Roller Compacted Concrete Pavement (RCCP) forms part of the road network linking dwellers in major oil palm plantation. These roads carry low traffic volume of less than 1000 vehicle per day which includes heavy vehicles carrying palm fruits and timber logs. These heavy vehicles have high axle loads of up to 16 tons. The design life of RCCP is normally up to 40 years. It is common practice in Malaysia to rehabilitate failed RCCP either by granular overlay or reconstruction. However, recycling technique has recently been introduced to treat failed RCCP as part of a comprehensive study on full depth Cold In-Place Recycling (CIPR). This paper presents the findings of a study on RCCP which was rehabilitated using the CIPR and conventional technique of granular overlay. Various stabilizing agents namely foamed bitumen, emulsion, cement and hydrated lime were used in the CIPR technique. This paper also highlights the tests involved in pavement evaluation carried out before and after construction, structural and mix design, as well as construction of the rehabilitated pavement. It was observed that minor and isolated cracks appeared as early as 12 months after construction on the foamed bitumen and emulsion treated sections. Whereas, for the cement and hydrated lime treated sections, similar degree of cracks appeared only after 36 months. The control section has not exhibited any crack. No rutting was observed on all sections. The International Roughness Index (IRI) measured 6 months after construction ranged between 2.0-2.5 m/km. After 36 months the IRI values had increased to between 2.5-3.5
m/km, with the cement treated section being the highest and the foamed bitumen section being the lowest. Based on the Falling Weight Deflectometer (FWD) test carried out 6 months after the construction, it was found that all treatments had reduced the pre-construction central deflection values of between 400-800 µm (microns) to between 250-380 µm. From 6 to 24 month period, the central deflections reduced further before they started to increase. After 36 month the control section had the highest central deflection while the foamed bitumen treated section had the lowest value. The monitored performance up to 36 months indicated that in general all sections performed similarly. Therefore, it could be concluded that the recycling technique provide a viable and cost effective option to rehabilitate RCCP.

**KEYWORDS**

Pavement, Cold in-place recycling, RCCP, Performance, Malaysia

**INTRODUCTION**

**Background**

The use of roller-compacted concrete pavement (RCCP) originated in Canada during the mid-1970s for the forest industries. RCCP is a stiff concrete with zero slump mixture comprised of aggregates or crushed recycled concrete, Portland cement, and low water content. The mixture is placed and compacted with static steel roller similar to that used for asphalt pavement construction.

In Malaysia, RCCP was first introduced in mid 1980s as part of the road network in major oil palm plantations. Typically this type of pavement uses a Grade 25 (25 to 30N/mm²) concrete. Due to its low water-cement ratio, RCCP typically has high strength to carry heavy vehicles with high axle loading (Portland Cement Association, 2009). Generally, these RCCPs have performed satisfactorily, some for more than 20 years with minimal maintenance. The primary modes of failures are in the form of cracks which, if left untreated, will permit water to enter the subgrade and present a continuing maintenance problem (Knight, 1983). It is common practice to rehabilitate failed RCCP either by structural overlay or reconstruction.

Cold In-Place recycling (CIPR), a pavement rehabilitation technique introduced in Malaysia in 1985, is a technique where the asphalt pavement section and a portion of the underlying materials are processed together to produce a stabilized base course. As part of a research program to study the performance of this technique, the Public Work Department of Malaysia (PWD), in collaboration with Kumpulan Ikram and Roadcare Sdn Bhd, has included RCCP in the program. This research program aims to produce a guideline on CIPR in terms of design and construction.

**Objectives**

The objective of this paper is to describe the design, construction and performance of recycled RCCP. It also highlights the field evaluation methodology and mix design procedures that uses laboratory strength parameters such as modulus, indirect tensile strength (ITS) and unconfined compressive strength (UCS) to determine the optimum binder content of recycled samples.
**METHODOLOGY**

**Research Site**

Route FT 1562 was constructed in 1987 serving the Federal Land Development Scheme, Felda Lepar Hilir in the state of Pahang. The existing RCCP was a layer of 100mm thick concrete laid on top of compacted sub-grade layer. This thin layer of RCCP was originally designed for low traffic volume with an Average Daily Traffic (ADT) of less than 1,000 and percentage of heavy commercial vehicles of less than 10 percent. Major activity around this area involves palm fruit plantation and trucks are plying this route to transport palm fruit to nearby factory for processing.

From the analysis of FWD back calculation, the E-modulus of the existing 100mm thick RCCP was found to be relatively poor with average values of less than 1500 MPa. From the visual surface condition survey, majority of the sections had exhibited crack type C5 (block cracks) with depression of up to 70mm. The overall riding quality in the form of International Roughness Index was found to be poor with average IRI values ranging from 6.2 m/km to 9.8 m/km. Figure 1 depicts the photos of the RCCP surface taken from the site.

![RCCP surface prior to treatment](image)

The research site was divided into four (4) 200m sections for four different stabilizers used, namely foamed bitumen, bitumen emulsion, cement, and lime. A control section of 200m length was also constructed using the conventional pavement rehabilitation method of granular and asphalt overlay.

**Pavement Structural Design**

Each section was designed for 10 years design life to withstand traffic loading of between 4 to 8 million standard axles (msa). The structural pavement design utilizes the *mechanistic-empirical* design method with the use of Shell fatigue and permanent deformation transfer functions. The parameters adopted for the design were as tabulated in Table 1. Table 2 summarizes the pavement design for each of the respective sections.
Mix Design Procedure

The existing RCCP was pulverized to the full thickness using a milling machine for about 50 meters and samples of existing material were obtained to determine the grading and its suitability for recycling. For this study, fresh crusher run was added to the pulverized sample at 50-50 proportions. This is to establish the expected grading of the material to be recycled, the optimum moisture content (OMC), and the cement or bituminous binder content required at this moisture content to obtain the specified strength.
The OMC was determined without the inclusion of cement, using the Proctor test. When working with bitumen emulsions, “Fluid Content” is used in place of Moisture Content in defining the moisture/density relationship. Maximum density is achieved at the optimum total fluid content (OTFC), which is the combined mass of moisture and bitumen emulsion (before breaking) in the mix.

The Unconfined Compressive Strength (UCS), Indirect Tensile Strength (ITS), soaked and unsoaked, tests were carried out to determine the amount of stabilizer required to achieve the minimum strength. The UCS is done on the specimens, prepared with a range of stabilizer contents and cured for 7 days, and tested in compression in accordance with test 11, BS 1924 or BS 1881: Part 116. For the ITS test, a standard Marshall Compaction technique of 75 blows per side is carried out (ASTM D1559) and samples are cured for 72 hours at 40°C. For cement and lime, the UCS values should be plotted against stabilizer using the average of each pair of results. For bituminous samples, the laboratory mixed stabilizer content required to achieve the specified strength can be selected from the average of binder content that yield the maximum soaked, unsoaked ITS, Tensile Strength Retained (TSR) and density. For the emulsion and foamed bitumen mixes, 1.5% active filler (cement) was incorporated in all samples. The specified mix design parameters in the PWD Specification are shown in Table 3.

Table 3. Specified Design Parameters

<table>
<thead>
<tr>
<th>Stabilizing agents</th>
<th>Requirements on test parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ITS soaked</td>
</tr>
<tr>
<td>Foamed/ Bitumen Emulsion</td>
<td>≥0.2 MPa</td>
</tr>
<tr>
<td>Cement</td>
<td>≥0.2 MPa</td>
</tr>
<tr>
<td>Lime*</td>
<td>≥0.2 MPa</td>
</tr>
</tbody>
</table>

*Interim values only
N.A. - Not applicable

Construction Methodology

Prior to the commencement of works, the area was thoroughly investigated and checked for the presence of any underground utilities especially cabling work to avoid damaged during the excavation. The existing RCCP was pulverized using milling machine prior to toping up with 100mm new crushed aggregates. The layer was then recycled using the CR 2200 recycling machine to a depth of 200mm as shown in Figure 2. For foamed stabilized section, bitumen and water tankers were connected to the recycler for production of foamed bitumen. The actual bitumen and water content to produce foamed asphalt was determined at laboratory prior to mixing in-situ. The required quantity of Ordinary Portland Cement (OPC) or lime was spread manually over the defined recycling sections.
Immediately after break-down compaction, a grader was used to re-profile the finished recycled layer. Further compaction by a pneumatic tire roller and vibratory roller was carried out to achieve the required degree of compaction. The recycled materials that have been stabilized needs to be properly cured to achieve the minimum strengths prior to opening to traffic (Sufian, et al, 2009). The surface to receive the premix was to be cleaned, free from dirt, loose materials and standing water.

In Malaysia, PWD requires the bituminous overlay to be carried out 3 days after recycling works is completed. Prior to overlaying of asphaltic concrete binder course (ACBC) and asphaltic concrete wearing course (ACWC), a layer of prime coat / tack coat was applied and allowed for curing. ACBC and ACWC were laid as per specified thickness and specifications including any necessary regulating works. Upon completion of laying ACBC and ACWC layers, the road was not opened to traffic until compaction has been completed and the material thoroughly cooled. This was usually not less than 4 hours from the initial compaction process.

**Field Test / Survey**

The field test program involved two (2) phases namely Phase I (pre-construction) for identification of existing condition and rehabilitation design; and Phase II (post-construction) for monitoring of performance during the 5-year research period. Table 4 summarizes the field test/survey carried out at each research section.
Table 4. Schedule of Field Test / Survey

<table>
<thead>
<tr>
<th>Test/Survey</th>
<th>Spacing</th>
<th>Time Interval (month)*</th>
<th>Parameters Obtained</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Manual Surface</td>
<td>10 meter-block</td>
<td>0,6,12,24,36,48,60</td>
<td>crack, rutting, and other surface defect</td>
</tr>
<tr>
<td>Condition Survey</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Asphalt coring and DCP</td>
<td>75 meter (6 no/section)</td>
<td>0,6</td>
<td>layer thicknesses</td>
</tr>
<tr>
<td>3. Falling Weight Deflectometer (FWD)</td>
<td>50 meter (25 meter staggered)</td>
<td>0,6,12,24,36,48,60</td>
<td>deflection bowl data, modulus and residual life</td>
</tr>
<tr>
<td>4. Traffic &amp; Axle Load Survey</td>
<td>-</td>
<td>0</td>
<td>traffic volume and loading</td>
</tr>
<tr>
<td>5. Walking Profiler</td>
<td>10 meter</td>
<td>0,6,12,24,36,48,60</td>
<td>International Roughness Index</td>
</tr>
</tbody>
</table>

**RESULTS AND ANALYSIS**

**Observed Performance**

The research site is monitored for their functional and structural performance. At this stage of the study, the performance of the pavement system as a whole is considered instead of the performance of individual pavement layer. The functional performance of the pavements is evaluated using the International Roughness Index (IRI). The structural performance is measured in terms of the FWD central deflection, Crack Index (CI) and Rut Index (RI). The CI and RI are defined as follows:

- C0: no crack
- C1: single crack
- C2: > one crack – not connected
- C3: > one crack – interconnected
- C4: crocodile cracks
- C5: crack with loose blocks
- R0: no rut
- R1: 1 ≤ R ≤ 5mm
- R2: 6 ≤ R ≤ 10mm
- R3: 11 ≤ R ≤ 15mm
- R4: 16 ≤ R ≤ 25mm
- R5: R > 25mm

**Pavement Functional Performance**

In general, all sections recorded high IRI values (averaging between 6.2 – 9.8 m/km) before rehabilitation was carried out. After rehabilitation, all sections recorded a significant reduction in IRI with average values ranging between 1.8 to 2.3 m/km at the 6 month post-construction monitoring. After 36 month the average IRI values had increased to between 2.5-3.5 m/km, with the cement treated section recording the highest (3.4 m/km) and the foamed bitumen section the lowest (2.5 m/km) as depicted in Figure 3. The increase in the IRI values within the monitoring period suggest that IRI is influenced by the continuous exposure to traffic loading and over time, as also found by Paterson (Paterson, 1986). Figure 4 depicts the photo of pavement surface after 36 month.
Pavement Structural Performance

The pre-construction FWD central deflection values were between 381-789 µm (1 micron = 0.001 mm). All sections indicated a significant reduction of between 30%-60% in central deflection values at 6 months after construction. From 6 to 24 months period, the central deflections reduced further before they started to increase. In general, up to 36 months all the deflection values are within the acceptable range of a sound pavement (< 400 µm). The control section had recorded the highest central deflection (372 µm) while the foamed bitumen section recorded the lowest value (248 µm).

During the first 6 months, no cracks were recorded in all sections. However, crack type C1 to C2 were recorded at localized areas for the foamed bitumen and emulsion stabilized sections after 12 months. It was noted that cement and lime stabilized section recorded C1 to C2 crack after 36 months. However, these cracks were found to be covering an area of less than 5% in each section and did not occur along the wheel paths. The control section has not exhibited any form of crack.
All sections recorded no rutting over a period of 36 months. Figure 5 summarizes the structural performance of FT 1562.

![Figure 5. Pavement Structural Performance over a period of 36 Months](image)

**Laboratory and Field Material Performance**

During construction samples were obtained from behind recycler and laboratory tests were carried out to determine the performance of the CIPR mixes. The tests included aggregate gradation, Indirect Tensile Strength test (ITS), Unconfined Compressive Strength test (UCS), Resilient Modulus test.

**Gradings**

Laboratory mix design for this site was carried out on samples taken from the existing RCCP pulverized using the milling machine. During construction the aggregate gradation of samples taken from behind the recycler showed a slight deviation from the designed gradation as shown in Figure 6. The field samples were coarser than the designed gradation and had relatively higher percentage of fine materials. However, all samples were within the PWD specified grading envelope.

![Figure 6. Aggregate gradation - mix design vs. field](image)
Moisture Content

The field moisture contents as determined by oven method were mostly lower than the OMC/OFC of laboratory design mixes. Lower moisture contents had been recorded on field samples either due to insufficient water being added or some reaction has taken place between cement active filler and water during the recycling process before the field determination of moisture content was carried out.

Binder Content

The field binder contents were calculated by the process of extraction. The field OBCs for emulsion and foamed treated materials were found to be within the tolerance limit with those of the design mixes. This is as expected since the injection of the bituminous binder is controlled by a computerized system of the recycler. Cement and lime contents of the recycled materials were not evaluated since their amounts were pre-determined and controlled by spreading the required quantities within a specified area.

Bulk density

The field bulk densities, as measured by the proctor test, did not differ significantly from the laboratory bulk densities at OMC for each treatment type. This suggests that slight variation in the aggregate gradation and moisture content has insignificant influence on the bulk density of the materials.

Indirect Tensile Strength Test

For emulsion mixes, the field samples registered higher ITS, ITS soaked and TSR values compared to the designed mix. The difference was highest for the ITS soaked value (63%) and lowest for the TSR value (8%). The TSR value was found to be 85% well within the allowable range of 75%. On the contrary, field samples of the foamed bitumen mixes recorded lower ITS, ITS soaked and TSR values than the designed mix. The difference was highest for the ITS soaked value (28%) and lowest for the TSR value (8%). However, it was also found that the TSR value was only 69% i.e. outside the allowable range.

Unconfined Compressive Strength Test

The Unconfined Compressive Strength (UCS) values for the field samples were found to be lower than those of the designed mix samples except for the lime treated sample. The field UCS value for the lime treated samples averaged at 3.05 MPa compared to only 1.8 MPa for the designed mix. The authors are of the opinion that the field value was much higher than the expected value of below 3 MPa for lime stabilized mix.

Indirect Tensile Stiffness Modulus

The field modulus value for foamed bitumen and emulsion treated samples were significantly higher than those of the design mixes. This is due in part to the coarser aggregates found in the field samples which resulted in higher modulus values. It was also observed that foamed bitumen stabilized sample produced higher modulus compared to emulsion stabilized sample after 3 days of curing. The detailed comparison between the mean test values of designed mix and field samples is shown in Table 5.
Table 5. Comparison between designed mix and field sample

<table>
<thead>
<tr>
<th>Stabilizer</th>
<th>Measured Parameters</th>
<th>Lab (%)</th>
<th>Field (%)</th>
<th>Bulk Density (g/cm³)</th>
<th>ITS (kPa)</th>
<th>Soaked ITS (kPa)</th>
<th>TSR (%)</th>
<th>UCS (MPa)</th>
<th>Modulus (MPa)</th>
<th>Grading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emulsion</td>
<td></td>
<td>2.9</td>
<td>6.1*</td>
<td>3.17**</td>
<td>2.262</td>
<td>2.39</td>
<td>252</td>
<td>377</td>
<td>197</td>
<td>322</td>
</tr>
<tr>
<td>Foamed Bitumen</td>
<td></td>
<td>3.1</td>
<td>6.4*</td>
<td>4.70**</td>
<td>2.262</td>
<td>2.16</td>
<td>488</td>
<td>378</td>
<td>364</td>
<td>260</td>
</tr>
<tr>
<td>Cement</td>
<td></td>
<td>-</td>
<td>6.5</td>
<td>5.79</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.1</td>
<td>-</td>
</tr>
<tr>
<td>Lime</td>
<td></td>
<td>-</td>
<td>6.5</td>
<td>6.72</td>
<td>2.262</td>
<td>2.30</td>
<td>-</td>
<td>-</td>
<td>1.8</td>
<td>3.05</td>
</tr>
</tbody>
</table>

* Optimum Fluid Content (OFC)
** Moisture content

Cost Analysis

The initial construction cost for each 200m treatment types are summarized as in Figure 7. It highlighted the cost for crushed aggregate top-up, CIPR works, coatings, and asphaltic concrete layers. It was noted that control section produce the lowest cost, followed by CIPR with cement, lime, foamed bitumen and finally CIPR with emulsion. However, the life cycle cost analysis for each treatment could not be ascertained yet since all sections have not undergone any major maintenance to date and there is no deterioration models had been established for this purpose.

**CONCLUSIONS**

Based on the findings as discussed above, treating failed RCCP using CIPR technique is proven to be a viable option. Mix design procedures similar to those carried out for bituminous pavement can be used for RCCP. The assumed seed modulus for recycled RCCP of 2000 MPa for bituminous stabilization is also achievable.

The research has shown that up to 36 months, the functional and structural performance of recycled RCCP sections are performing as well as the conventionally rehabilitated section. In fact, the foamed bitumen
treated section showed a better performance especially in terms of the roughness index and FWD central deflection values.

It is concluded that the aggregate gradation of samples obtained by milling differ significantly from those obtained from behind recycling machine. The aggregate gradation greatly influences the strength parameters of the recycled mix.

REFERENCES


LIST OF ABBREVIATIONS

ACBC  Asphaltic Concrete Binder Course
ACWC  Asphaltic Concrete Wearing Course
ADT   Average Daily Traffic
ASTM  American Society for Testing and Materials
BS    British Standards
CIPR  Cold In-Place Recycling
CR    Crushed Aggregate
DCP   Dynamic Cone Penetrometer
FT    Federal Trunk Road
FWD   Falling Weight Deflectometer
IRI   International Roughness Index
ITS   Indirect Tensile Strength
MPa   Megapascal
msa   Million Standard Axles
OMC   Optimum Moisture Content
OPC   Ordinary Portland Cement
OTFC  Optimum Total Fluid Content
PWD   Public Work Department
RCCP  Roller Compacted Concrete Pavement
TSR   Tensile Strength Retained
UCS   Unconfined Compressive Strength