pattern, the pos1 and pos3, at d2 sensor was located on the paving block subjected to load, whereas in S pattern, d2 sensor was locates on the paving block subjected to load at pos2.

2.1 Analysis of the deflection method

In each zone of the pavement the deflection at the sensors d0, d2 and d3 were standardized to a load of 40 kN for each test position. The average of the maximum deflection (aver_d0) was calculated for the three test positions in H layer pattern and two positions in S layer pattern. The relative range Rr (Ec.1) at d0 deflection was determined to analyze the difference between the maximum deflection and the minimum deflection at d0 for different load positions.

$$Rr = \frac{(MAX_do(i) - MIN_do(i))}{aver_do} \quad \text{(Ec.1)}$$

$MAX_do(i)$: maximum deflection at d0 for the i test position in each zone of the pavement.
$MIN_do(i)$: minimum deflection at d0 for the i test positions in each zone of the pavement.

In zones where Rr exceeded the 15 % it was considered that the pavement was subjected to an excessive compaction or excessive deformation during the test routine.

The quotient between the deflection at d2 sensor and d3 sensor (Ec. 2) was used to analyze the load transfer capacity of the joint.

$$d2/d3\ (pos_i) = \frac{d2_pos_i}{d3_pos_i} \quad \text{(Ec.2)}$$

d2_pos_i: standardized deflection to 40 kN at d2 sensor for the i test position.
d3_pos_i: standardized deflection to 40 kN at d3 sensor for the i test position.

The deflection at progressive distances from the center of the load plate decreases in a normal test development. Thus d2/d3 is greater than one. Considering that the test zone had a normal behavior, (neither compaction or excessive deformation) the test position in which both sensors are on the same paving block will present the lowest d2/d3 quotient (identified as the reference position); on pavements with H layer pattern the reference position was the pos2 and on pavement with S layer pattern was the pos1.

The comparison of the d2/d3 quotient to the reference position allowed analyses the behavior of the joint. A significant difference in this quotient involved a relative movement between paving blocks; in this case the joint didn't present an adequate load transfer capacity. Three ranges (good, regular and poor) were adopted for the behavior of the jointing (Table 2) depending on the d2/d3 quotient to the reference position (pos2 or pos1 according to the layer pattern).

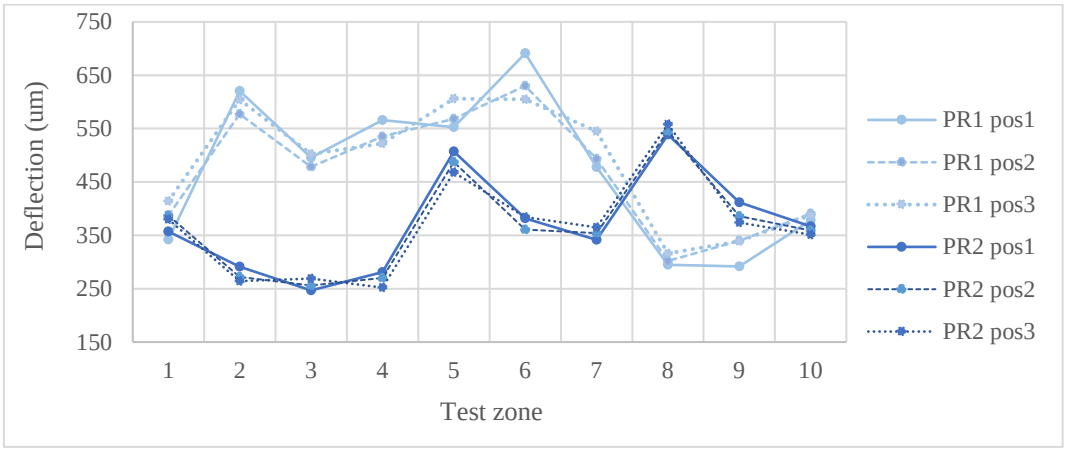
Table 2. Criterion adopted for the behavior of the joint.

d2/d3 quotient for reference position (%)	Interpretation for the load transfer capacity	Table representation
< 4 %	Good	Green
Between 4 % y 8 %	Regular	Yellow
>8 %	Poor	Red

3. Results and discussion

3.1 Maximum deflection at d0

The PR1, PR2, H and FL pavements with H layer pattern were tested in three positions (pos1, pos2 and pos3 according to Figure 2.a). The R8 pavement with S layer pattern was tested in two positions (pos1 and pos2 according to Figure 2.b). Figure 3.a) plots the d0 deflection for each position test and test zone on the PR1 and PR2 pavements, while Figure 3.b) shows the plots for the H, FL and B8 pavements.



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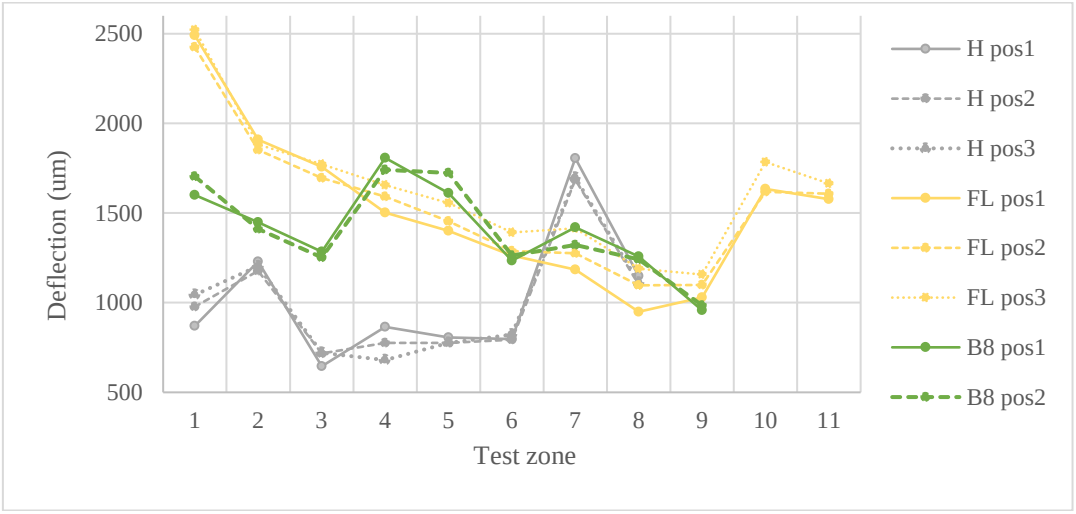


b)

Figure 3. Plots the d0 deflection: a) PR1 and PR2 pavements; b) H, FL and B8 pavements.

Table 3 shows the average of the maximum deflection at d0 (aver_d0) and the range of variation Rr (according Ec.1). The zone where Rr exceeded the 15% was represented in red. At the same time, for these zones the test position that had the greatest deviation from the average deflection was also indicated in red.

Table 3. d0 maximum deflection in each zone: a) PR1, PR2 and H pavements; b) FL and B8 pavements.

zone	do (µm) - PR1					d0 (µm) - PR2					do (µm) - H				
	pos1	pos2	pos3	aver_d0	Rr	pos1	pos2	pos3	aver_d0	Rr	pos1	pos2	pos3	aver_d0	Rr
1	342	387	414	381,0	0,19	357	387	380	374,6	0,08	871	978	1044	964,3	0,18
2	621	577	604	600,6	0,07	291	272	264	275,7	0,10	1230	1178	1204	1203,9	0,04
3	496	478	502	491,8	0,05	247	256	269	257,3	0,09	646	717	721	694,6	0,11
4	566	535	522	540,9	0,08	281	270	252	267,6	0,11	865	775	680	773,2	0,24
5	553	568	606	575,5	0,09	507	487	468	487,3	0,08	806	776	776	786,0	0,04
6	691	630	605	642,0	0,13	382	361	384	375,6	0,06	798	793	823	804,7	0,04
7	478	493	545	505,2	0,13	342	354	365	353,6	0,07	1806	1686	1697	1729,6	0,07
8	295	302	316	304,3	0,07	539	545	558	547,2	0,04	1149	1101	1113	1120,9	0,04
9	292	340	339	323,6	0,15	412	386	374	390,7	0,10	-	-	-	-	-
10	378	391	388	385,8	0,03	367	359	351	358,9	0,04	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

(Rr in red exceeds the limit of 0,15. Positions in red indicates the greatest deviation from the aver_d0. "," indicated decimal number.)

a)

zone	do (µm) - FL					do (µm) - B8				
	pos1	pos2	pos3	aver_d0	Rr	pos1	pos2	pos3	aver_d0	Rr
1	2491	2425	2522	2479,3	0,04	1600	1704	-	1652,0	0,06
2	1910	1853	1883	1882,0	0,03	1448	1412	-	1430,1	0,03
3	1758	1695	1772	1741,7	0,04	1285	1252	-	1268,3	0,03
4	1502	1591	1655	1582,5	0,10	1808	1741	-	1774,3	0,04
5	1401	1454	1556	1470,4	0,11	1612	1723	-	1667,4	0,07
6	1263	1288	1392	1314,3	0,10	1234	1263	-	1248,4	0,02
7	1185	1276	1415	1292,0	0,18	1420	1322	-	1370,8	0,07
8	949	1097	1190	1078,8	0,22	1257	1241	-	1249,1	0,01
9	1029	1098	1157	1094,7	0,12	958	985	-	971,3	0,03
10	1634	1618	1784	1678,8	0,10	-	-	-	-	-
11	1576	1608	1664	1616,2	0,05	-	-	-	-	-

(Rr in red exceeds the limit of 0,15. Positions in red indicates the greatest deviation from the aver_d0. "," indicates decimal number.)

b)

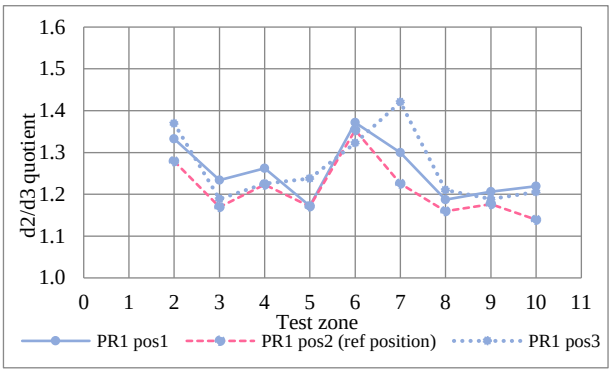
The PR1 and PR2 (Port pavements) presented the lowest deflection with and aver_d0 deflection between 257,3 µm and 642 µm. For the access pavement to the concrete precast plant (H), d0 deflection was between 694,6 µm and 1729,6 µm. For FL (pedestrian and vehicular pavement) and B8 (pavement in a waiting area for trucks at the entrance of the scale in a national route) aver_d0 deflection was between 971,3 µm and 2479,3 µm.

The zone 1 in PR1, the zones 1 and 4 in H, and the zone 7 and 8 in FL had a considerable difference in the d0 deflection obtained between pos1 and pos3. For these zones it was considered that the pavement was subjected to an excessive compaction (for zone 4 in H the d0 at pos1 was greater than pos2 and pos3) or an excessive deformation (for zone 1 in PR, 1 in H, zones 7 and 8 in FL d0 at pos3 was greater than pos2 and pos1) during the test routine. These zones were excluded from the analysis of the jointing behavior.

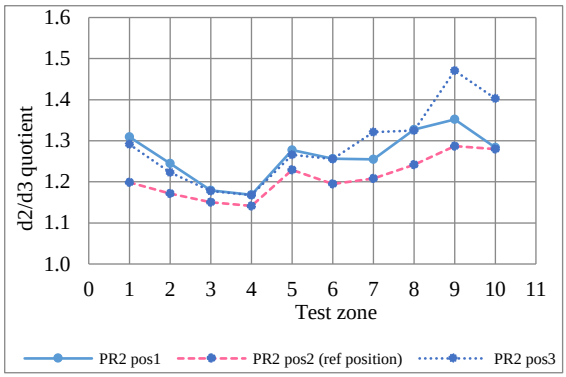
3.2 Load transfer capacity of the joint between paving blocks. Analysis of the d2/d3 quotient.

In every test position, the d2/d3 quotient (Ec. 2) was calculated excluding for the zones 1 in PR1, 1 and 4 in H and 7 and 8 in FL. These zones presented an excessive compaction or deformation during the test routine. For all zones and test positions the deflection at d3 sensor was lower than the deflection at d2 sensor (quotient greater than 1). For pavements with H layer pattern (PR1, PR2, H and FL) the pos2 was considered the reference position and for the S layer pattern the pos1 was considered the reference position. In this position both d2 and d3 sensor were located on the same paving block (according Figure 2).

The d2/d3 quotient was between 1,14 and 1,42 for the PR1 pavement, between 1,14 y 1,47 for PR2, between 1,15 and 1,53 for H, between 1,21 and 1,70 for FL and for B8 between 1,22 and 1,55 (Figure 4). Differences on the d2/d3 quotient were observed depending on the test position. On plots of Figure 4 the continuous line represents the quotient in the pos1, the dotted line represents the quotient in the pos2 and the soft dotted line represents the pos3. The pavements with H layer pattern (PR1, PR2, H and FL) present the lowest d2/d3 quotient in the pos2 (reference position) in most zones, while in the pavement with S layer pattern it was in the pos1 (reference position).



a)



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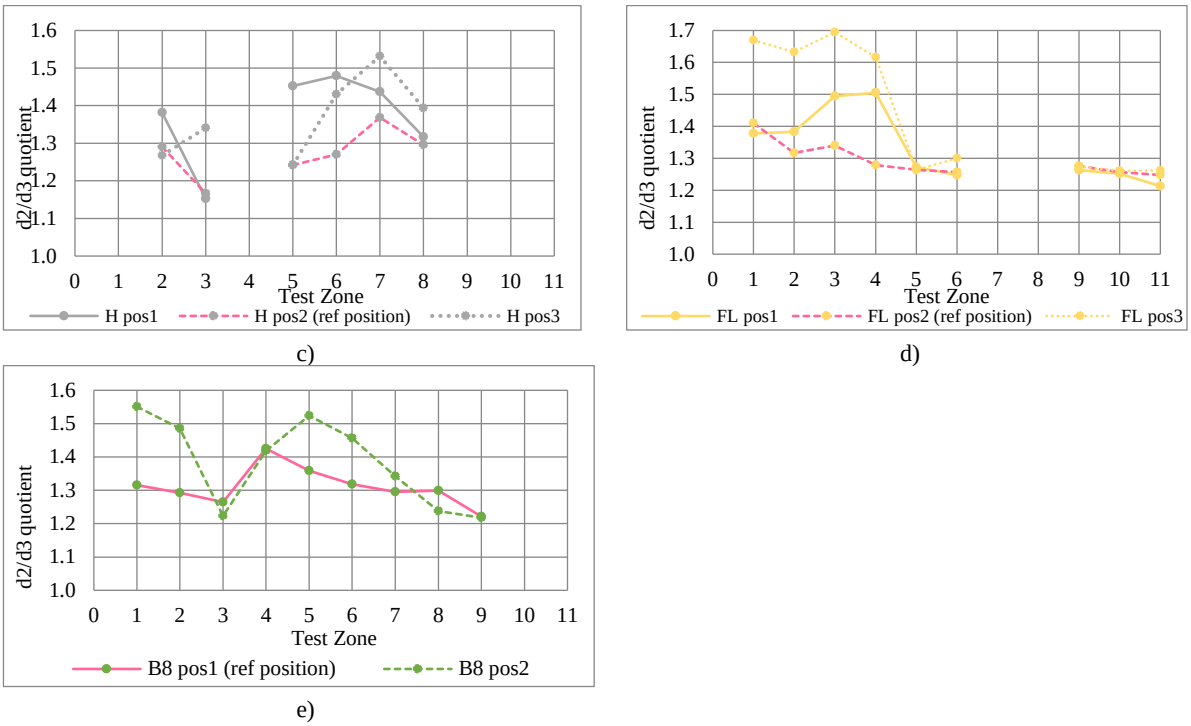

Figure 4. d2/d3 quotient for the different test positions; a) in PR1, b) in PR2, c) in H, d) in FL and e) in B8.

The d2/d3 quotient referred to the reference position (Table 4) was calculated. According to the adopted criterion of Table 2, a difference smaller than 4 % indicated a good behavior of the joint (zones in green). A difference between 4 % and 8 % meant a regular behavior (zones in yellow) and a difference greater than 8 % was considered as a poor behavior (zones in red).

Table 4. d2/d3 quotient referred to the reference position.

zone	d2/d3 referred to pos2 - PR1		d2/d3 referred to pos2 - PR2		d2/d3 referred to pos2 - H		d2/d3 referred to pos2 - FL		d2/d3 referred to pos1 - B8
	pos1	pos3	pos1	pos3	pos1	pos3	pos1	pos3	pos2
1	-	-	1,09	1,08	-	-	0,98	1,18	-
2	1,04	1,07	1,06	1,04	1,07	0,98	1,05	1,24	1,18
3	1,05	1,02	1,03	1,02	0,99	1,15	1,12	1,26	1,15
4	1,03	1,00	1,02	1,02	-	-	1,18	1,26	0,97
5	1,00	1,06	1,04	1,03	1,17	1,00	1,01	1,00	1,00
6	-	-	1,05	1,05	1,16	1,13	0,99	1,03	1,12
7	-	-	1,04	1,09	1,05	1,12	-	-	1,11
8	1,02	1,04	1,07	1,07	1,02	1,08	-	-	1,04
9	1,03	1,01	1,05	1,14	-	-	0,99	1,00	-
10	1,07	1,06	1,00	1,10	-	-	1,00	1,00	-
11	-	-	-	-	-	-	0,97	1,01	-

(Green: good load transfer capacity. Yellow: regular load transfer capacity. Red: bad load transfer capacity. "," indicated decimal number.)

The PR1 pavement presented some zones with a good behavior of the joint (d2/d3 quotient less than 4 %) and others with a regular behavior (between 4 % and 8 %). The PR2 pavement presented zones of good behavior and other zones of regular and poor behavior (the maximum difference was presented by zone 9, 14 %). The H and FL pavements presented the three behaviors (in H pavement the zone 5 presented the maximum difference, 17 % and in FL pavement the zone 3 and 4 presented the maximum difference of 26 %). B8 pavement had zones with good load transfer capacity of the jointing and other zones of poor behavior (the zone 2 presented the maximum difference of 18 %).

On pavements with H pattern (PR1, PR2, H and FL) the joint located between the d2 and d3 sensors was not the same for the pos1 as for the pos3 (as indicated in Figure 2.a). In some zones of these pavements the joint located between the d2 and d3 sensors for the pos1 did not present the same behavior as the joint located between the same two sensors but in the pos3.

The measurements of the deflection presented typical errors of the test. According the information supplied by the equipment and the measuring system, the error can be of 2% at the d2 sensor and 2% at d3 sensor. Therefore, small differences in the d2/d3 quotient at reference position (both sensors on the same paving block) are admissible. According to authors judgement, a tolerance of 4 % in d2/d3 was consider as a result for a good joint behavior.

The jointing sand plays a major role in promoting load transfer between blocks. It is important for the load transfer to larger areas in lower layers. For optimum load spreading by friction, it is necessary to provide uniform, narrow, and fully filled joints of width up to 5 mm [1] [2] [7] [8]. In the pavements tested in this work (H, FL, and B) it was observed during a visual inspection, that some zones didn't present joint material at all, in other zones the joint was filled with clay and presence of organic material.

Yaginuma and Kasahara [8] and Yaginuma et al. [3] proposed a test routine to evaluate the load transfer capacity of the joint. In the test routine the HFWD (Handy Falling Weight Deflectometer) was used and the radius of deflection curvature (R) and the quotient between deflection (d1'/d1) with sensors located in all the tests on both sides of the joint were considered for the analysis. The current work here exposed differs from previous works in the equipment used (the FWD) and the methodology used for the analysis, where was compared the quotient of the deflection located on both sides of a joint referred to another position in which both sensors were located on the same pavement block.

4. Conclusion

From the test routine with the FWD presented and the analysis of the deflections at the d2 and d3 sensors - located both on the same paving block and on different paving blocks - it was possible to evaluate the behavior of the joint between paving blocks related to its capacity of load transference in the CBP. A good behavior of the joint implied a minimum relative vertical displacement between blocks (comparing the d2/d3 quotient at the d2 and d3 sensors located on different blocks and both on the same block). When the difference in this quotient increased the capacity of the joint between blocks decreases.

The load transfer capacity of the joint is necessary for a correct interlocking of the paving block and load spreading to larger areas from the wearing surface towards the lower layers in the CPB. The test routine indicated here was applied to four types of pavements with H layer pattern and one with S layer pattern. All these pavements were made with UniStone type paving blocks (8 cm and 10 cm of thickness). A greater number of pavements should be evaluated to allow more cases for analysis. At the same time, a periodic evaluation of these pavements should be carried out to their service-life behavior and their relation to the load transfer capacity of the joint between blocks.

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