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The Effect of Groove-Underside Shaped Concrete Block on Pavement Permanent Deformation

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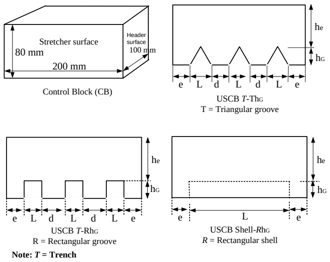
Graphical abstract



Categories of groove shape

Abstract

The aim of this study was to investigate the permanent deformation of Concrete Block Pavement (CBP) with the underside surface grooved. Permanent deformation is one of the important factors that influence pavement performance and often happens due to increases in axle load and tire pressure. Such increments have also resulted in greater increment of contact pressure at the tyre-pavement interface. In this study, a new CBP was developed with the concrete blocks grooved at the underside block surface to reduce pavement permanent deformation, termed as Underside Shaped Concrete Blocks (USCB). 13 USCBs were manufactured in the laboratory in this study with their patterns divided into three categories. The CBP models were constructed, from bottom to top, with hard neoprene, 70 mm thick loose bedding sand, and jointing sand which was used to fill in the gaps between USCBs. The test pavement was subjected to 10,000 rounds of load repetition under 1,000 kg single wheel load using the first Malaysian accelerated loading facility called Highway Accelerated Loading Instrument (HALI). The pavement was examined in terms of transverse deformation profile, average rut depth along the wheel path, and longitudinal rut profile other than being visually inspected. Results indicated that permanent deformation is significantly influenced by USCB geometry, groove shape, groove depth, bedding sand settlement during block setting, and load repetitions. From the results, it has been proven that USCB is a potential choice for CBP construction to reduce permanent deformation.

Keyword: Concrete block pavement; rut; permanent deformation; groove

Abstrak

Kajian ini bertujuan untuk mengkaji ubah bentuk kekal terhadap Turapan Blok Konkrit (TBK) dengan permukaan bawah beralur. Ubah bentuk kekal adalah salah satu faktor penting yang mempengaruhi prestasi turapan dan ia sering berlaku disebabkan oleh peningkatan beban gandar dan tekanan tayar. Peningkatan tersebut mengakibatkan peningkatan yang tinggi oleh tekanan sentuhan pada permukaan tayar terhadap turapan. Dalam kajian ini, TBK baru telah dibangunkan dengan bentuk alur pada permukaan bawah blok untuk mengurangkan ubah bentuk kekal turapan, yang diistilahkan sebagai Blok Konkrit Terbentuk Permukaan Bawah (BKTPB). 13 BKTPB telah dibangunkan di makmal di dalam kajian ini dengan corak bentuk masing-masing yang terbahagi kepada tiga kategori. Model TBK telah dibina dari lapisan bawah hingga ke permukaan atas dengan neoprena keras, pasir pengalas gembur 70 mm tebal dan pasir sambungan yang digunakan untuk mengisi ruang diantara BKTPB. Ujian turapan dikenakan 10,000 kitaran dengan 1,000 kg beban roda tunggal dengan menggunakan Instrumentasi Bebanan Pecutan Lebuhraya (IBPL). Turapan dinilai melalui profil ubah bentuk melintang, purata kedalaman aluran sepanjang laluan roda, profil aluran memanjang selain itu keadaan penglihatannya diperiksa. Keputusan menunjukkan bahawa ubah bentuk kekal diperngaruhi oleh geometri BKTPB, bentuk alur, kedalaman alur, pemendapan pasir pengalas semasa blok terkukuh, dan ulangan beban. Dari keputusan yang diperolehi, terbukti bahawa BKTPB adalah berpotesi dipilih sebagai TBK bagi mengurangkan ubah bentuk kekal.

Kata kunci: Turapan blok konkrit; aluran; ubah bentuk kekal; alur

■1.0 INTRODUCTION

Concrete Block Pavement (CBP) consists of interlocking blocks placed over one or more layers of unbound granular material and thin bedding sand layer, an unbound granular base (not always applied), and sand sub-base over the subgrade. CBP has been used extensively in commercial, industrial, and municipal applications. These blocks, which are normally concrete blocks bedded and jointed in sand, function as the major load-spreading component. In this context, ‘interlock’ is defined as the inability of an individual block to move independently from its neighbors and has been categorized as having three components: horizontal, rotational, and vertical. This inability is of major importance to prevent horizontal paver movements under trafficking. This paper discusses the experimental results of pavement permanent deformation of a CBP with Underside Shaped Concrete Blocks (USCBs) measured by the Highway Accelerated Loading Instrument (HALI).

In CBP, the load spreading capacity of concrete block layer depends on the interaction of individual blocks with jointing sand, as such interaction is expected to build up considerable resistance against the applied load. In addition, the shape, size, thickness, laying patterns, and etc., are some important block parameters that can influence the overall performance of the pavement. This applies to the shape of the blocks as well, since it has been postulated that the effectiveness of the load transfer system depends on the vertical surface area of the blocks [1].

CBP is generally available in three thicknesses which are 60 mm, 80 mm, and 100 mm. 80 mm blocks are usually adopted for general trafficking and this includes the heaviest loads. For industrial usage, the thickness of block must be at least 80 mm [2]. The laying course thickness differs from country to country; most European countries prefer the 50 mm thick compacted bedding sand [3], [4], but Australia has specified a compacted thickness of 20 mm to 25 mm. This is a very thin layer and will therefore require the surface of the underlying base to be very smooth [5].

Adequate compaction is required to minimize the settlement of CBP and this is normally performed in two cycles with the laying course material and blocks compacted using a vibrating plate compactor. The first cycle compacts the bedding sand and causes this material to rise up the joints, and the second cycle is applied once the sand has been brushed into the joints. Some blocks may require a rubber or neoprene face sole plate to prevent damage to the block surfaces [6]. In regard to this, the Interlocking Concrete Pavement Institute has specified that the block paved area should be fully compacted right after the full blocks and cut blocks have been laid to achieve finished pavement with a design level tolerance of ± 10 mm under a 3 m straightedge [7].

‘Permanent deformation’ is defined as depression in the wheel paths from axle load and tyre pressure due to a great increase in the contact pressure at the tyre-pavement interface [8]. It also delineates the capability of absorbtion load energy to the pavement withstanding the deformations without full disintegration [9]. Factors that affect the permanent deformation behaviors of pavement layers are, for example, number of load repetitions, the stress state due to the loading magnitude, and loading. Studies have shown that with increasing repetitions of load and tyre pressure on pavement surface, permanent deformation in many highway pavements have become severe [10]. Eventhough most permanent deformations are often associated with asphalt concrete pavement, it may also happen to CBP. In fact, permanent deformation is a primary criterion of structural performance in many pavement design methods.

Nowadays, numerous studies have been conducted to explain the behavior of full-scale prototype CBP under load chosen to simulate truck wheel loads, which can be further categorized into three categories: static or repeated-load test on prototype pavement, observation of actual concrete block pavement under real traffic, and accelerated trafficking tests of prototype pavements [11]. Certain pavements have also been simulated to carry dynamic loads with a variety of vehicles configured over a wide range. Accelerated trafficking tests have also been executed to compare the performances of concrete block pavements installed in herringbone, stretcher and basket weave bonds [12]. The greatest deformations are found in pavements laid in stretcher bond patterns, particularly when the bond lines lay along rather than across the direction of traffic [11], [13].

The Highway Accelerated Loading Instrument (HALI), is the first Malaysian accelerated loading facility established to evaluate the structural performance of concrete block pavements and design assumptions as well as to investigate the relationship between vehicle loading conditions and deterioration of pavements. According to Ling, *et al.* [14], design assumptions are tested by collecting data describing the long term performance of pavements under scrutiny.

■2.0 MATERIALS AND EXPERIMENTAL WORKS

2.1 Materials

The USCBs were manufactured in the laboratory. The length, width and thickness of these rectangular concrete blocks are 200 mm, 100 mm and 80 mm respectively with the length to width ratio set as 2 [15]. All USCBs have grooved patterns on the underside surface, which can be further classified into three categories: Shell-Rectangular (Shell-Rh_G), Trench Groove-Triangular (TG-Th_G), and Trench Groove-2 or 3 (2 or 3 number of grooves) Rectangular (TG-2 or $3Rh_G$). The symbol ‘h_G’ refers to groove depth. Table 1 and Figure 1 show the geometry detail of 13 USCBs with different groove types and the control block used in this study.

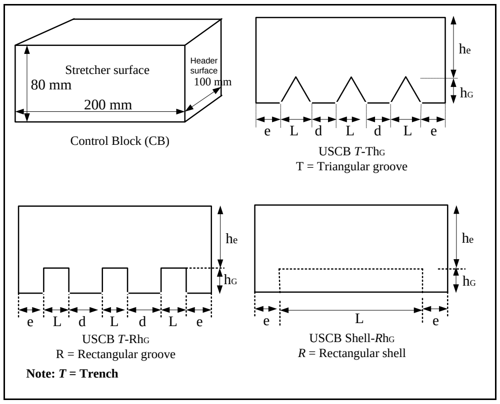


Figure 1 Categories of groove shape

2.2 Test Setup

A pavement track model was prepared for the accelerated pavement loading test. Initially, a sheet of hard neoprene (3 mm thick) was laid and fixed into the 0.9 m × 5.5 m test bed of HALI. A pavement of 200 mm × 100 mm × 80 mm concrete blocks, a bedding sand layer with thickness of 70 mm before compacting, and adequate jointing sand were subsequently laid on top of the test bed. In this experiment, the USCB were laid in stretcher bond pattern into three sets of pavement track. Two sets of pavement track consisted of five types of USCB and another set consisted of four types of USCB measured at 0.9 m × 0.9 m for each type of size. The USCB pavements were then compacted using a vibrating plate compactor of 800 N static weights vibrating at a frequency of 3,000 rpm. Grid lines were marked along the pavement track length and width at a distance of 220 mm between 22 lines and 100 mm between 8 lines, as illustrated schematically in Figure 2.

HALI was programmed to a constant speed of 0.25 m/s @ 0.91 km/h and would work continuously until it achieved 150 cycles per hour. The simulation of traffic load was done by setting the wheel load to 1,000 kg as axle load and a complete trafficking process was comprised of up to 10,000 load repetitions.

2.3 Test Procedures

Bedding sand thickness and concrete blocks level after the laying and compaction processes were the two dimensions that were measured at the early stage. Then, the rut depth and permanent deformation under HALI testing were measured with reference to a fix datum after 100 to 2,000 repetitions until the maximum repetitions (10,000 repetitions) had been achieved. The Low Voltage Displacement Transducer (LVDT) was used to record the data at reference points to measure the deformation of pavement after commencement of the accelerated trafficking test and the process was repeated three times. The measurement process is as shown in Figure 3. The measured data were then averaged and graphically reported with the range of Standard Deviation (SD) shown in respective figures. In addition, the permanent deformation was analyzed and plotted in the form of two-dimensional (2D) and three-dimensional (3D) models using the SURFER computer program [16]. The joint widths at along the wheel path were also visually observed.

Table 1 USCBs dimension according to groove patterns

USCB type	**Groove Width, B (mm)**	**Groove Length, L (mm)**	**Groove Depth, h_G (mm)**	**Effective thickness, h_e (mm)**	**Numbers of Groove**	**Distance Between Grooves, d (mm)**	**Edge Length, e (mm)**	**Groove Volume, V_G (cm3)**	**Block Volume, V_B (cm3)**
CB				80				0	1600.0
Shell -R15	60	160	15	65	1	0	20	149.5	1450.5
Shell -R25	60	160	25	55	1	0	20	245.5	1354.5
Shell -R35	60	160	35	45	1	0	20	341.5	1258.5
TG-T15	100	40	15	65	3	20	20	90.0	1510.0
TG-T25	100	40	25	55	3	20	20	150.0	1450.0
TG-T30	100	40	30	50	3	20	20	180.0	1420.0
TG-T35	100	40	35	45	3	20	20	210.0	1390.0
TG-3R15	100	33.5	15	65	3	30	20	135.0	1465.0
TG-3R25	100	33.5	25	55	3	30	20	225.0	1375.0
TG-3R35	100	33.5	35	45	3	30	20	315.0	1285.0
TG-2R15	100	70	15	65	2	20	20	182.0	1418.0
TG-2R25	100	70	25	55	2	20	20	322.0	1278.0
TG-2R35	100	70	35	45	2	20	20	462.0	1138.0

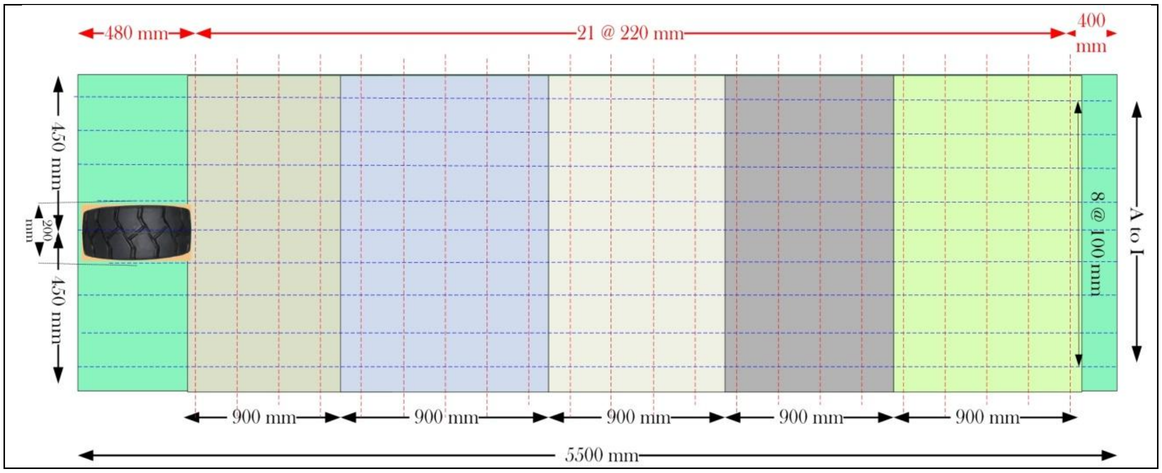


Figure 2 Grid points for HALI test setup

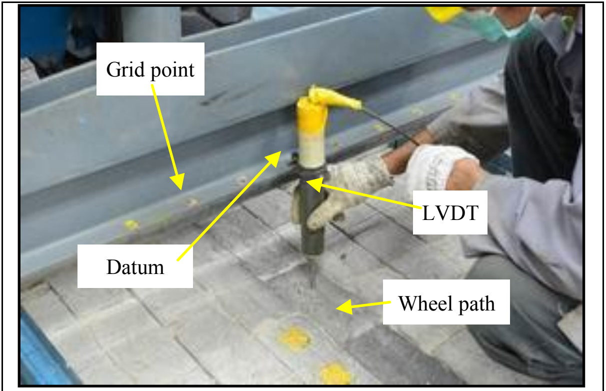


Figure 3 Rutting and settlement measurement

■3.0 RESULTS AND DISCUSSION

3.1 Effect of USCB Groove Patterns on Bedding Sand

The effect of 13 USCBs with different groove patterns on the bedding sand is as shown in Figure 4. These results were compared to that of the control block. Generally, the settlements at USCB pavements were higher than that of control block, and the settlement increased with every increment of groove depth. Additionally, the settlement pattern is typical for all patterns where the 35 mm and 15 mm groove types are associated with higher and lesser settlement, respectively.

It can also be induced from Figure 4 that differences in groove depth, size, and pattern have significant effects on the settlement of bedding sand. Compaction effort during the initial test is crucial as it will influence the degree of settlement where an adequate compaction will fully-fill the groove with sand. Higher groove depth provides good interaction between USCB and bedding sand as well [17].

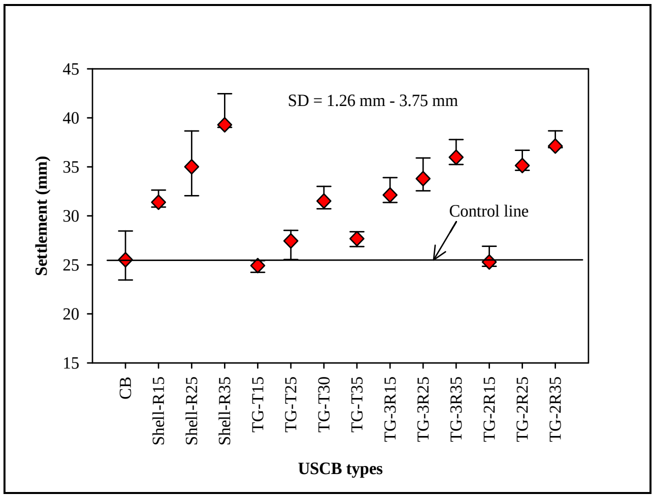


Figure 4 Average bedding sand settlement of different USCB types

3.2 Relationship Between USCB Weight, Groove Volume, and Settlement

Relationship between USCB weight, groove volume (i.e., size), and settlement is as shown in Figure 5. In this study, the USCBs were lighter than the control block, and this lighter weight had resulted in higher settlement of bedding sand. On the contrary, increasing the groove size had led to increased settlement of bedding sand. It is postulated that this occurred as the lighter USCBs can be compacted more easily than heavier blocks. According to Azman, *et.al*. [18], at the same time the settlement of bedding sand is also dependent on the groove volume; when the groove volume increases, it becomes easier for the sand to fill into the gaps and thus, settlement will increase. In other words, when the blocks are lighter and the groove sizes are bigger, the sand can fill into the gaps more easily once it is compacted and this will increase the overall settlement of the bedding sand layer.

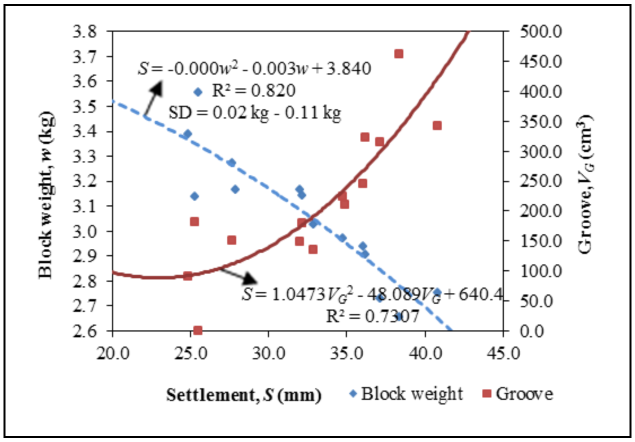


Figure 5 Relationship between USCB weight, groove volume and settlement

3.3 Relationship Between Settlement and Groove Depth

The relationship between settlement and groove depth is illustrated in Figure 6. From the figure, two settlement trends can be observed, i.e, linear and concave trends. The linear trend is for Shell-R and TG-3R USCBs and has shown a gradual increment of settlement with every increment of groove depth. Meanwhile, the concave trend for TG-T and TG-2R USCBs has shown that increment of USCB settlement happened up to 25 mm to 30 mm groove depth and there was no further settlement after that. The smaller USCB settlement is attributed to the filling up of groove depths with bedding sand during the compaction process. From the result, the 15 mm groove depth was able to settle less than the higher groove depth. The overall trend showed that the rate of settlement is strongly influenced by the groove type and pattern. Nevertheless, it should be emphasized that there was no settlement for a groove depth of up to 30 mm groove depth for TG-T and TG-2R USCBs.

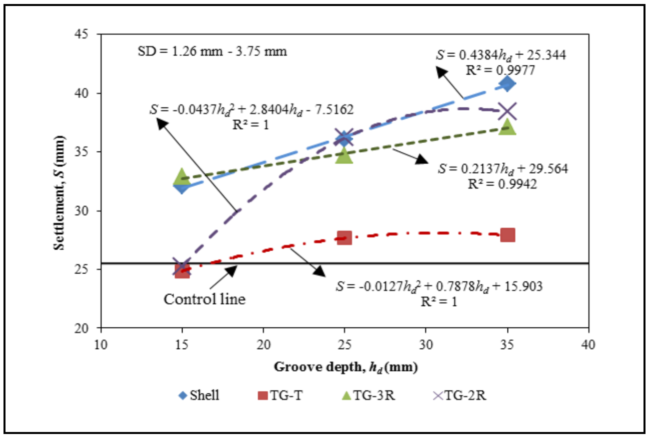


Figure 6 Relationship of groove depth to settlement

3.4 Effect of USCB to Rut Depth in the Wheel Path

Figure 7 shows that rutting occurred as a result of USCB movement under repeated traffic loading and this has led to major structural failure. The overall trend shows that the USCB pavement had its deflection increased in a nonlinear fashion when there were more load repetitions. TG-R and Shell-R USCBs experienced decreasing rut depth, while TG-T USCB underwent increasing rut depth forming which was more severe than the control blocks. One the other hand, the Shell-R USCB had the least rut depth.

Decreasing rut depth indicates that the bedding sand has 'settled-in' after maximum load repetitions. The result also revealed that lesser rut depth is caused by thinner bed thickness and more compacted bedding sand. The same applies to the case of TG-T USCB where the rut depth increased after the bedding sand "settled-in", which was concurrently reflected in its higher pavement displacement. As mentioned before, from visual observation, Shell-R USCB had the least rut depth; this means that this USCB has higher resilience to carry movement load as compared to others, mainly because of its shape. In fact, it has already been established that USCB having lesser rut depth produces stiffer pavement when there is an increase in the number of load repetitions [19].

3.5 Transverse USCB Pavement Deformation

Figure 8 shows the results of transverse rutting/cross-section profile of the wheel track loaded with standard wide single tyre obtained from trafficking test of 10,000 load repetitions. Each result is depicted in the mean of three cross-section transverse profiles. As expected, most rutting occurred under the wheel path and heaves at each side of the wheel track increased with increasing number of load repetitions. The total average minimum and maximum rut depth in the wheel path after 10,000 load repetitions were 6.07 mm (type Shell-R35) and 15.76 mm (type TG-T15), respectively. From observation, both sides had almost equal heave levels.

Rutting occurs when there is a distribution of stress from the tyre pressure to USCB after repeated compaction (load repetition); lesser rut depth indicates better USCB performance and vice versa. The graph showed that Shell-R USCB is the best among others. To conclude, a groove size of 35 mm in depth together with the groove shape significantly affects the rutting of pavement.

3.6 Relationship Between Rut Depth and Bedding Sand Settlement

The relationship between rut depth and bedding sand settlement is shown in Figure 9. The trend noted that deeper groove depth gives higher settlement of bedding sand and leads to lesser rutting. From the figure, the 15 mm and 35 mm groove depths had low and high settlement of bedding sand, respectively. The 35 mm groove depth also experienced the least rutting among other groove categories except for TG-3R USCB, even though the trend is slightly the same. Generally, the results depicted that increasing the groove depth will make the USCB perform better and there will be less rut. The USCB transfers the external load to the bedding sand by virtue of its geometrical shape.

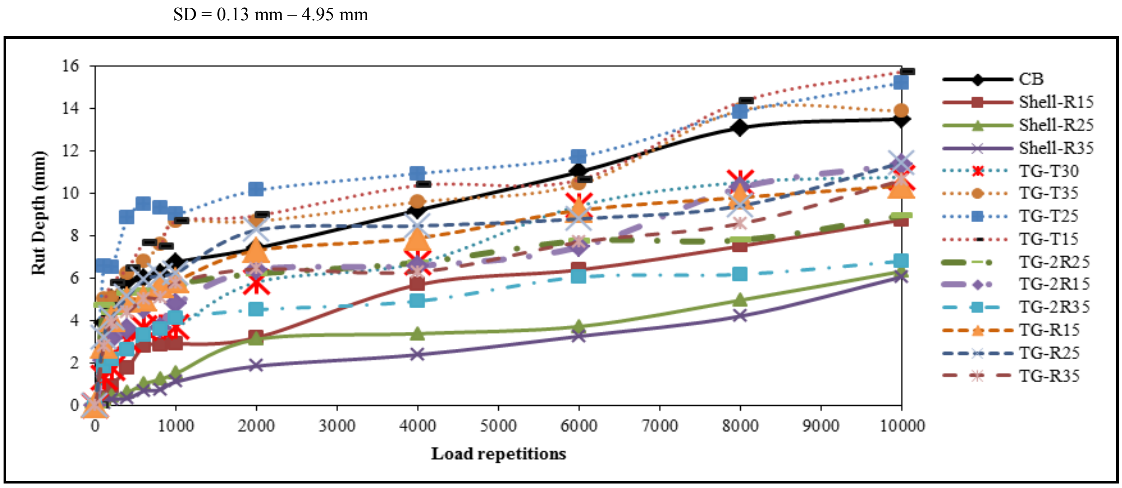


Figure 7 Average rut depth of test pavement for different blocks types up to 10,000 load repetitions

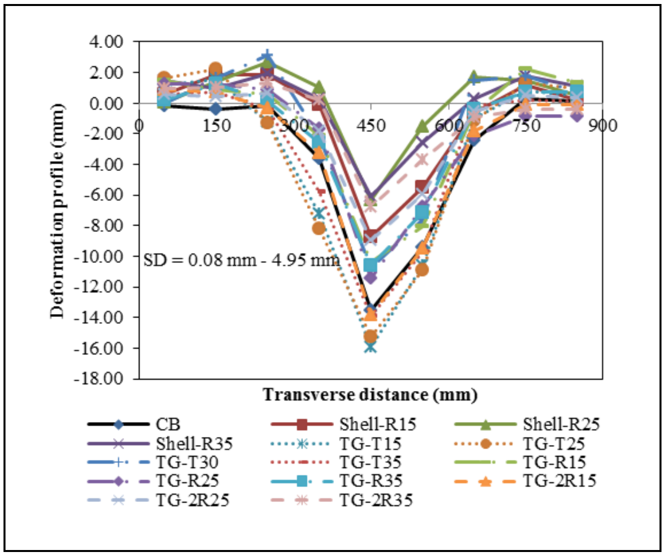


Figure 8 Transverse deformation profiles after 10,000 load repetitions

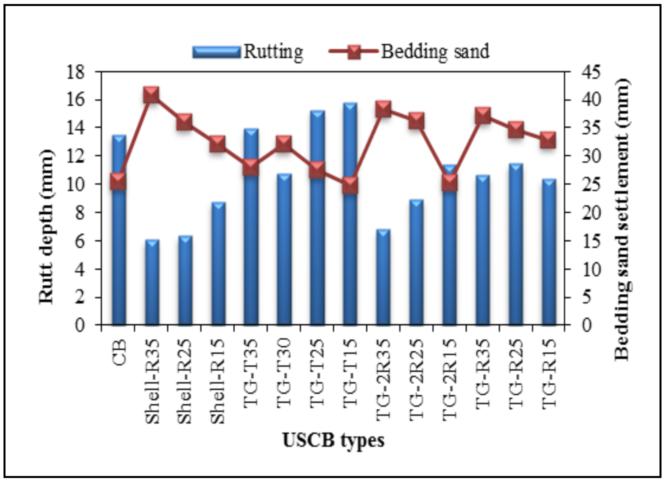


Figure 9 Relationship between average rut depth after 10,000 load repetitions and average bedding sand settlement

3.7 Visual Observation of Joint Width in the Wheel Path

Figure 10 and Figure 11 show the joint width in the wheel path. Various joint widths were visually observed during the testing. The small and wide gap occurred at joints directly under the wheel center and at the sides of the wheel path, respectively. During the HALI test, blocks along the side of the wheel path tend to slant after the wheel load has been repeatedly applied, but the final heave level is almost equal. The overall formation of USCB pavement also shifted slightly during the test, as clearly depicted in Figure 10. Small and wide gaps formed gradually at the joint width after some load repetitions. Physical observation also showed that gaps within the joints widenend along the longitudinal and transverse pavement directions, which also meant that deformation of pavement had increased as the number of load repetitions increased.

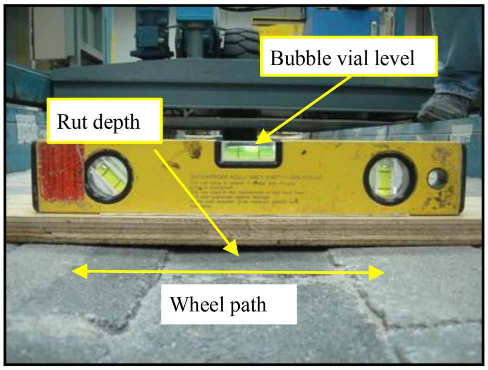


Figure 10 Permanent deformation after 10000 load repetitions

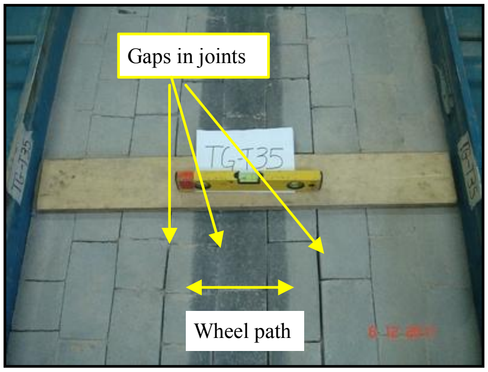


Figure 11 Various gaps sizes in the joint between blocks

3.8 Three-dimensional and Two-dimensional View of Deformed Pavement

Three-dimensional (3D) and two-dimensional (2D) views of deformed surface were generated using the SURFER computer program and are as presented in Figure 12 and Figure 13, respectively. These graphs are important to investigate the development of deformation after load repetitions.

Figure 12(a)-(c) shows that heaving occurred after 10,000 load repetitions along the entire cross sections of the pavement of different block types. Heave formed when the paving blocks transferred the external load to adjacent blocks. This deformation had been clearly visualized in the 2D contour views in Figure 13(a)-(c). The intensity of the contours shows the seriousness of the deformation; darker lines reveals more serious deformation and vice versa. Table 2 shows the maximum and minimum permanent deformation achieved after 10,000 load repetitions.

The results showed that the lesser the groove volume, the higher the deformation under wheel path. This had been proven through the performance of CB and TG-T USCBs. However, generally, all groove types had lesser deformation compared to CB, except for TG-T25. Thus, it is clear that the deformation of pavement widely depends on the groove volume and concrete blocks without groove or has lesser groove volume give higher deformation.

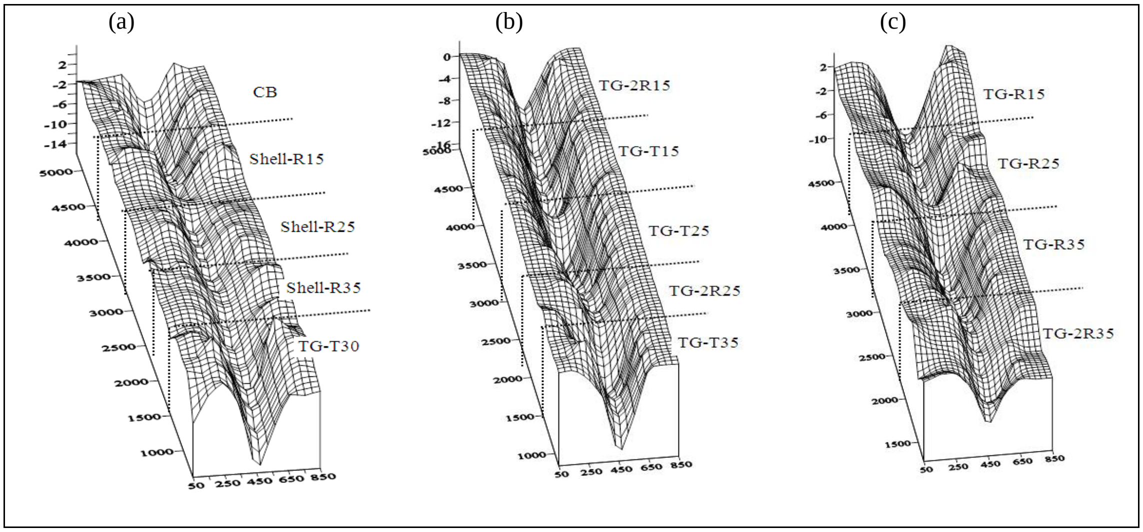


Figure 12 3D view of deformed pavement

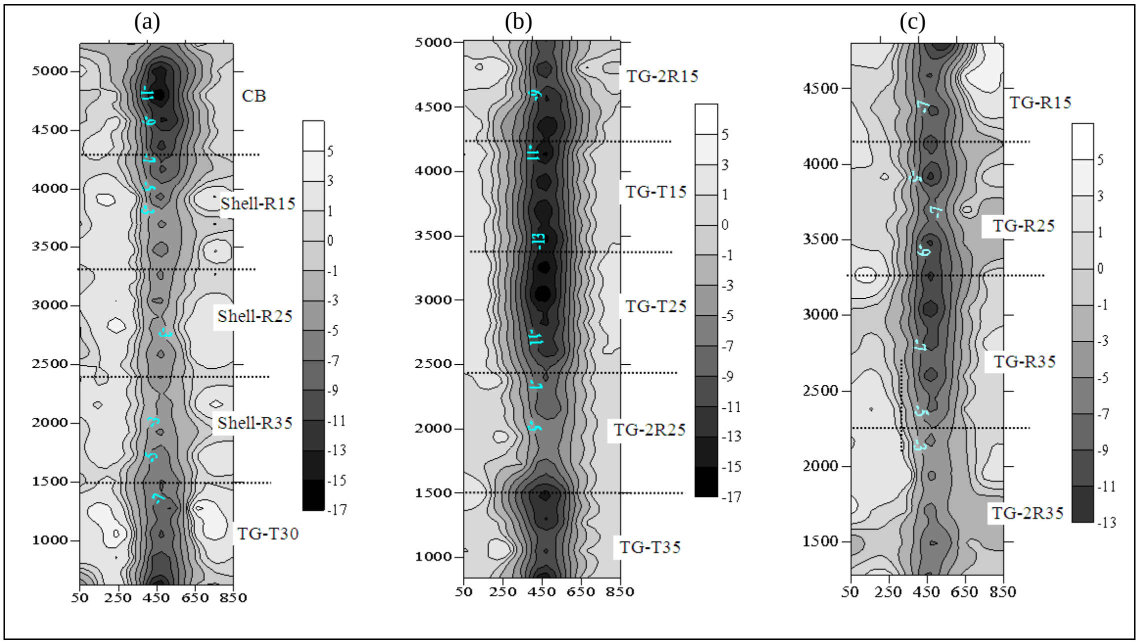


Figure 13 2D view of deformed pavement

Table 2 Maximum and minimum pavement deformation with different types of grooving pattern

Groove Type	Deformation (mm)	
	Maximum	Minimum
CB	-18.39	1.90
Shell-R15	-12.52	3.79
Shell-R25	-7.01	4.14
Shell-R35	-8.28	3.70
TG-T15	-16.57	1.60
TG-T25	-18.13	2.61
TG-T30	-16.62	6.61
TG-T35	-16.14	3.55
TG-R15	-13.28	4.29
TG-R25	-12.74	4.07
TG-R35	-13.60	3.17
TG-2R15	-15.11	2.69
TG-2R25	-9.88	1.68
TG-2R35	-8.21	4.07

In conclusion, the Shell-R groove category had the least deformation as its underlying layers had been fully compacted and no energy was lost during additional loadings. Therefore, it is established that block pavement stiffens progressively with every increment in load repetition. Additionally, the un-trafficked adjacent blocks on the side of the wheel track underwent excessive deformation in the wheel paths as well when the load repetition achieved 10,000 rounds for all categories.

4.0 CONCLUSIONS

The conclusions that can be drawn based on the results from the study are as follows:

- The geometry of USCB, especially in terms of grooves depth and groove size, has significant effect on the settlement of bedding sand.
- Reducing the weight of USCB causes the settlement of bedding sand to increase.
- The rut depth of USCB pavement is highly influenced by groove depth and groove category, and such influence becomes more obvious as the number of load repetitions increases.
- The groove category of Shell-R performed better than the other groove categories. Also, it exhibited a lesser rut depth with every increment in the number of load repetitions. Additionally, the Shell-R35 USCB produced the lowest rut depth among all Shell-R categories.
- Increasing the groove depth causes higher settlement of bedding sand and leads to lesser rut.
- Gap between joints formed under and at the side of the wheel path. The corresponding USCBs tend to slant when the number of load repetition increases. Additionally, the deformation of pavement occurred simultaneously along the longitudinal and transverse pavement directions when there are more load repetitions.
- Heave at each side of the wheel track increased almost equally with increasing number of load repetitions, and this happened due to excessive load transfer from wheel to adjacent blocks.
- When the underlying layer had been fully compacted, only minimal deformation would occur and no energy would be lost during additional loadings.
- High settlement means that the USCBs are capable of receiving higher stresses and such, the pavement deformation during trafficking will lessen.

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