Laboratory performance of crumb rubber concrete block pavement

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Abstract

The aim of this study was to investigate laboratory performance of crumb rubber concrete block pavement (CBP). Four different paving blocks containing 0% (control), 10%, 20% and 30% rubber by total sand volume with compressive strength ranging between 23 MPa and 64 MPa were used. The test pavement was subjected to 10 000 cycles of load repetition under a single truck wheel via a tyre inflated to 600 kPa. Nine measurements of pavement deformation and joint width were made at various stages of the trafficking. Additional tests, including, pull-out, skid resistances and falling weight test were then carried out. Overall, crumb rubber CBP is observed to show inferior performance than conventional CBP in rut, deformation, skid resistance and shear resistance but showed a great improvement in toughness. Thus, all paving blocks studied in this project has great potential to be used according to traffic volume and types of applications.

Keywords: accelerated; performance; deformation; paving block; crumb rubber

1. Introduction

Interlocking concrete block pavement differs from other forms of concrete pavement in that it is made from small mass-produced paving blocks manufactured in a factory rather than in-situ. Beneath the Concrete paving blocks (CPB), the pavement normally comprises of a layer of bedding sand, compacted base and, sometimes, sub-base laid over a compacted or stabilised sub-grade. The purpose of the compacted base is to distribute loads so that stresses and strains developed are passed to the sub-base and sub-grade, within the capacity of the materials in these layers.

CPB are usually mass-produced and good control can be exerted over the variability of the product. The blocks can therefore be manufactured to achieve excellent dimensional and strength tolerances. However, in spite of the high quality (characterized as composite material with high compressive strength), failure such as spallings and cracks are still observed on the blocks when they are subjected to traffic due to low toughness. Furthermore, there is no doubt
that a CPB is more liable to break (fail in flexural) than to be crushed (fail in compression) under traffic.

Thus, it is anticipated that an ideal concrete block for pavement used should be durable with low maintenance cost. A new idea of CPB mixed with crumb rubber was introduced to resolve some of the known existing CPB problems such as moderate tensile strength and low toughness (Sukonrasukkul and Chaikaew 2006, Ling and Nor 2006a). One of the objectives of crumb rubber-filled in concrete is to provide good resistance in cracking and fracture which is very desirable because normal concrete is a brittle material (Li et al. 2004). In addition, it is also to enhance the toughness and ability to absorb fracture energy.

When taking a closer look to concrete block pavement, it is very important not only to consider the mechanical properties of paving blocks but also the structural performance when subjected to trafficking loading repetitions. Rutting, pavement deformation and effect of joint width were evaluated before the commencement of trafficking and after 50, 100, 250, 500, 1000, 2500, 5000 and 10 000 load repetitions by means of Highway Accelerated Loading Instrument (HALI). A series of tests, including shear resistance, skid resistance, and impact resistance were also conducted in order to compare their performances with conventional paving blocks.

2. Crumb rubber concrete paving block
The manufacturing of high quality new paving block mixed with crumb rubber was produced in actual industrial production conditions (specialized manufacturing equipment under vibration and extreme pressure) based on formulations developed in laboratory trials (Ling and Nor 2006a). Two independent mixers were used with different capacity and worked in parallel to ensure facing layer being added for appearance. Initially, aggregate, coarse sand, cement and crumb rubber were mixed in body mix mixer, water was then added to the materials and mixed again until the desired moisture content for these mixtures was obtained.

The mixtures were transferred from the pan mixer to a feed hopper and closely controlled by an automatic weighting system. The hopper discharged the correct amount of mixture into the mould with internal dimensions of 210 mm long × 105 mm wide × 60 mm depth. The mould was filled by the body mix and first vibration and pressing were applied. The face mix was poured into the mould for second layer, and then final compaction and vibration were applied. The hydraulic ram was released and the head lifted to allow early stripping of CPB from the steel moulds. The detail process of CPB making can be found in (Ling and Nor 2006b).

2.1 Properties of concrete paving block
Table 1 shows the properties of paving blocks. All these four mixtures including the control mixture are prepared with cement, aggregate and sand in the proportion of 1: 1.87: 3.77 by weight, and are expected to achieve a target compressive strength of not less than 30 MPa at the 28 days of age. The crumb rubber used in this study to replace partial sand at facing layer and body layer were 1-3 mm and 1.5 mm, respectively. Due to low specific gravity of rubber particles, the weight of blocks decreases with the increase in the percentage of rubber content. Moreover, increase in rubber content creates more air content, which in turn reduces the unit weight of the mixtures (Siddiquw and Naik 2004). The decrease in weight of paving block is negligible when
rubber content is less than 10% of the total aggregate volume.

<table>
<thead>
<tr>
<th>Mix Notation</th>
<th>Rubber Content (%)</th>
<th>Depth (mm)</th>
<th>Top Surface (mm)</th>
<th>Weight (kg)</th>
<th>Strength (MPa)</th>
<th>Visual Observations</th>
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<tbody>
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<td>Type I</td>
<td>0</td>
<td>59.6</td>
<td>5.5</td>
<td>2.82</td>
<td>64</td>
<td>Very good</td>
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<tr>
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<td>5.0</td>
<td>2.82</td>
<td>63</td>
<td>Good</td>
</tr>
<tr>
<td>Type III</td>
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<td>5.0</td>
<td>2.74</td>
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<td>Fair</td>
</tr>
<tr>
<td>Type IV</td>
<td>30</td>
<td>59.8</td>
<td>3.3</td>
<td>2.68</td>
<td>23</td>
<td>Small crack, delamination</td>
</tr>
</tbody>
</table>

As for the results of the visual inspection of two-layer paving block, no honeycombs, cracks or outstanding deformation were found on the blocks in mix Type I and II. On the other hand, at the higher rubber content in Type III and IV blocks, cracks may appear on the facing layer and delamination occurred between the layers.

2.2 Surface colour

Figure 1 show the surface colour of the paving blocks in the mixes with crumb rubber replacement ratios of 20% and 30% is slightly darker than that with the crumb rubber substitution ratios of 0% and 10%. This slight coloration would not cause problem for trafficked pavement use.

![Figure 1. Four mixes of crumb rubber concrete paving blocks.](image)

3. Project description

One method to evaluate the performance of the concrete block pavement is to use accelerated pavement loading devices (Steven et al. 1999). Accelerated loading devices have been widely used during the last decade to evaluate the long-term pavement performance in a relatively short period of time. Many accelerated pavement loading devices have been developed ranging from full-scale to model devices and can be operated under controlled laboratory conditions.

The construction of pavement test sections of HALI is schematically illustrated in figure 2. This instrument was developed in the year 2006 by authors and all operational characteristics and detail description was documental by Ling et. al. (2006). The design of HALI mainly referred to the design of RUB-StraP carried out by Koch (1999) and NUROLF designed by Professor John Knapton in the year 1991. HALI consist of several components which are attached to the base.
frame. The loading mechanism is applied to the pavement by a mobile carriage. The mobile carriage which is mounted on two rigid and frictionless guide rails, enables loading to be moved forward and backward along the rail. The performance of this instrument was calibrated and assessed (Ling et al. 2007).

The paving blocks were installed on a steel test bed with 1000 mm width and 5480 mm length. A steel plate was covered with a 3 mm thick hard neoprene which simulates subgrade layer. Over the hard neoprene, a 0.2 mm thick plastic sheet was used as an experimental expedient to cover it in order to avoid contaminating the hard neoprene with the bedding sand (Knapton 2000). The dry bedding sand from single source of river in accordance to BS 1377 Part I (1990) was used and spread in a uniform layer to give a depth of 50 mm. This value was selected based on the experimental results by Shackel (1994). The figure of 50 mm is also seen as a trade-off between the desire for the sand layer to be as thin as possible to avoid excessive deformation and practical construction constraints (Sharp and Armstrong 1985). Prior the test, the sand was oven dried at 110°C for 24 h to maintain uniformity in test results. A maximum dry density of 1.73 kg/m$^3$ was obtained.

Over the bedding sand, the paving blocks were laid manually by hand. Where necessary, at the edges of the test frame, blocks were sawed to fit the test frame. The blocks were installed with joints 5 mm wide. The jointing sand was placed and compacted by a plate vibrator. The second joint filling operation was carried out to ensure that the joints were fully filled. Finally, the pavement was compacted again until the entire pavement was fully compacted.

The detailed layout of the test pavement is shown schematically in figure 3. As shown in figure, four types of paving blocks: Type I, II, III and IV with equal areas were constructed under HALI (1000 mm x 645 mm, 27 blocks/section) for trafficking test. A test width was set at about 1000 mm for lateral movements by beam carrying a single loading wheel.

Prior to the testing, load cell and data logger were used for the instrument calibration. Throughout the test in this project, a control panel was programmed to a constant speed of 0.18
m s\(^{-1}\). When working continuously, HALI achieved 150 cycles per hour. Typically, for road vehicle, the axle load of 1000 kg with a tyre (contact) pressure of 600 kPa was set to the wheel load to apply uniform pressure acting over circular contact areas (Ling et. al. 2007). The instrument was run up to 10 000 repetitions for a complete trafficking test.

![Diagram of Traffic Testing Layout](image.png)

Figure 3. Layout detail of test pavement.

4. Pavement investigation and testing methods

4.1 Rut and three-dimensional deformation measurements

Rut and permanent deformation under the HALI testing was measured with reference to a fixed datum after 50 repetitions to the maximum repetitions of 10 000 cycles. Nine dial gauges were mounted at 110 mm apart laterally (X-axis) on the mobile carriage rigid beam. The measurement process involves the manual positioning of the rigid beam for each of the twelve cross sections longitudinally (Y-axis) to measure the deformation of pavement after the commencement of the accelerated trafficking test. Once a cross section data was recorded, the rigid beam was moved to the next cross section and the process was repeated. By this means, the system provides 108 height measurements at known plan positions on the surface (on a 1000 mm x 2580 mm grid test bed). When all the cross sections has been measured, the survey data was processed using the SURFER program which uses a Kriging routine to generate a representative surface from the survey data (Mills et al. 2001). A three-dimensional view of the deformed surface is obtained from using the SURFER computer program.

4.2 Joint width measurement

The measurement of joint width is important because it partly determines the failure of the pavement. During this study, irregular joint widths were visually inspected. An area that exhibited this distress was identified. Figure 4 shows a digital vernier calipers was inserted into the joint below the chamfer at the middle of the length of the block and measurement was read. This
measurement technique is introduced by UNILOCK (1997) for joint width identification. Location of the joint width at panel A, B, C and D of three cross sections is indicated in figure 4. For a test section, each panel joint width value represents the average result of three cross sections.

Figure 4. Joint width measurement using digital vernier calipers.

4.3 Pull-out test

Figure 5 shows the pull-out test equipment which allows an individual block to be extracted from the pavement. To ensure that adjacent blocks did not rotate during the extraction process and thereby grip the block being extracted, the test equipment applied its reaction load directly onto adjacent blocks.

In order to eliminate the effects of the bedding sand under the blocks, the equipment was designed to allow unrestrained upward movement under load of an individual block from its matrix without affecting the surrounding blocks. In this way the shear resistance would apply to the joints only. It is noted that in practice a load applied to the pavement would induce stresses...
principally in a downward direction but no means of measuring the effect on the joints could be devised. The extraction force measured by the equipment was considered to be equal to the shear force developed between blocks (except for the weight of the block). The equipment therefore provides an effective yet a simple means of identifying actual stress within the joints occurring under a variety of simulated loading conditions (Clifford 1984).

Load application and measurement were facilitated using a hydraulic jack and an electronic load cell of 100 kN capacity stacked centrally on the reaction beam. The two anchor bolts were extended in length using threaded studs and studs connectors. The upward movement was measured at each end of the block at mid-point using two linear voltage displacement transducers (LVDT’s) accurate to 0.01 mm, impinging upon datum brackets to the surface of the block.

4.4 Skid resistance test
The British Pendulum device is a portable skid resistance tester for measuring the skid resistance of a wet pavement surface. The apparatus measures the frictional resistance between a rubber slider and the pavement surface. The rubber slider is mounted on the end of a pendulum arm. The blocks (under the wheel path) of each test sections were therefore chosen to represent the pavement in use.

The visual inspection and skid resistances at four test sections were monitored prior to trafficking. Monitoring was stopped at the end of the trafficking test after 10 000 load repetitions. In accordance to American Society for Testing and Materials (ASTM) the average of four readings was calculated for each of the tested block (ASTM E-303 Standard test method for measuring surface frictional properties using British Pendulum Tester). Some aggregates or rubber particle polish under traffic were recorded.

4.5 Falling weight test
To perform impact resistance test, a similar falling weight method conducted by ACI Committee 544 (1988) was used. A 3.76 kg falling weight was dropped from a height of up to 50 cm, directly onto a paving block sitting on a constructed pavement model. The loading face had a diameter of 44.6 mm for the purpose of uniformly transferring the impact load to the paving block. Test was conducted at the end of the trafficking test, loading was dropped on a single block of the pavement model which consisted of a layer of 50 mm thick lose bedding sand.

5. Results and analysis
5.1 Transverse rutting profiles
Figure 6 shows the results of transverse rutting/cross section profiles of the wheel track loaded with the standard wide single tyre. This figure was obtained from the results of test pavement of 50 and 10 000 load repetitions. Each of the results shown is the mean of 3 cross section transverse profiles. As expected, most of the rutting occurred under the wheel path. It is clearly seen that the heaves at each sides of the wheel track increases with the increasing number of load repetitions. The total mean rut depth in the wheel path after 50 and 10 000 load repetitions of 1000 kg load magnitude is approximately 2.0 mm and 14.5 mm, respectively. An interesting observation obtained is that the right side heave level of the wheel path is higher than the left
side heave level. There is a difference of 9.53 mm between the right heave level and the left heave level after 10 000 cycles of load repetitions.

This difference of heaves level at both sides is believed caused by the off-centered load distribution from the wheel. Therefore during trafficking test; the load distribution of the wheel concentrates more on the right hand side of the wheel path. As a result, the heave level at the right side is higher.

![Graph showing mean rut depth in the wheel path](image)

**Figure 6.** Transverse deformation profiles after 50 and 10,000 load repetitions.

### 5.2 Mean rut depth in the wheel path

Figure 7 shows a composite graph of mean rut depth in the wheel path of the four test sections from the initial reading to the final reading at 10 000 load repetitions. The trend shows that the pavement deflection increases in a nonlinear manner when the load repetition cycles keep increasing. It is also noticed that the rate of deflection decreases when the load repetitions keep increasing.

During loading, additional compaction of sand under blocks occurs, and some part of the energy was lost during the process. From the visual observation, after a certain number of repetitions, the compaction of the underlying layer could reach its full extent and no energy was lost during additional loadings. As a result, the deflection and recovery become the same. Thus, it is established that block pavements stiffen progressively with an increase in the number of load repetitions.

From the figure, it is observed that the test bed had “settled-in” after 10 000 load repetitions during which the rate of rut depth formation was relatively rapid. The rate of increase of rut depth with load repetitions was substantially reduced. Differences in settling-in deflections are shown in the results given in the figure. Practically, the pavement would be trafficked over a greater width, and settlement would not generally be limited to a narrow section.

The deflections from all the test sections are almost the same; despite Section I which is slightly better in rut resistance than other test sections block pavement. Comparing Section II, III and IV, results are similar, irrespective of the percentage of crumb rubber content mixed in paving block.
5.3 Longitudinal rut depth

The longitudinal rut depths are taken from the central wheel path along the pavement. All the blocks at each section response to loading is substantially controlled by the bedding and jointing material which allows dissipation of stresses by a flexible mechanism. The function of the bedding sand is to respond to compressive forces induced by vertically applied loading through individual blocks. In addition, the bedding and jointing sand to some extent resists the deformation of individually loaded blocks due to transmits forces laterally by means of shear stresses.

Figure 8 shows the typical longitudinal view of rut depth at different load repetitions. It is seen that the test Section IV of the pavement track has an approximately 5% greater deflection than the other test sections. At Section IV, rutting is subjected to increase slightly higher at the last three cross sections of the pavement track with a distance of 660 mm. Other than that, the rutting remains relative constant at the Section I, II and III of the pavement track. The constant rutting distance of the pavement section is approximately 1980 mm, which started from the 1st cross section to the 9th cross section of the test pavement.

These findings are in agreement with the earlier researches (Shackel 1979, Shackel 1980, Rollongs 1982, Panda and Ghosh 2002) which have concluded that the compressive strength of the paving units has little influence on the response of block pavements subjected to traffic due to their small size subjected to compressive stress with negligible bending stress. It is also noticed that, the elastic modulus of the entire block layer is much higher than that of underlying materials. The blocks behave as rigid bodies in the pavement and transfer the external load by virtue of its geometrical characteristics, rather than its strength, to the adjacent blocks and underlying layer. It is established that load-associated performance of block pavements is independent of the compressive strengths of the blocks considered in this study (compressive strengths range from 23 MPa to 64 MPa). Therefore, CPB incorporating crumb rubber has a great potential to be used as an alternative pavement where high toughness of concrete is required.
However, these findings should not be interpreted to mean that compressive strength is unimportant because high concrete strength is often needed to ensure adequate ability to sustain traffic loading.

5.4 Three-dimensional view of deformed pavement

A three-dimensional view of the deformed surface is obtained from using the SURFER computer program. These three-dimensional view graphs were plotted to investigate the development of deformation after having undertaken various load repetitions.

From figure 9, it was observed that heaving occurred in the whole cross sections homogenously instead of the individual block. These points to the similarity of four test sections paving blocks in transferring the external load to adjacent blocks. Figure 9(a) reveals a ridge running along the length of the pavement surfaces, which is due to deformation after 50 load repetitions. The ridge becomes more pronounced after load repetitions achieved 10,000 (see figure 9(b)). However, figure 9(a) shows a rougher pavement surface compared with figure 9(b) due to bigger scale in Z axis.

Figure 9. Three-dimensional view of four sections deformed pavement after (a) 50 load repetitions and (b) 10,000 load repetitions.
A comparison was made on the three-dimensional profile and contour views of deformed pavement between these four test sections in figure 10(a), 10(b), 10(c) and 10(d). Maximum and minimum permanent deformation achieved under the test wheel of 10,000 load repetitions for Section I, II, III and IV were (14.11, -13.50), (16.87, -14.08), (12.09, -13.67) and (14.54, -14.39), respectively.

The results show that all the test sections have slightly different level of developed deformation with Section I having performed best and the others having developed greater deformations. The untrafficked adjacent blocks on the other side of the wheel track were be influenced by the excessive deformation in the wheel paths when load repetition achieved 10,000 at all four sections.

![Three-dimensional profile and contour views](image)

Figure 10. Three-dimensional profile and contour view of single section deformed pavement after 10,000 load repetitions (a) Section I, (b) Section II, (c) Section III and (d) Section IV.

5.5 Joint width

Figure 11 shows the mean joint width at both sides of the wheel path for various load repetitions.
From the data, it is clearly seen that similar results were obtained for all test sections. The mean joint width for panel B and C decreases with the increments of the load repetitions. The panel B and C finally decrease to 0 mm when 2 blocks nearby were stuck together adjacent and no joint width was exposed when the load repetitions reached 2500 and 500, respectively. Joint widths that were too narrow at these panels can be precursors to edge chipping or interlock damage.

Meanwhile, the mean joint width for panel D increases significantly when the load repetitions keep increasing. It was also observed that joint width was too wide after 2500 cycles due to the loss of jointing sand in the joint spacing. Thus, the degree of shear resistance (or shear transfer) between blocks was then reduced. However, the joint width for panel A keeps increasing up to 2500 cycles and then substantially decreased with additional load repetitions. Comparing the joint widths show in figure 12(a) and 12(b) indicates that the joint width for panel A after 2500 cycles was wider than after 10000 cycles. This was mainly influenced by excessive deformation in the wheel paths to the untrafficked blocks on left site of the test section. Referring to figure 12(b), the failure can be accounted for in terms of insufficient densification with as associated poor bearing capacity in the bedding sand layer.

Figure 11. Mean joint width at various load repetitions.

Figure 12. Effect of excessive deformation adjacent to untrafficked area after (a) 2500 and (b) 10,000 load repetitions.
### 5.6 Shear resistance (pull-out force)

Two unit blocks at each test section were selected (refer to figure 3) for pull-out test. Two 12 mm diameter holes spaced at 125 mm and along its centerline were drilled to a depth of 40 mm and installed during the pavement construction. Once the trafficking test was completed, 12 mm diameter masonry anchors were installed into the drilled holes for pull-out test.

Figure 13 shows the relationship between pull-out force and displacement over Type I, II, III and IV. Typically, when extracted, Type I blocks display a linear load/displacement relationship until the load attains approximately 1.07 kN at a displacement of 3.2 mm. While, for Type II, III and IV blocks, sudden reduction in force occurred before the 2.0 mm displacement. At that force, it is noticed that a slip occurred as interlock is lost. The block rotates then grips its adjacent blocks so that it continues to sustain pull-out force until eventually the block is fully extracted out. In the case of the Type II block, initial slip occurred at loads of 0.59 kN. The Type III block lost interlock at 0.81 kN and the Type IV block lost interlock at 0.68 kN. Therefore, only Type I block met the minimum acceptable extraction force proposed by Clifford (1984) of 1 kN.

![Graph showing pull-out force vs. displacement](image)

**Figure 13.** Relationship between pull-out force and displacement.

The maximum pull-out force is often referred to by others but it is not the critical value. It is of less interest than the relationship between pull-out force and displacement at low levels of displacement that occurs at working displacement (Knapton 2000). This is considered to be a more relevant figure since it is the displacement at which initial loss of interlock occurred and is closer to the surface elastic displacements in a highway or heavy duty pavement.

Thus, comparison was made for the pull-out force in kN at a displacement of 1.0 mm. As shown in the figure, sustained force of the Type I, II, III and IV at a displacement of 1.0 mm were 0.68, 0.47, 0.65 and 0.61 kN, respectively. Type II block showed the lower shear resistance, reflecting weaker interlocking among the others.
One of the reasons may be caused by the higher shoving occurred in that particular sections which may influence the function of joint to provide a good shear resistance.

In general, the low pull-out force gained in this study may be due to wide (5 mm) joint width installed in this study. It can be clarified that shear strength of the joint depends largely upon width and the average particle size of jointing sand rather than strength of the block (Clifford 1984). The joint width in between blocks should be properly filled with sand and an optimum joint width proposed was 3 mm by Mudiyono et al. (2006). For joint widths less than the optimum, the jointing sand was unable to enter between the blocks.

5.7 Skid resistance
The results presented in figure 14 shows a systematic reduction in skid resistance with the increase in rubber content from 0% (Type I) to 30% (Type IV). Overall, all types of blocks showed similar reduction in the British Pendulum Number (BPN) after 10 000 cycles of load repetitions.

![Figure 14. Skid resistance before trafficking test and after 10,000 load repetitions of trafficking test.](image)

From the figure it is clearly shown that all the values met the minimum requirement in accordance to ASTM requirement. The BPN of Type I block approached 73, whilst the other types did not exceed 65 after 10 000 cycles of load repetitions. The high values on the blocks at the end of the testing were encouraging from the points of view that no deterioration but only a little polishing of the block surface had occurred for Type III and IV. However, there was no damage caused to any or the block units even at the end of the trafficking test.

It is found that skid resistance is slightly higher for low percentages of crumb rubber in CPB. It might be contributed by the rough surface texture of the paving blocks that creates more friction as the pendulum passed across it. In addition, rubber particles appeared at facing layer decreased the contact area between test surface and pendulum slider also caused the reduction in skid resistance.
5.8 Impact resistance

Table 2 shows the number of drops that were required to cause damage by using the falling weight test on a set of paving blocks. The initial height of drop for the loading was set at 50 cm for this test. However, after the 5th drops, Type IV suffered hairline crack only. The height was then increased to 100 cm, and the loading was dropped. Examination of the Type III and IV showed that both only suffered small cracking at the 7th and 9th drops, respectively. After the 13th and 15th drops, number of cracks occurred at all directions. However, Type I and II had the cracked first at the 1st and 3rd drops, respectively. After the 3rd and 8th drops, the blocks were broken completely. This means that the rubber-filled blocks were capable in absorbing dynamic load and in resisting crack propagation.

The failure patterns of the Type I, II, III and IV under the impact test are shown in figure 15. A comparison of the failure patterns of Type I and II showed transverse crack and failed breaking into two pieces after a few number of shocks. As the volume of rubber was increased to 20% and 30% for Type III and IV, the cracks occurred in all directions instead of transverse and the size of the failure zone was found to increase on block surface, but maintained the integrity the broken pieces. From the figure, it is observed that the energy absorption by rubber-filled blocks (exhibit a higher displacement and does not show a clean split of the sample into two halves at failure mode as rubber content increase) is much larger than that by the control block.

<table>
<thead>
<tr>
<th>Degree of Damage</th>
<th>Sample</th>
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<th>2</th>
<th>1</th>
<th>2</th>
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<th>2</th>
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</table>

Figure 15. Failure patterns of Type I–IV blocks (a) plan and (b) side views.

6. Conclusion

The conclusions that can be drawn based on the results presented in this project are as follows:

• In general, Section I showed a slightly better performance in transverse rut depth profile, mean rut depth and longitudinal rut depth than rubber-filled test sections. All paving blocks behave as rigid bodies and established a load-associated performance of the test.
pavements. Therefore, it is believed that the performance of the test pavement is independent of the compressive strength of the blocks.

- It must be noted that the deformation was a result of underlying layer consolidation and densification since the blocks themselves were not much affected by the loading in terms of compressibility. Distress in bedding sand was caused by lateral movement, loss into voids in lower layer due to compaction and densification, thus it caused the deformations to become excessive and substantial rotations. Visual observations indicated heaving occurred in the whole cross sections instead of the individual block. This point at the similarity of the four test sections in transferring the external load to adjacent blocks.

- Joints have opened out as a result of substantial movement of the blocks after 10 000 of loading repetitions. The open joint width results from the entire panel A, B, C, and D were similar, irrespective of whole cross sections. However, the mean joint width for panel A and panel D increases whilst panel B and C decreases significantly with the increments of the load repetitions.

- Comparison was made for the pull-out force in kN at a displacement of 1.0 mm of Type I, II, III and IV. Type II showed the lower shear resistance, reflecting weaker interlocking among the others. One of the reasons may be caused by the higher rut depth and shoving occurred in that particular cross section and influence the function of joint to provide a good shear resistance.

- Skid resistance results obtained showed a systematic reduction in BPN with the increase in rubber content. At the end of the trafficking test, all types showed similar reduction in BPN. However, the values met the minimum requirement in accordance to ASTM requirement. The only observation after trafficking was that no deterioration but only a little polishing of the rubber particles happened in Type III and IV block surface.

- Nevertheless, the falling weight test results have shown that the rubber-filled blocks have a significant improvement in toughness, energy absorption and more flexibility than control blocks. Comparing the types of the blocks, Type III and IV perform better than Type I and II. It was observed that extra forces was needed to fully open the high rubber-filled blocks because it’s maintained the integrity the broken pieces even after number of falling weight drops.

- Based on the unique characteristics of four type blocks, the blocks can be categorised as high strength and low toughness (Type I); high strength and moderate toughness (Type II); Low strength and high toughness (Type III and IV). Therefore, all types of blocks tested in this study can be introduced to various types of pavement according to their pavement traffic volume and application such as sidewalks or playground where high strength of concrete is not as important.

One of the significant finding in this research is adding crumb rubber in CPB resulting paving block has a very high toughness. This is very desirable because the conventional CPB is a brittle material and easily liable to break, fail in flexural. These issues have been major concern for pavement designer even though there are many advantages to use conventional CPB as a pavement material. Therefore, high toughness suggests that the crumb rubber concrete block pavement has a higher capability in absorbing dynamic load and in resisting crack propagation.
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