9th. International Conference on Concrete Block Paving. Buenos Aires, Argentina, 2009/10/18-21
Argentinean Concrete Block Association (AABH) - Argentinean Portland Cement Institute (ICPA)
Small Element Paving Technologists (SEPT)

APPLICATION AND TESTING OF CONCRETE BLOCK PAVING IN URBAN LIGHT RAIL TRANSIT LINES

ISHAI, Ilan, Professor.

Dept. of Civil & Environmental Engineering, Technion, Haifa 32000, ISRAEL.
Tel.: +972-52-2539668, Fax.: +972-9-7714198, iishai@013.net

LEVIATHAN, Ehud, Engineer.

Engineering, 96 Yigal Alon Street, Tel-Aviv, 67891, ISRAEL.
Tel.: +972-50-7419920, Fax.: +972-3-6244322. udi@ehudl.co.il

LISKEVITCH, Gadi, Engineer.

Head Road Laboratory, ISOTOP Ltd., P.O.Box 2, Gedera, 70700, ISRAEL.
Tel.: +972-54-2511671, Fax.: +972-8-8697008. gadi@isotop.co.il

Note: The following is the notation used in this paper: (.) for decimals and ( ) for thousands.

Summary

As a part of the Transportation Master Plan for the city of Jerusalem, a network of Light Rail Transit (LRT) lines is planned. The first line, stretches from "Pizgat Zeev" in the north to "Mount Herzl" in south, is now under construction. This LRT line is 13.8 km. long, and it contains 23 stations and 4 "Park and Ride" facilities.

Among the different solutions for the upper pavement structure inside the Swept Path of the LRT line, the Concrete Block Paving (CBP) technology was selected for most of the line length. According to vehicle traffic forecasts in Herzl Street and other JLRT sections, and based on the local "Guidelines for the Design of Urban Streets", the following pavement structure was suggested for the JLRT sections: 80 mm of Concrete Block Pavers, 30 mm of Sand Bedding Layer, 70 mm of Controlled Low Strength Material (CLSM) and 400 mm of concrete Slabs (as also designed to support the track rails).

In order to provide the ultimate possible structural capacity, a complete herringbone laying pattern solution was adopted between the rails in the entire width of the Swept Path (with 200 mm x100 mm, 100 mm x100 mm, and 160 mm x 100 mm blocks), using a uniform block thickness of 80 mm. As for the confinement and lateral support of the CBP structure against the rails, a modular confining element was installed to "encapsulate" the track rails, and to provide the proper confining and supporting unit. This element is made from a "Filler Block" dense-rigid rubber.

Due to the uniqueness of this application, and in order to validate the vertical and horizontal stability and sustainability of the CBP structure, an experimental test track was constructed. Several in-situ non-destructive tests are being performed, such as: Plate Loading bearing test; Falling Weight Deflectometer (FWD) test; and stress-deformation measurements under actual vehicle movements, using pre-installed pressure cells.

This paper outlines the summary of the final design and recommendations regarding the utilization of CBP for the Swept Path in the first Jerusalem LRT (JLRT) Project. It specifies the basic

preliminary pavement design and laying patterns, and also presents the mechanical in-situ testing that are used to validate and assess the sustainability of the engineering paving solutions.

1. PAVEMENT SURFACE SOLUTIONS FOR LRT LINES

Several typical pavement surface solutions are often used around the world for the LRT strip ("Swept Path"). They mainly consist of an asphaltic wearing course, concrete slabs, and segmental paving. The segmental paving can be of natural stones or flags, or industrial concrete pavers. Typical examples of LRT pavement surfaces, in selected European cities, are shown in Figures 1 to 6.



Figure 1. Asphaltic surface in Amsterdam, The Netherlands.



Figure 2. Concrete slabs in Nottingham, United Kingdom.



Figure 3. Small natural stones in Amsterdam, The Netherlands.



Figure 4. Large natural stones in Strasbourg, France.



Figure 5. Concrete pavers, Amsterdam,



Figure 6. Large concrete pavers in Strasbourg,

The Netherlands. **France.**

2. THE JERUSALEM LIGHT RAIL TRANSIT (JLRT)

As a part of the Transportation Master Plan for the city of Jerusalem, a network of LRT lines is planned. The first line, from "Pizgat Zeev" in the north to "Mount Herzl" in the south, is under construction. This LRT line is 13.8 km long, and has 23 stations and 4 "Park and Ride" facilities.

The Concessionaire was chosen in 2002 – the "CityPass Consortium", comprised of Connex Transport AB (from the international Vivendi Group), and the renowned French train manufacturer Alstom; and two Israeli companies: Ashtrom Construction and Infrastructures, and Pollar Investments. CityPass undertook to build the first line, and to operate it for a period of 30 years in accordance with the terms defined in the agreement with the government. Work by the Concessionaire was started in 2005, and the inaugural trip along the LRT system is expected for 2010 (see Figure 7).



Figure 7. Futuristic image of LRT operation in Jaffa Street, Jerusalem.

Among the different solutions for the upper pavement structure inside the Swept Path of the LRT line, the CBP technology was selected for most of the line length. Other surface solutions, like decorative natural stone flags, are adopted in the old section of Jaffa Street.

3. BASIC PRELIMINARY CBP STRUCTURE DESIGN

The basic preliminary design of the upper CBP structure inside the Swept Path was set in July 2007. According to traffic forecasts in Herzel Street and other JLRT sections, and based on the "Guidelines for the Design of Urban Streets" set by the Ministry of Housing and Construction (Israel MHC, 2000). The design traffic loading was set between "Medium Light" and "Heavy" Traffic Categories. These categories are equivalent to 3.6×10^5 – 1.5×10^7 passes of 18,000 lbs Standard Axle Load in the critical lane for a 20 years design period. Accordingly, the following pavement structure was suggested for the JLRT sections that are to be paved with CBP (Ishai, 2009):

Table 1. Structure for the JLRT.

Concrete Block Pavers	**80 mm**
Sand Bedding Layer	**30 mm**

CLSM	**70 mm**
Concrete Slabs	**400 mm**
Type A Subbase Layers	**Varies According to Subgrade properties**

A typical cross section of the LRT pavement structure is presented in Figure 8.

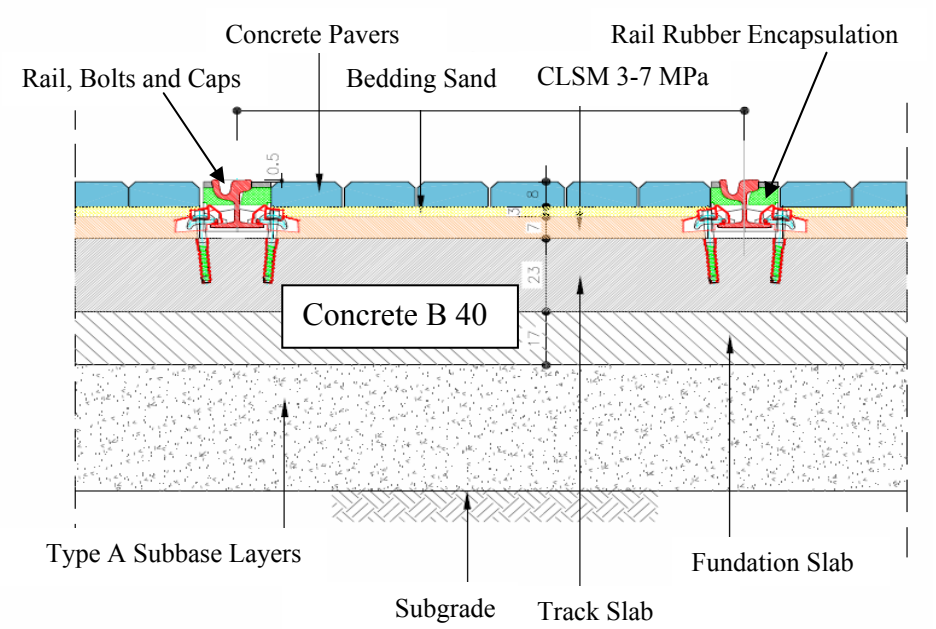

Figure 8. Typical cross section of the JLRT pavement structure.

In the design documents it was clearly specified that the materials & construction of the CBP structure above the CLSM layer should be fully comply with the Israeli Standards: I.S. 1571, and I.S. 8 (Israel ISI, 1998 and 2000).

4. ORIGINAL AND MODIFIED LAYING PATTERNS

As originally designed, the first two sections of the LRT line were paved using 200 mm x 100 mm x 80 mm surface "splitter pavers" in a herringbone pattern, confined by a "piano" pattern of 130 mm x 100 mm x 60 mm or 200 mm x 100 mm x 60 mm edge pavers near the rails. It should be mentioned that due to the rail bolts and plastic cover caps constraint, the edge piano pavers were 60 mm thick, while the inner herringbone pavers were 80 mm thick. This creates severe construction difficulties due to the two thickness levels of both the pavers and the bedding sand, and also to the weak support created by the bolt cover caps.

At a later stage, a proper solution was found to modify the plastic caps for lower coverage of the rail bolts. Under this solution it was possible to install 80 mm blocks above the caps, even with a minimal thickness of sand layer. Therefore, the modified final CBP structure was composed of a complete herringbone laying pattern between the rails in the entire width of the Swept Path (with 200 mm x 100 mm, 100 mm x 100 mm, and 160 mm x100 mm blocks), using a uniform block thickness of 80 mm, as shown in Figures 8 and 9.

5. VALIDATION BY MECHANICAL FIELD TESTING

5.1 Background

Due to the weakness point that may be created above the bolt cover caps in any of the CBP thicknesses and laying pattern solutions, and in order to validate the sustainability of the rail encapsulation confinement solution (see Figures 8 and 9), it was decided to perform mechanical repeated loading tests on actual test tracks that will be constructed according to the final recommended solution. The mechanical tests were designed to simulate the repeated passes of vehicle wheels under actual range of traffic loading.

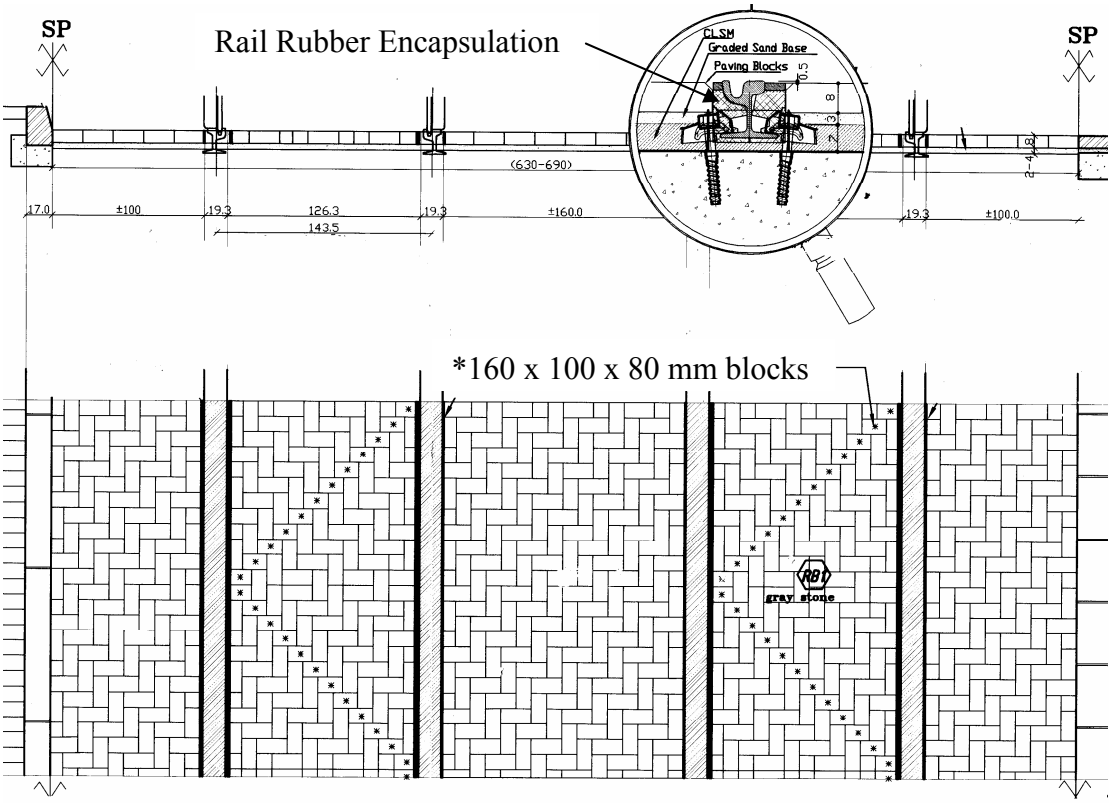

Figure 9. The final modified laying pattern solution for CBP in the JLRT Swept Path.

Generally, the tests were planned to be performed on old constructed JLRT line sections and on an experimental test tracks that were constructed to simulate the entire width of the Swept Path, with a length of about 150 m. Each test and measurements were performed on at least three typical points: Adjacent to the rail - Above a cover cap and between caps, and in the middle of the track between caps.

5.2 Mechanical testing performed

The following tests were outlined and performed:

- Static Plate Loading Bearing Test: This test is designed to evaluate the static bearing capacity of the CBP and its confinement system for restraining both vertical and horizontal displacements. Generally, the 200 mm diameter plate was loaded at intervals with recovery after initial intervals and at the end of the test, up to a contact stress of about 7 kg/cm^2 (0.7 MPa).
- Falling Weight Deflectometer (FWD): This test provided a tool for evaluating the dynamic response of the CBP structure by measuring the elastic deflections resulting from a drop of a

heavy weight on the pavement surface. Deflection monitoring at several offset points provides a mean for characterizing the lateral deflection-basin beneath the pavement. The test was performed using a 300 mm diameter plate. The falling weights were dropped at increasing loading (combinations of heights and dead loads) intervals, until reaching a dynamic load of 7 500 kgf (as standard in Israel for FWD tests on top of the asphaltic surface course in highways).

- Direct Stress Measurements (using pressure cells) under intervals of repeated movements of real vehicles, at variable loading levels (private car and heavy truck). This enabled the determination of the mechanical response of the CBP system in 1:1 scale under actual loading conditions.
- Visual inspection of repeated moving truck loading (38 t to 40 t) up to 60 coverages along 40 ms path. Loading configuration was: Left wheels path - adjacent to the rail above bolts and caps; Right wheels path - in the middle between the two tracks.

The performance of these mechanical field tests is described in Figures 10 to 13.



Figure 10. The configuration and performance of the Static Plate Loading Bearing test.



Figure 11. Performing the Falling Weight Deflectometer Test (FWD) on LRT CBP surface.



Figure 12. Installation of a Pressure Cell on top of the CLSM layer.



Figure 13. Moving truck loading on top of Pressure Cells and for visual inspection.

5.3 Outline of the four testing sections

5.3.1 The Rupin Section

Located on Herzl Street just north of Rupin junction. This section was constructed and completed in 2007 and was left without any vehicle traffic. The section was paved according to the old pattern solution, using 200 mm x100 mm x80 mm surface splitter pavers in a herringbone pattern, confined by a thinner "piano" pattern of 130 mm x100 mm x 60 mm or 200 mm x100 mm x 60 mm edge pavers near the rails.

5.3.2 The Tirtza Section

Located on Herzl Street just north of Tirtza Street. This section was specially and carefully constructed to serve as the main dedicated Testing Section. The section was paved using the proper solution with the modified plastic caps for lower coverage of the rail bolts. Under this solution, it is possible to install 80 mm blocks above the caps, even with a minimal thickness of sand layer. Therefore, the final CBP structure in this section is composed of a complete herringbone laying pattern between the rails in the entire width of the Swept Path (with 200 mm x100 mm, 100 mm x100 mm, and 160 mm x100 mm blocks), using a uniform block thickness of 80 mm, as shown in Figures 8 and 9. In this section, a longitudinal perforated drainage pipe was installed between the rails. These pipes were imbedded within the CLSM layer.

5.3.3 The Pik Section

Located on Herzl Street just in front of Pik street. It was paved with the same block laying pattern as the Tirtza Street, but the longitudinal drainage pipe was replaced by a drainage channel within the CLSM layer, filled with uniformly graded 10 mm to 14 mm aggregates, covered by a geotextile strip.

5.3.4 The Concrete Section

FWD tests were also performed on top of the upper concrete slab (track slab) that supports the rails and the CBP structure. This was done on an unpaved (no CLSM, sand and blocks) un-railed section, in Herzl Street.

6. SUMMARY OF MECHANICAL FIELD TESTING RESULTS

Typical results of the FWD test are presented in Figure 14. The results of a typical Static Plate Loading Bearing test are presented in Figure 15. Representative results of a pressure cell loading are presented in Figure 16.

The summary of the results of the FWD Tests is presented in Table 2. The summary of the results of the Static Plate Loading is presented in Table 3. The results of the Moving Truck Loading, as measured by the Pressure Cells, are presented in Table 4, where P1 is located above a cap, P2 – between caps, and P3 - between the rail and the drainage pipe. Finally, the results of the visual inspection of the Moving Truck Loading are presented in Table 5.

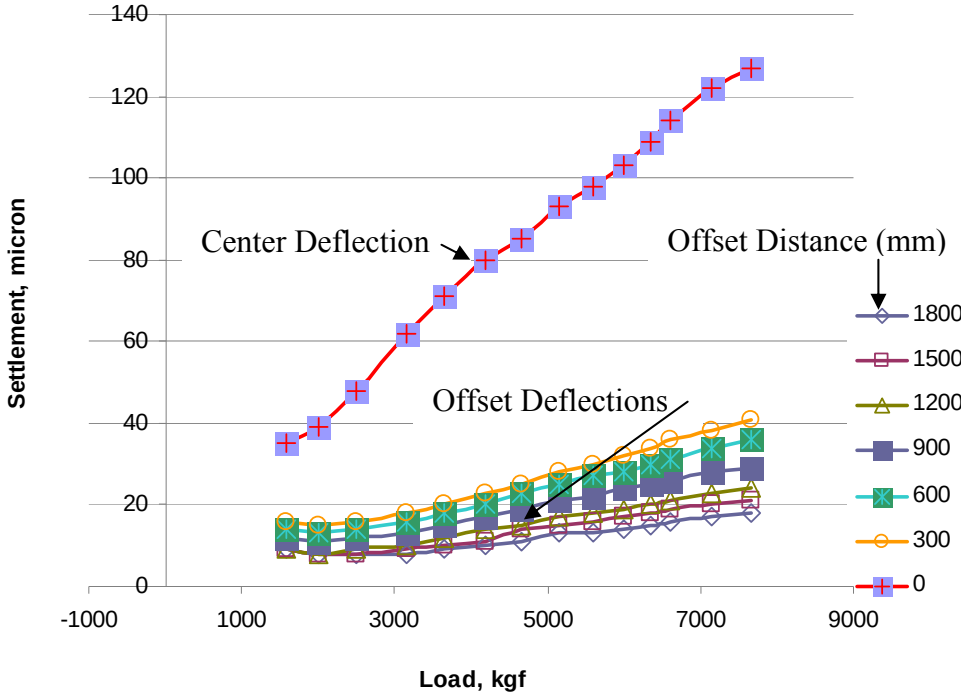

Figure 14. Typical CBP surface deflection vs. loading increments in the FWD test.

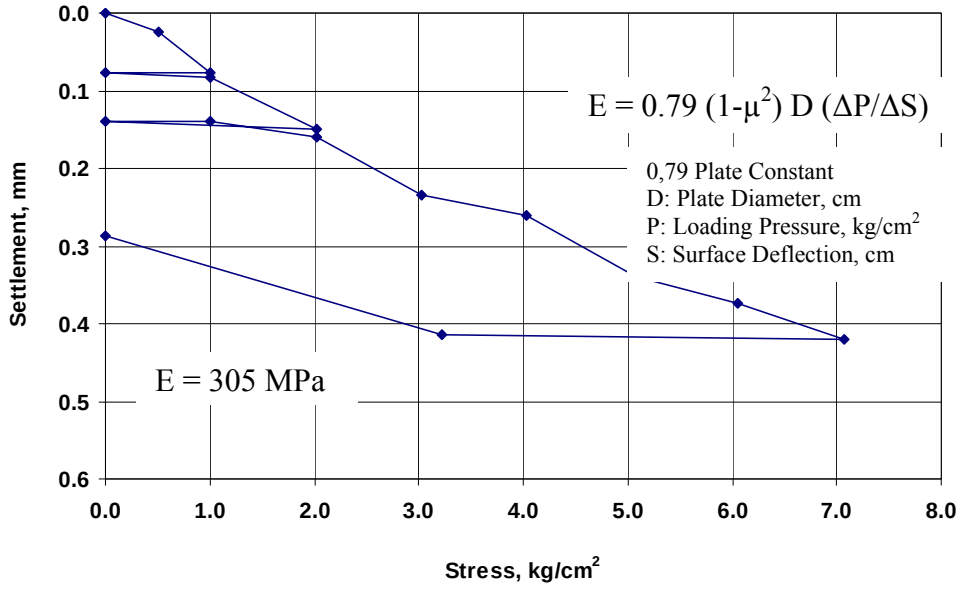

Figure 15. Typical results of the Static Plate Loading Bearing test on CBP surface.

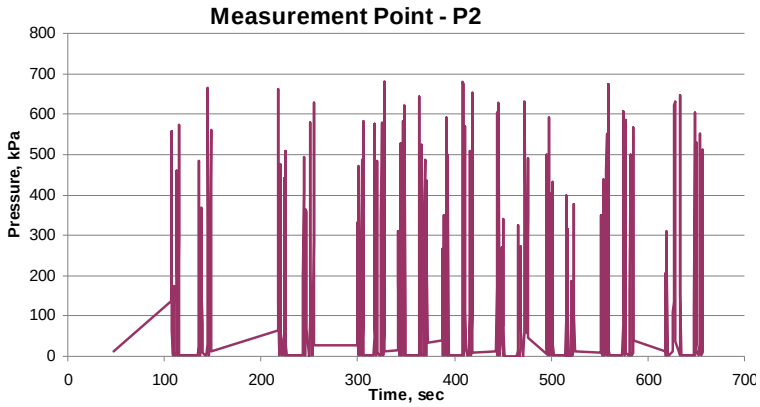

Figure 16. Typical response of the pressure cells to repeated truck movements on LRT CBP surface.

Table 2. Summary of the results of the FWD Tests on LRT CBP surface.

SECTION AND DATE	POINT	TESTING POINT DESCRIPTION	CENTER DEFLECTION (µm) AT 7.5 t	DEFLECTION AT 300 mm OFFSET (µm)	REMARKS
Rupin 4.2.09	1A	Between rails	130	50	Old laying pattern
	2A	Above cap	230	55	"
	3A	Between caps	130	40	"
	4A	Between rails	135	40	"
Tirza 4.2.09	1A	Between rails	1,300	90	Above a drainage pipe
	2A	Above cap	170	84	Regular new CBP structure
	3A	Between caps	220	105	"
	4A	Between rails	115	65	"
Pik 8.3.09	P1	Between rails	455	75	Above a drainage canal
	P2	"	180	50	Regular CBP structure
	P3	Between rails	240	80	Above a detectors box
	P4	"	160	35	Regular new CBP structure
	P5	Between rails	230	60	Above middle main pipe
Concrete 8.3.09	B1	Middle strip	115	95	Above 400 mm solid concrete
	B2	"	100	90	"

Table 3. Summary of the results of the Static Plate Loading Bearing Test on LRT CBP surf.

SECTION AND DATE	POINT	POINT DESCRIPTION	MAXIMUM DEFLECTION AT 7.2 t LOADING (mm)	RESIDUAL DEFLECTION AFTER LOAD RELEASE (mm)	EQUIVALENT MODULUS E*(kg/cm^2)	REMARKS
Rupin 9.2.09	A	Between rails	0.46	0.40	395	Old laying pattern
	B	Above cap	0.58	0.29	213	"
	C	Between caps	0.42	0.29	305	"
	D	Between rails	0.65	0.53	131	"
Tirtza 3-4.2.09	1A	Between rails	1.90	1.05	59	Above a drainage pipe
	2A	Above cap	0.35	0.20	305	Regular new CBP structure
	3A	Between caps	0.13	0.12	928	"
	4A	Between rails	0.48	0.30	225	"

* For definition, see Figure 15

Table 4. Summary of results of Load Cell response to Moving Vehicles on LRT CBP surface.

MEASURING POINT	NUMBER OF TRUCK COVERAGE	AVERAGE PEAK RESPONSE AT 5.0 km/h VEHICLE SPEED (kPa)		REMARKS
		HEAVY LOADED TRUCK, 38-40 t, TIRE PRESSURE 800 kPa	PRIVATE CAR, 1.0 t, TIRE PRESSURE 200 kPa (AFTER TRUCK OPERATION)	
P1 – Between Rail and Pipe	0-20	365	55	Adjacent to the wheel path
P2 - Above Cap	0-20	615	83	At wheel path
P3 - Between Caps	21-40	390	51	At wheel path

Table 5. Summary of results of the visual inspection of the moving truck on LRT CBP surf.

SECTION AND DATE	NUMBER OF TRUCK COVERAGE	LEFT WHEEL (NEAR RAIL) PERFORMANCE	RIGHT WHEEL (MIDDLE BETWEEN TRACKS) PERFORMANCE	REMARKS
Rupin 9.2.09	60	No signs of any deformation or damage.	No signs of any deformation or damage.	Old laying pattern.
Tirza 3-4.2.09	40	No signs of any deformation or damage.	Blocks breakage, rutting.	Above a drainage pipe.
Pik 8.3.09	60	No signs of any deformation or damage.	No signs of any deformation or damage.	Above a drainage channel.

7. DISCUSSION AND CONCLUSIONS

The following are the major conclusions that can be drown from the analysis of the testing results:

- As can be seen, the deflection bowl of all FWD test performed on the "young" CBP that were recently constructed, is characterized by a high peak of center deflection and comparatively very low offset deflections (very sharp deflection bowl). This mainly reflects the non-continuous small elements layout of the CBP structure, as very different from the continuous layers of flexible or rigid pavement (as can be seen by the flat deflection basin measured in points B1 and B2 in the concrete section (see Table 2). It is also reflects the premature interlocking conditions of the young, non-trafficked, CBP (this interlocking usually promotes vertical load transfer between adjacent pavers). It means that the load transfer of the CBP, under the current young conditions, is still quite localizing to the loading area.
- In general, the magnitude of the FWD center deflections above regular CBP structures (not above any weak point) is in the range of 115 microns to 230 microns under dynamic loads of 7.5 t. These results are quite comparable with results obtained in super highway pavements under similar loading conditions. It can be also seen that these results are in the same order of magnitude compared to those obtained directly above the massive concrete structure (see Table

2). It also means that the CBP structure above the concrete (CLSM + bedding sand + blocks) does not weaken the entire pavement structure within the Swept Path.

- The FWD center deflections measured above regular CBP structures at different locations within a specific test section, are quite comparable. It means that the carrying capacity of the CBP structure adjacent to the rails is quite uniform, whether it is above a bolt cap or between them. It also means that the new bolt cover is rigid enough and do not create a weak zone. This also confirms that CBP structure adjacent to the rails in the JLRT Swept Path is very well supported by the lower structure as well as by the special confining rigid rubber encapsulation system.
- The above trends and conclusions can also be drawn from the Static Plate Loading tests (see Table 3). As can be seen, the loading of the bearing plate up to a contact pressure (stress) of 26 kg/cm^2 (about 2.5 times than that in the top load of the FWD test), resulted with a total deflection of 0.13 mm to 0.65 mm in al tests above regular CBP structures. This reflects a quite high bearing capacity. The results of this test also reflect the sound vertical support of the CBP structure as well as by the sound confining support of the encapsulation system.
- The visual inspection of the CBP surface at the testing points after completion of all tests revealed that in all cases, the pavement surface remained intact without any excessive deformation and without any breakage of blocks.
- By comparing the results of the Rupin and Titza sections, especially that of the Static Plate Loading test (see Tables 2 and 3), it can be concluded that the new laying pattern (complete "herringbone" interlocking of uniform 80 mm blocks) is superior to that of old pattern, especially adjacent to the rails and above the caps.
- The FWD, the Static Plate Loading tests, and the Moving Truck Loading, were found to be sensitive enough to locate the weak points in the CBP structure. The longitudinal drainage pipe in Tirtza site created a very weak and unacceptable area in the Swept Path. The alternative solution, the drainage canal, provides a better solution, but still weaker than the regular CBP structures. Due to the traffic forecast of occasional truck movement within the Swept Path, even the somewhat higher deflection found above the drainage canal still indicates a proper stability and bearing capacity, as was reflected in the FWD tests. In any case, the visual inspection of the Moving Truck Loading, did not located any weak point above the drainage canal.
- The response of the pressure cells to truck and private cars repeated movements (as summarized in Table 4), indicate that the paver-sand structure transfers lower stresses than the contact pressure down to the CLSM layer. The results of Table 4 also indicate that initial pavers interlocking did occur after the first 20 truck coverages. This is expressed by the much lower stress response monitored in P3 as compared to P2.
- The interim conclusions after this analysis of the mechanical field testing, is that the CBP structure in the JLRT Swept Path possesses relatively high bearing capacity, and it is very well supported by the lower structure as well as by the special confinement of the unique rigid rubber encapsulation system. The test also confirmed that the bolt cap does not create any weak area in the CBP structure. The very weak strip created by the perforated drainage pipe was very well located. This drainage system was replaced by a better structural solution.
- In general, it is expected that the early life low mutual vertical load transfer of the CBP structure, will be overcame by the time and traffic-related "lock-up" process of the CBP structure. In any case, the early life vertical load transfer between the blocks and the encapsulation system was found to be quite sound and solid. It was found to be quite comparable to, and in several cases even stronger than, that in the center between the rails.

8. REFERENCES

ISHAI, I., (2009) "Concrete Block Paving for the Swept Path in the Jerusalem Light Rail Transit Project - Summary of Deign and Recommendations". Final Report, Prepared for ASHTROM, JLRT, Fourth Version, January 2009.

ISRAEL MINISTRY OF HOUSING AND CONSTRUCTION – MHC (2000), "Design Guidelines for Urban Streets – Roads, Aprons and Sidewalk Pavements", Volume 3.

ISRAEL STANDARD INSTITUTE – ISI (1998) "Concrete Block Pavements", Israeli Standard I.S. 1571.

ISRAEL STANDARD INSTITUTE – ISI (2000) "Prefabricated Concrete Products for Paving", Israeli Standard I.S. 8.

9. ACKNOWLEDGEMENTS

This paper was prepared within the framework of Pavement Consulting Services provided to Ashtrom JLRT and CityPass Consortium. The author wishes to thank these companies for their sponsorship and help in this project. Acknowledgment is also due to Engrs. Moshe Benjo and Zvi Pink for their assistance and support. The equipment and tests were installed and performed by ISOTOP Testing Laboratories, Ltd.